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# Flow Visualisation Techniques in Wind Tunnels Part I – Non optical Methods

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**In this article, an attempt is made to describe and review the most widely used methods for flow visualization. The first part describes the basis and applications of different visualization methods (non optical) for subsonic and supersonic flow in wind and water tunnels: direct injection methods, (smoke, dye, fog and different small particles) visualization methods by electrolytic and photochemical dye production, gas and hydrogen bubbles, special techniques, flow visualization by tufts, oil, liquid crystals, pressure and temperature sensitive paints.**
**A considerable attention is paid to flow visualization techniques performed in VTI wind and water tunnels and almost all presented photos have been recorded during tests in laboratories of VTI.**
**Optical methods and their application for compressible flow visualization will be given in the second part of the article.**

*Key words*: **flow visualization, wind tunnel, water tunnel, research method.**

## Introduction

FOR centuries, fluid flow has been studied in various ways and today, fluid flow is still an important field of research. The areas in which fluid flow plays a role are numerous. Gaseous flows are studied for the development of cars, aircraft and spacecraft, and also for the design of machines such as turbines and combustion engines. Liquid flow research is necessary for naval applications, such as ship design and is widely used in civil engineering projects, chemistry, medicine and so on.

In all kinds of fluid flow research, the visualization is an important tool in experimental fluid mechanics, which can provide the overall picture of the flow field. Flow visualization has probably existed for as long as fluid flow research itself [1-6]. Experimental flow visualization techniques are applied for several reasons:

– to get a picture of fluid flow around a scaled model of a real object, without any calculations;
– to develop or verify new and better theories of fluid flow or models.

If the flow could be made visible by some kind of flow visualization technique, it would be possible to observe flow phenomena which are essentially inviscid (e.g., vortex flows, flows distant from surfaces) as well as those phenomena which are dominated by the effects of viscosity (e.g., boundary layer flows, separation) [1-38]. In addition to qualitative observations, under certain conditions it would be possible to make quantitative measurements from flow visualization data as well [1-6, 8-10].

Flow visualization may be divided into surface flow visualization and off-the-surface visualization. Surface flow visualization involves tufts, fluorescent dye, oil or special clay mixtures, which are applied to the surface of a model. Visual inspection of such tufts and coatings as a function of time or after some time, will give valuable information on such things as the state of the boundary layer (laminar or turbulent), transition, regions of separated flow and the like. It must be remembered in such visualization that what is observed on the surface is not always indicative of what is happening in thee free streams.

The second type of visualization involves the use of such tracers as smoke particles, oil droplets or helium-filled soap bubbles. Each of these methods requires appropriate lighting and some device for recording the image such as a still or video camera. If the flow field is illuminated in a plane by appropriate masking of the light source it is possible to examine discrete sections or slices of the flow.

The optical methods can be used to visualize compressible flows. The three principal optical methods for flow visualization are: shadow, schlieren and interferometry. These methods will be the subject of the second part of the article.

The advent of computer technique and digital image processing make it possible to automatically analyze flow visualization effects and extract qualitative and quantitative information, which may not be readily available from conventional flow measurements [1, 5, 12, 21, 23, 30, 32, 36, 38]. Recently, a new type of visualization has emerged: computer-aided visualization. Experimental flow visualization is a starting point for flow visualization of numerical simulations using computer graphics. In the area of fluid dynamics, computers are extensively used to calculate velocity fields and other flow quantities, using numerical techniques to solve the Navier-Stokes equations. To analyze the results of the complex calculations, computer visualization techniques are necessary and very often used. One possible classification of the flow visualization techniques is the following.

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**II Optical methods:**
1. Shadow method
2. Schlieren method (parallel or focused, grey or colour)
3. Interferometry (classical, holographic)
4. Electronic speckle interferometry and shearography
5. Holographic and Laser Doppler anemometry

**III Special methods:**
1. Energy adding
2. Refractometry
3. Laser light sheet
4. Particle Image Velocimetry

VTI uses several non optics flow visualisation techniques [7-11]:
- wall tracing method with pigment oil film (TiO2, colour pigments, graphite powder, lampblack, fluorescent dye) and liquid crystals
- surface tuft methods with thin nylon or silk monofilaments and fluorescent mini tufts
- smoke visualization techniques: smoke produced in smoke generator; smoke introduced at front of the test section and by vaporization of TiCl4 for local application
- water tunnel flow visualization by the use of gas bubbles, milk as tracer, aniline and methylene dye, aluminium powder and polystyrene particles. Some results of VTI tests are used to illustrate the flow visualization techniques.

## Tracer Methods

The visualization technique of streamlines, filament lines or particle paths, which injects some foreign material into a flow as a tracer is the most popular one and has been widely used over a long period, up to now. These three curves coincide if the flow field is stationary. But in the flow that depends on space and time as well, the three types of curves are different from one another. Which curves will be visualized depends on: where the particles are introduced, the length of the exposure time and the reference system from which the flow is observed or photographed.

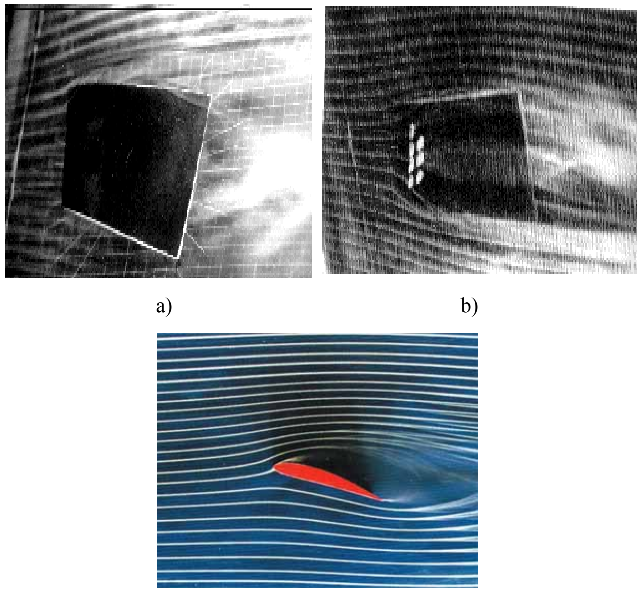
There is no difference between liquid and gaseous flows [1, 2]. The tracer may be smoke, dye, pigment, milk, air or hydrogen bubbles, ozone, fluorescent dye, powder, sawdust, aluminium particle, bakelite etc.

*Smoke Visualization of the Flow*

Recent developments indicate that smoke visualization in wind tunnels, one of the oldest flow visualization techniques, will continue as an important experimental tool in the study of complex flow dynamic phenomena. Improvements in generation and injection of smoke as well as in lighting (laser as a light source), in techniques of acquisition and computation have continued to increase the scientific value of this method [1-3, 5, 9, 15]. Similar results are obtained by flow visualizations with fog and vapour.

The smoke can be very useful in a wind tunnel with low turbulence. There exists no upper limit of speed for smoke line visualization (it was possible to extend the range of smoke line visualization even to supersonic flow velocities).

Smoke line can be generated in a wind tunnel (smoke tunnel) by introducing smoke (produced by smoke generated devices) through small pipes placed in front of a test model, or through holes on the model surface. The choice of using smoke in a wind tunnel depends on several aspects. The smoke must be dense and white for visibility, non toxic and non corrosive. The quality of the observed or photographed smoke line depends also on the choice of the illumination system.



a) b)

c

**Figure 1**. Flow visualization in the VTI smoke wind tunnel (a and b) and in Onera smoke tunnel (c)

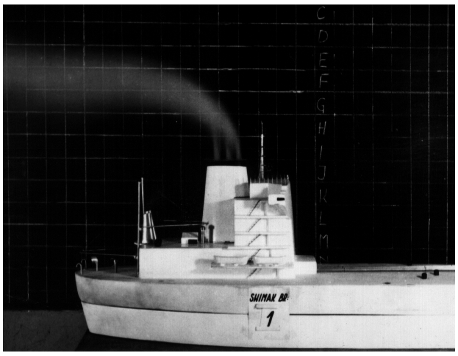
There are three basic types of smoke suitable for wind tunnel experiments: smoke generated by the vaporization of a mineral oil (paraffin, kerosene) mist resulting from the vaporization of certain substances containing bromide or chloride and smoke from burning or smouldering wood, paper or tobacco. The burning or vaporization is done in a smoke generator.

Fig.1 shows the smoke line in the VTI small smoke tunnel (1a and 1b) and in Onera smoke tunnel (1c). Fig.2 shows the visualized effect obtained with smoke introduced in the flow trough the ship chimney.

The flow visualization without smoke generator is possible if a drop of $TiCl_4$ (titanium tetrachloride) or $C10H_7Br$ (bromnaph-thalin) is deposited onto the surface of test model in a wind tunnel; a white stream of smoke will originate from this drop. Liquid $TiCl_4$ in contact with the moist air develops powder $TiO_2$ and HCl. $TiCl_4$ liquid and vapour are corrosive and toxic because of HCl. For this method, the smoke generator is not necessary. $TiCl_4$ has also been used in open-air tunnel, in a large number of experiments. Protection must be employed [1, 2, 3, 13]. This method can be applied for flow visualization in the whole test section as well as for local parts of the model. The following pictures show the effect of smoke flow visualization with $TiCl_4$. Fig.3 shows the flow around airplane model and sphere visualized by $TiCl_4$ drops in the small VTI wind tunnel T-32.

One of the significant improvements in the filed of smoke visualization over the past several years has been the introduction of laser light illumination. The laser beam passing through either cylindrical lens or glass rod usually produces the sheet of laser light. By using a light sheet, cross section of the wake can be illuminated and the position of the vortices can be located. Unsteady flow can be tested by pulsed ruby laser. Recording of the flow visualized effects can be affected by still or moving camera.

Sometimes, that method is classified as special flow visualization method.



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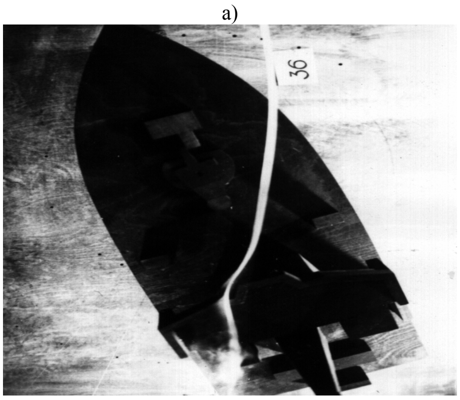

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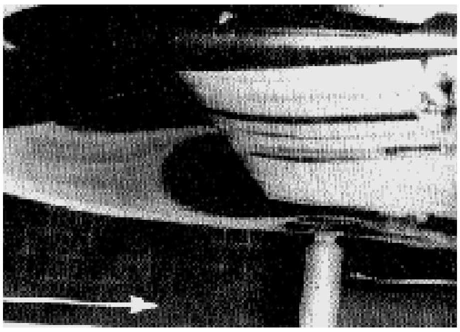
**Figure 2**. Flow visualization with smoke from ship chimney in small subsonic wind tunnel T-32



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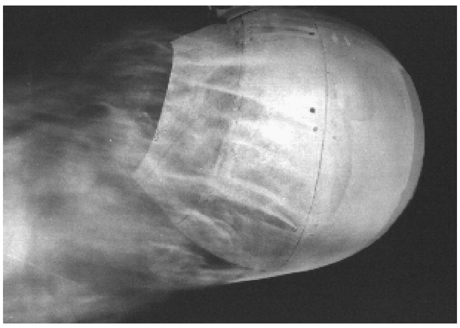

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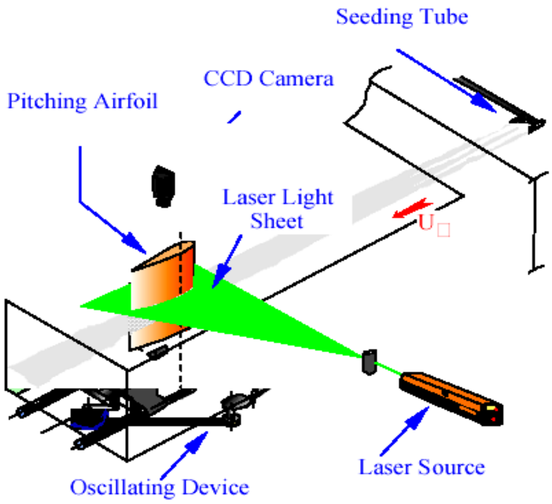
**Figure 3**. Flow visualization with $TiCl_4$ around airplane model (a) and sphere (b) in T-32

Fig.4a shows a possible setup for smoke visualization using laser light sheet [6, 7, 14, 15, 25] and the effects of visualization of vertical flow on the upper surface of the delta wing. Therefore, this sheet can be used to illuminate any cross-section of an airflow that has been seeded with particles. The laser light will reflect from the particles, but dark images will be observed where there is an absence of particles, such as in the centre of a vortex (Fig.4b).

*Visualization using dye*

The visualization of the liquid flow patterns by ejection of dye is an analogy of the smoke visualization technique [1-9, 15, 18, 21, 23, 35, 38]. The mixing of smoke and air is more intense than that of dye and water. A dye for the flow visualization of filament line has to fulfil several requirements: stability with respect to diffusion, the same specific weight as the working fluid and high contrast. Dye can be injected in a tested flow either from a small ejector tube placed at a desired position or from small orifices, that are provided in the wall of a model (Fig. 6a), without the component perpendicular to the model surface. Dye can also be generated in the flow, without disturbing the flow.

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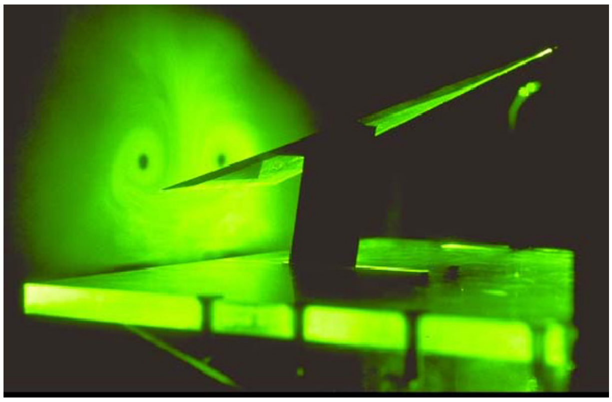

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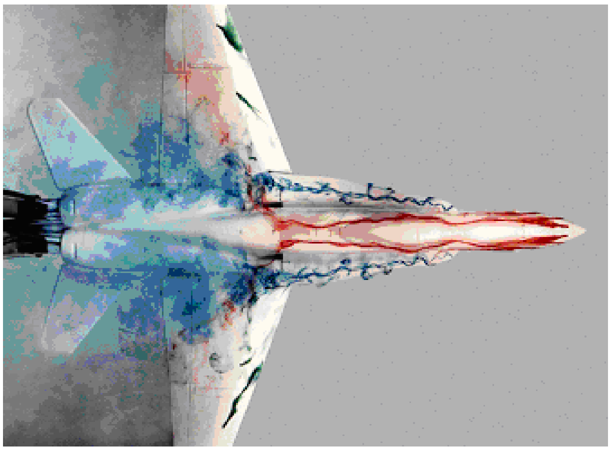
**Figure 4.** Wind tunnel setup (a) and smoke laser sheet visualization of vortical flow on the upper surface of the delta wing (Von Karman Institut)

For the purpose of flow visualization the food colouring dyes, aniline, methylene, potassium permanganate, ink or fluorescent dyes (fluorescent rhodamine) can be used mixed in milk or alcohol. The fattiness of the milk retards diffusion of the dyed solution into water and gives high contrast of the dye line. In a rotating flow, it is important to have dye solution with the same specific weight as working fluid (mixing dye with alcohol).

The aniline violet, red and blue dye, injected from small orifices placed on the top of the model, in the cabin region, visualize the flow around the tested models: 1/48 scale model of F-18 aircraft in the flow visualization facility (ONERA, Fig.5a [18]) and in VTI water tunnel, Fig.5b. Fig.6 shows water tunnel flow visualization by wall dye streaks, around triangular fin mounted on a flat plate [11]. Fig.7a shows flow visualization around hydrofoil in VTI water tunnel with aniline dye and 7b visualization of numerical path line superposed on experimental visualization photos.

The dye methods used in a closed circuit water tunnel increasingly contaminates the water. The tunnel has to be emptied and refilled after each experiment. Visualization with dye is not suited for turbulent flow, since the filaments would decay and the dyes would mix with the surrounding fluid immediately after being ejected [36-40].



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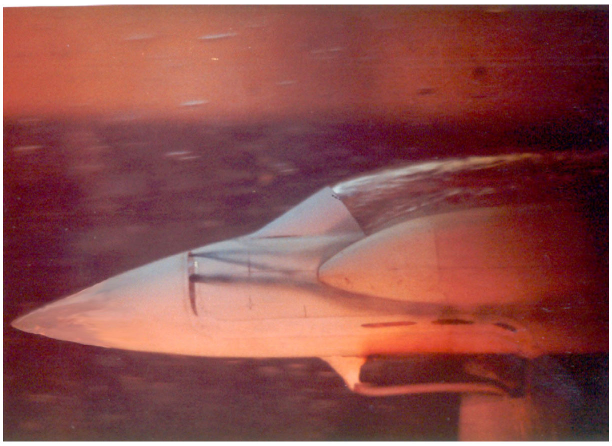

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**Figure 5.** 1/48 scale model of F-18 aircraft in flow visualization Facility (ONERA) (a) and flow visualization with dye in VTI water tunnel.

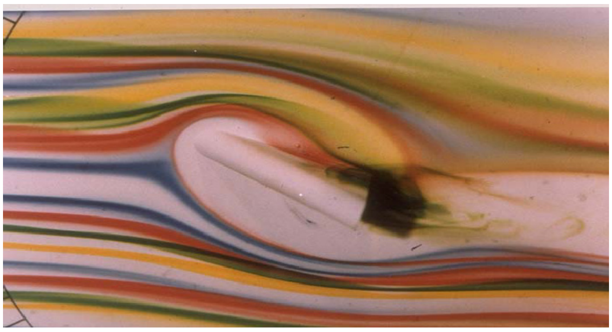
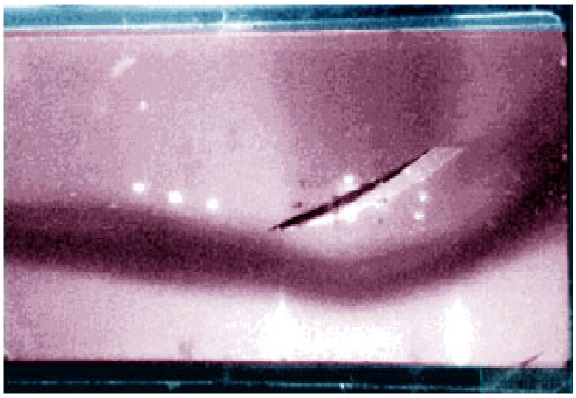


**Figure 6.** Water tunnel flow visualization by wall dye streaks. (Von Karman Institute [15])

Electrolytic and photochemical reactions can produce different dyes in aqueous solutions, which allows flow visualization and velocity profile measurements. Simultaneous production of dye at all points along a defined curve and exact temporal control are the principles by which these methods differ from the conventional dye techniques [2]. Focusing light from a flash tube or pulsed ruby laser onto a point in the photoactive solution fluid (pyridine dissolve in ethyl alcohol or nitrospyran in kerosene) initiates a photochemical reaction, which yields a spot of blue dye within a few microseconds. The dyed portion of the fluid reverts to the colourless form a second after the initial exposure [1]. The recording of those effects must be performed within this time interval with a sodium lamp.

*Visualization by different small particles*

Adding small particles in the flow (water or air) can enable visualization and measuring of the flow velocity. The fundamental assumption is that the velocity of the particles and fluid is identical. The particle tracer can be either solid, liquid or gaseous and the fluid liquid or gaseous, for e.g.: dust, magnesium (Mg), Al2O3, TiO2, aluminium (Fig.8) and polystyrene or cosmetic powder, licopodium, hostaflon, cigarette smoke, metaldehyde, atomized DOP, glass sphere, marble dust, oil drops, water drops, hydrogen, gas, helium bubbles,... The diameter of the particle is between 0.1 to 20 microns [1, 5].



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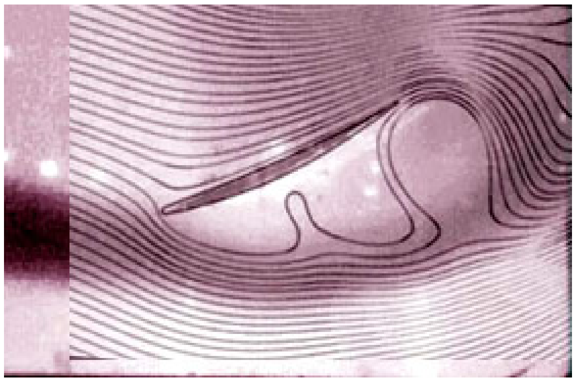

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**Figure 7.** Flow visualization around hydrofoil in VTI water tunnel with: (a) violet aniline dye, (b) experimental and numerical path line visualization (layers opacity 50%) [23, 35, 38]

The presented methods combine the quantitative tracer method with a computer system for the automatic analysis. Same methods are based on tracing a small single foreign particle and sensing its successive location by one or three TV cameras at a certain interval.

For determining the trajectory and local velocity of a spherical particle, the equation of the motion of a single particle must be solved. It is necessary to complete the equation of the motion with gravity and "lift force" acting on the particle in the flow with velocity gradient. The particle velocity approaches exponentially the constant fluid speed. The faster approach, the smaller, the density and the size of the particle. In the compressible flow with shock waves, particles of finite mass and size cannot follow such an abrupt change of the state of motion.

General requirements for the selection of the particles to be used are that the particles are as small as possible, neither corrosive nor toxic and with a high degree of light reflectivity. The device where the particles are injected into the fluid should be located far enough upstream the test regime. The choice of the system for recording the particle movement is primarily dependent on the range of expected velocities and on the particles size and reflectivity. In principle, two methods exist; to take a single or multiple photograph of the flow field with controlled exposure time or to take exposure of the flow field so that each moving particle is reproduced on the photograph by a single streak of finite length. Stereoscopic photos or holograms may overcome the problem of localization of the particle. Nowadays, there are a lot of methods for illuminating and recording [2, 7, 9, 14].

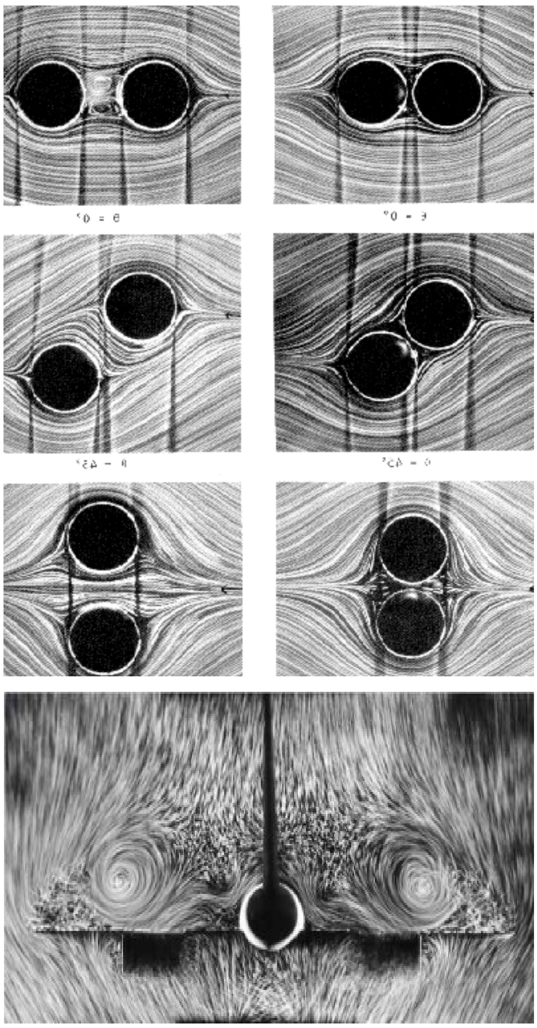


**Figure 8.** Visualization of the flow around two cylinders (a) and around model of Concorde with Al powder (ONERA) [1, 9]

Particle Image Velocimetry (PIV) is an experimental method for indirect flow visualization but method providing direct, instantaneous velocity vector measurement in a cross section of a flow. The method is classified as special method or as the flow visualization method by small particles. The basic principle involves photographing the motion of microscopic particles that follow the fluid flow [9, 10, 14, 15]. PIV is non-intrusive and therefore the measurements obtained are free from disturbance and thus highly accurate. The technique is ideal for unsteady aerodynamic flows.

The positions of the particles are recorded by CCD camera when the light sheet is pulsed $t$ and $t+\Delta t$. The data processing consists of either determining the average displacement of the particles over a small testing region in the image or the individual particle displacements between pulses of the light sheet. Knowing $\Delta t$ permits computing of the flow velocity. The PIV technique may be: 2D PIV, 3D stereoscopic PIV, stereoscopic, holographic PIV (HPIV) the technique for recording of 3D image of particles [14, 15], PIV for two-phase flow, PIV for the micro flow with dimensions lower than 300μm and PIV for combined measuring of velocity, concentration and temperature.

The general error of PIV measurement of air velocity in a wind tunnel experiment is an average of about 3 to 5%. PIV is increasingly used for aerodynamic research [14]. The PIV technique allows recording of the complete flow velocity field in a plane of the flow within a few microseconds. Thus, it produces information about unsteady flow fields, which is difficult to obtain with other experimental techniques. The short acquisition time and fast availability of data reduce the operational time, and hence test cost. One of the main components of commercial PIV systems is the laser: frequency doubled neodium pulse (Nd:YAG), lasers (50 up to 2500 pulse/s), high speed diode pumped Nd:YLF lasers (up to 10,000 pulse/s). Low or high speed cameras for PIV have been including to provide the best combination of resolution, sensitivity and frame rate. The software for PIV is a visual programming language combining complete control of the acquisition, redaction and analysis. The application of PIV method is illustrated in Figures 9 and 10.

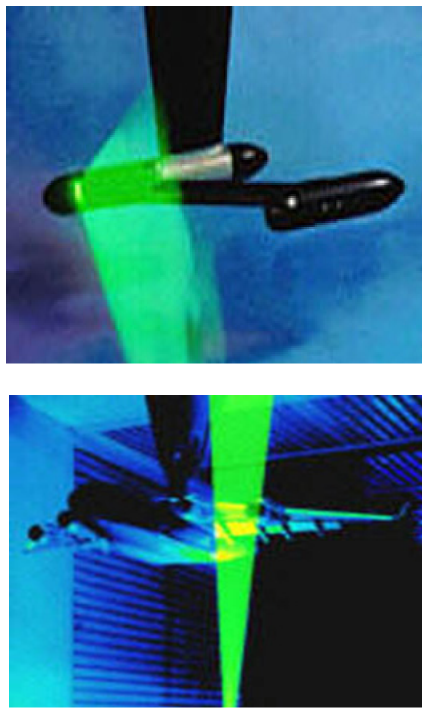
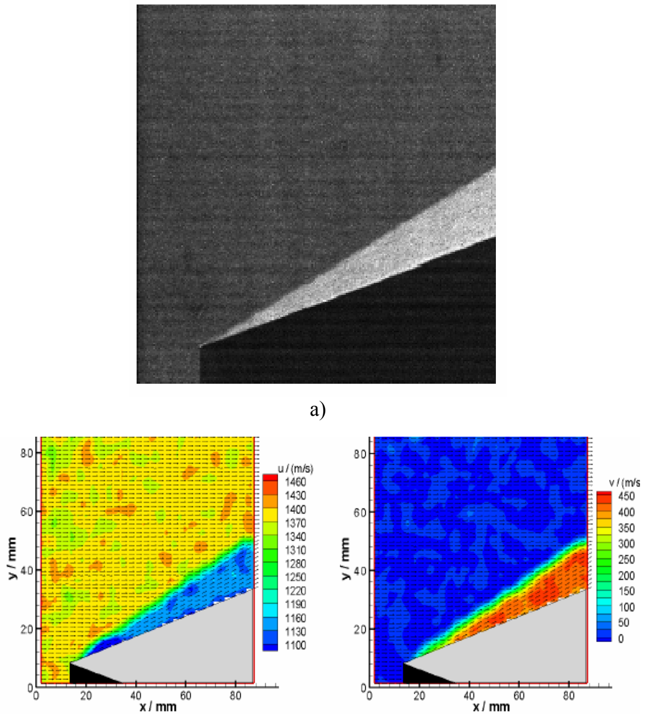


**Figure 9.** Measurements of velocity vector by PIV around the probe and wing (Boeing Company) [16]

Fig.10a shows PIV image of the flow with the Mach-4.5. The shock wave is very well visible on the upper part of the 20°- half angle wedge where the particle density is increased. The fluid density increases by a factor of 3.1

across the shock. For a laser pulse delay of 0.8 μs, a field of view of 90 x 90 mm was imaged with a camera lenses focal length of 135 mm at f-5.6. The measured velocity distribution is shown in Figures 10b and 10c for the horizontal and vertical velocity components respectively.




a)

b) c)

**Figure 10.** a) PIV pictures of wedge, b) horizontal flow velocity, c) vertical flow velocity [22]

*The gas bubble visualization*

Gas bubbles visualization is a tracer method where tracer particles have lower (in the water) or density similar (in the air) to the flow. The observation of such gaseous tracers in a gaseous flow requires the use of optical visualization methods. The gas bubbles change their shape during the motion and in consequence, the drag coefficient of these gaseous tracer particles is not only a function of the velocity difference between the fluid and particle, but also a function of the deforming forces acting on the particle. The gas bubbles can be injected in the flow or generated by electrolysis [2, 18, 40, 50].

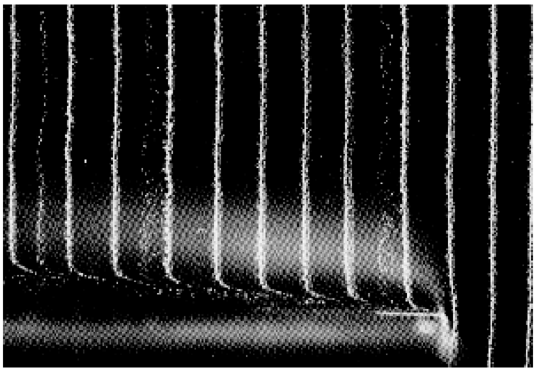
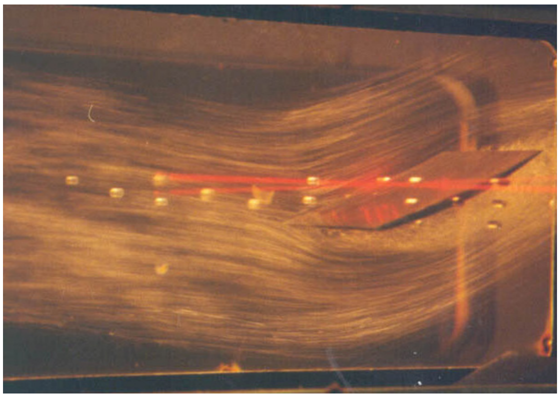


**Figure 11.** Rows of the hydrogen bubbles indicete the velocity profile over the plate[1]

In a conventional arrangement (Fig.11), a thin, fine wire (made of platinum or stainless steel with diameter of the order of 0.01 to 0.02 mm) can be placed in the flow under study. This wire is used as the cathode for electrolyzing the fluid. The anode is placed in some other position. Normal water may serve as the electrolytic fluid, or sodium sulphate or sodium chloride may be added. Hydrogen bubbles are produced on the cathode. They mark a line of fluid elements whose position coincides at a given instant with the position of wire. Any later position of these rows of tracer particles is called a "time line", which is a measure of the local velocity profile. The local velocity can be determined by measuring the distance between the bubble rows divided by the time between the electric pulses.



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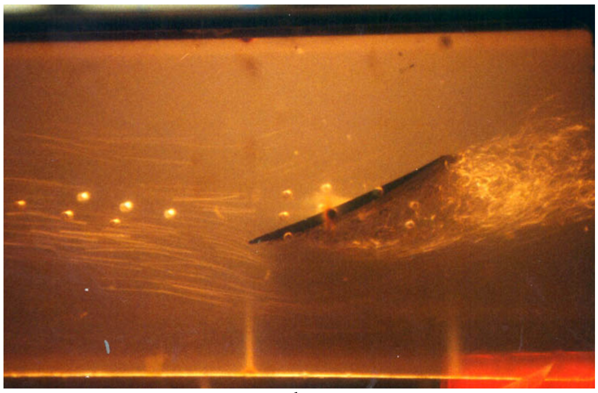


b

**Figure 12.** Flow visualization in VTI water tunnel with air bubbles around hydrofoil with different quantity of injected air [36]

The bubble motion can be recorded with a still or moving camera. Bubbles observation time in the flow is limited by the dissolution of the gas bubbles in the fluid (in water the time is approximately 3 s). The application of this method is limited in the laminar, low speed flow [2, 3, 18]. Fig.12 shows the flow around hydrofoil in the water tunnel (VTI) visualized by air bubbles [38].

## Flow Visualization by Tufts

Very frequently, flow visualization in the vicinity of the model in the subsonic flow is performed using tufts. [1-10, 16-20]. However, tuft size, distribution on the model's surface and sticking are important for turbulent flow testing and higher quality boundary layer visualization on complex models. If tuft diameter is less than 0.1mm, the problem of recording occurs due to a small amount of reflected light and long exposure time. Tufts can be used for testing the entire flow field in the wind tunnel. A grid with attached or glued tufts as screen can be used to visualize the vortex shedding behind the model or in the interaction regime of different fields. The grid should be placed in the wind tunnel normal to the mean flow direction and the tufts pattern should be observed or photographed from downstream (Fig.13.) [2].

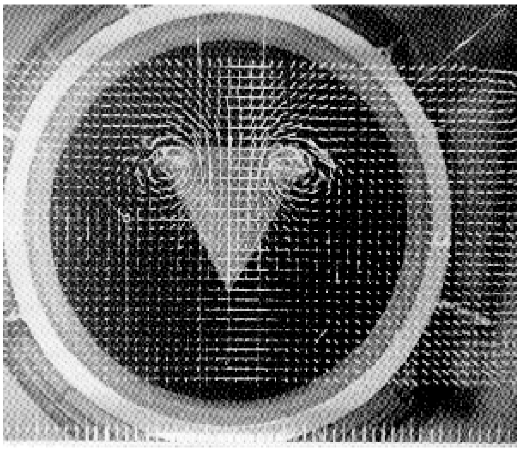


**Figure 13.** Trailing vortices behind delta wing

Fluorescent tufts have numerous advantages in comparison with the ordinary silk tufts [1, 5, 16-20]. By using fluorescent dyes, the tuft diameter virtually increases as well as the illumination, thus allowing higher quality of recording and using thinner tufts (0.01-0.1 mm). They can be stuck onto the model surface using very small glue quantities, (0.04 mm), thus avoiding boundary layer disturbances. Strong centrifugal forces interfering with flow field act on tufts stuck onto the model surface and their resultant determines tuft orientation. Aerodynamic forces are proportional to tuft diameter, while centrifugal forces are proportional to the square of the diameter [17]. The problem with small size diameter is overcame by dying tufts with fluorescent dyes and using light source with rich ultraviolet part of the spectrum, or special filters transmissible to that part of the spectrum. This increases tuft luminance making it look much thicker and brighter. Hg or Xe lamp with UV filters for $\lambda$= 350 nm are used for steady flow testing. Stroboscopic light sources are most frequently used for unsteady flow. Visualization effect can be recorded by still or TV camera. Fluorescent tufts are also used for flow visualization in water tunnels, as well as in-flight flow testing.

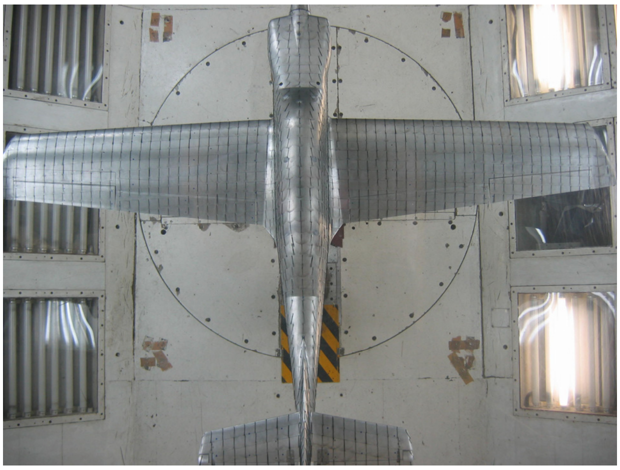


**Figure 14**. Flow visualization with cotton tufts in wind tunnel T-35 for flow with V= 100m/s [37]

Figures 14 and 15 demonstrate the results of the experiments in T-35 and T-32 wind tunnels; flow visualization with ordinary cotton and fluorescent silk tufts. Light combat aircraft model has surface painted in opaque black with 840 tufts stuck onto it. Tufts are made of silk 0.05 mm and 20 mm long (Fig.15). Fluorescent spray was used for tuft dying. The flow speeds have been between 20 and 40 m/s and angle of attack altered from -8 to +24$^{o}$. UV lamp with 100 W has been used as light source. Visualization effects are recorded with still camera Minolta. Black and white Ilford HP film (1600 asa) is used. Exposure time is from 1/60 to 3 s. [20].

In order to overcome the problem of non defined model edges, fluorescent dyes were used for marking. Another method for providing the differentiation of model and the background is to select proper background with different reflexive coefficient relative to model or elevate the film sensitivity to more than 1600 asa.

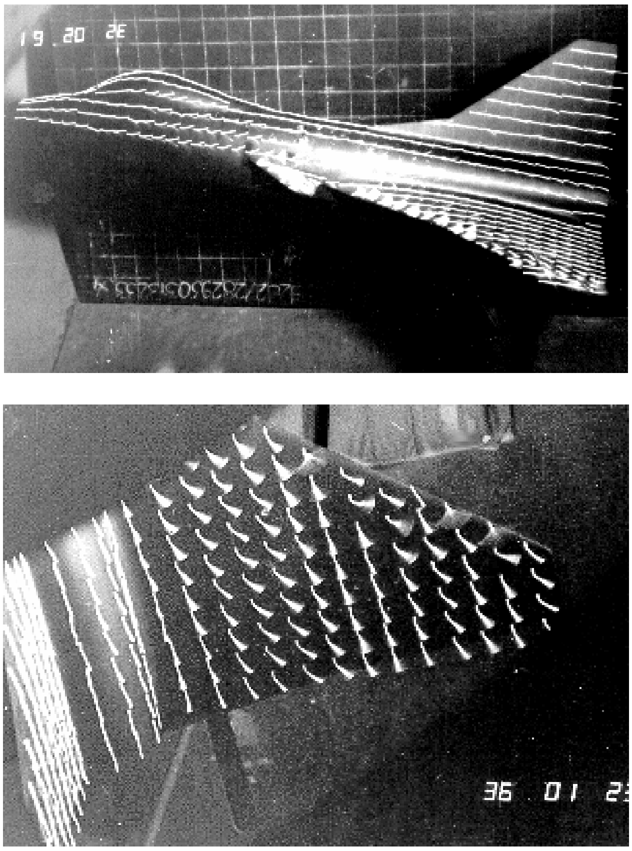


**Figure 15.** Flow visualization with fluorescent tufts in T-32 wind tunnel [20]

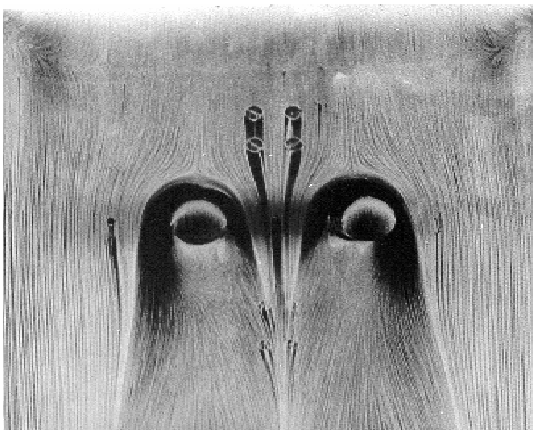
## Surface Flow Visualization Methods

For observation of flow characteristics close to the wall of the model, the body wall can be coated with a certain material which indicates the local wall temperature, surface pressure, or the streamline pattern of the flow adjacent to the wall [1-11].

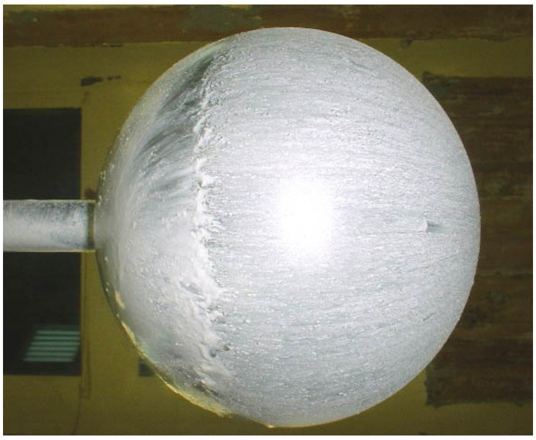
### *Surface Oil Film*

Oil film or dots on the model surface enable obtaining a picture of the flow pattern at the surface of the model placed in the wind tunnel quickly and easily [1-5, 9, 24, 26-36]. The special mixture can be prepared from an appropriate oil and fine pigment ($Al_2O_3$; T $iO_2$, powder, fluorescent dye, colouring pigments, graphite). The technique allows observation of the lines of separation and reattachment of the flow to the body.

Fig.16a shows the visualization with $TiO_2$ + oil on the surface around two vertical cylinders fixed on the plate in T-35 for V=50 m/s and around the sphere used for turbulence test for $M_\infty = 0,2$ (Fig.16b) [9]. Fig.17 gives oil flow visualization of the airflow on the end wall of a turbine blade cascade. Boundary layer flow visualization on the laser guided bomb model with an oil film, performed in the T-38 wind tunnel, (a) top of the model with fins and flow on the fin upper surface (b) for $M_\infty$= 0.9 are presented in Fig.18.



a)

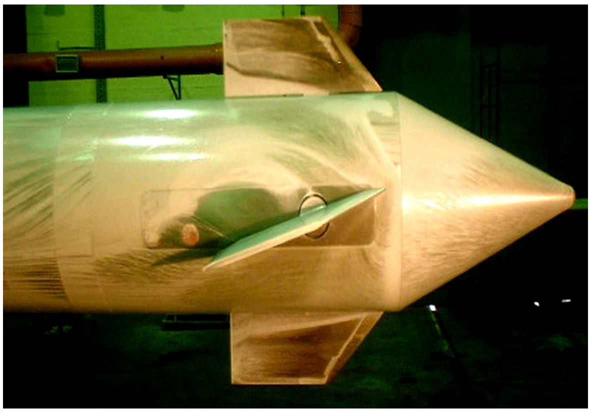


b)

**Figure 16.** Flow visualization around two cylinders fixed on the plate in the large wind tunnel T-35 for $M_\infty = 0,5$ with oil film (a) and around sphere for $M_\infty = 0,2$ (b), [9]

**Figure 17.** Oil flow visualization, airflow on the end wall of a turbine blade cascade. (Von Karman Institute) [15]

Test of the flow field around the axy-symmetrical body – model of the torpedo without fins and control surfaces, was performed in the trisonic wind tunnel T-38 of VTI, for the speed of undisturbed flow that corresponds to Mach number $M_\infty = 0.3$ . Aerodynamic forces and moments were measured by six-component internal strain gage balance. Oil emulsion film with addition of oleic acid and $TiO_2$ powder was used for flow visualization in the boundary layer (Fig.23) [31-33].

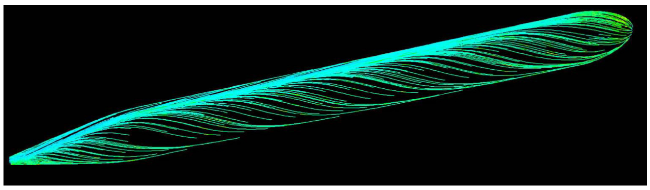


a)

b)

**Figure 18.** Boundary layer flow visualization on the laser guided bomb model with oil film,(a) top of the model with fins and (b) flow on the fin upper surface for $M_\infty = 0.9$ [29, 34].

a)



b)

**Figure 19.** Flow pattern on the model obtained by the experiment (a) and by the simulation of the flow for $M_\infty = 0.3$ and $\alpha = 8^\circ$ (side view) (b) [31, 32].

The goal of the experiment was to make comparison of the aerodynamic coefficients and flow pattern obtained by the experiment and by the simulations of the flow possible. Fluent 6 was used for simulating the flow. Analysis of the shown photographs (Figures 19a and 19b) demonstrates an excellent agreement of flow patterns obtained by the experiment and numerical simulations. Certain differences are visible in the area behind the model support sting and in its immediate vicinity because the sting is not included into the numerical model [47, 50, 51].

*Liquid crystals and temperature sensitive paints*

A surface-temperature distribution can be gained by coating a test model with cholestric liquid crystals [1, 2, 9]. If they are illuminated with white light under a certain angle of incidence, liquid crystals reflect only one light wavelength at each viewing angle, depending on small temperature changes in the crystal sheet. Liquid crystals are able to respond to finer changes of temperature in the boundary layer, due to laminar-to-turbulent transitions or indicate the place of shock waves. The colours of liquid crystals are reverse if the temperature changes in the opposite direction. Therefore, liquid crystals are very attractive for boundary-layer studies. Model to be tested should be made of a material with low heat conductivity and coated with black paint as base. Fig.20 demonstrates the application of liquid crystals for hot streams visualization in a little smoke wind tunnel.

The surface temperature, the local heat transfer rate and coefficient on a body tested in high speed flow facility can be measured by means of temperature sensitive paints. An important difference between liquid crystals and temperature sensitive paints is, that the temperature span over the liquid crystals colour change is much smaller (a few degrees only) than that of paints (several hundred degrees).

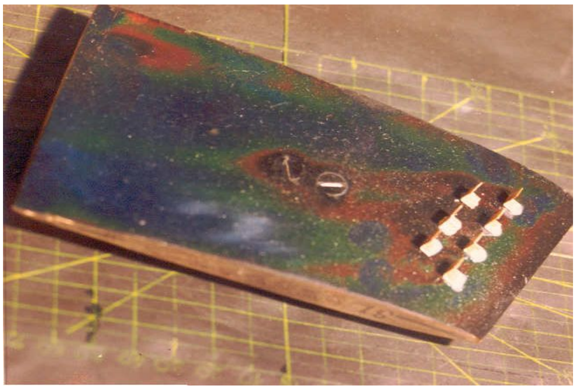


***Figure 20.*** *Flow visualization in the small wind tunnel with liquid crystals [8, 9]*

*Pressure sensitive paint (PSP)*

The spatially continuous pressure and temperature distribution on aerodynamic test surfaces is important for understanding complex flow mechanisms and comparison with predictions of computational-fluid-dynamics models [9, 14, 36]. Conventional pressure measurements are based on pressure taps and electronically scanned transducers. Pressure taps provide pressure information only at discrete points.

PSP technology has emerged as an alternative for determining static and transient surface-pressure fields for aerodynamic applications and flow visualization. The pressure sensitivity is based on the oxygen ($O_2$) quenching of luminescent molecules dispersed in a film that is coated onto a test surface. In practice, the PSP/TSP (temperature sensitive paint) coating is illuminated with light of the appropriate energy (colour) to excite the coating-entrapped probe molecules. The resulting luminescence output is inversely proportional to the surface pressure or temperature of the test model.

The resulting luminescence from the model can be imaged using a CCD camera. Pressure is correlated with the ratio of PSP images acquired at a reference condition of the known pressure and temperature (wind-off) and condition (wind on) through a modified form of the Stern-Volmer relationship. Calibration of this intensity ratio $\left(I_{ref} / I\right)$, or lifetime ($\tau$) is then correlated with the output of the CCD, providing a convenient tool for generation of a spatially continuous pressure map, allowing the entire test surface to be sampled simultaneously. CCD cameras have a million or more pixels and this technique provides continuous surface-pressure measurements with high spatial resolution. The output of the CCD array can be visually represented as a two-dimensional image, with the luminescence corresponding to a grey or false-colour scale. Fig.21 represents the illustration for PSP applications.

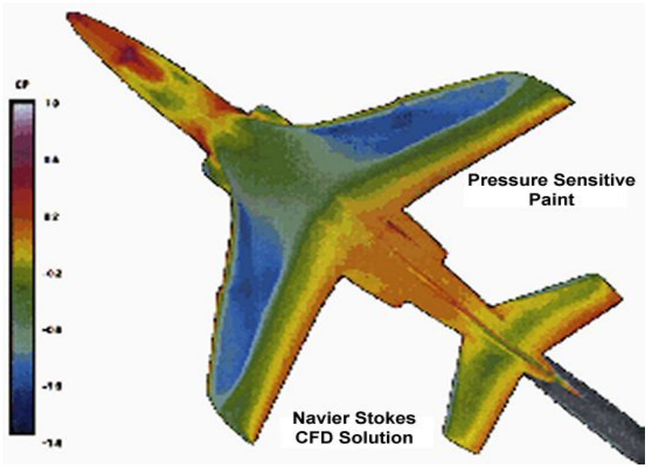



**Figure 21**. A comparison of pressure results between PSP (right side of model) and Computational Fluid Dynamics (left side) [36]

*Flow Visualization with Special techniques*

Third group of visualization methods is based on two principles: introducing a foreign invisible substance into the incompressible flow and visualizing the density variations in the flow by optical methods. The foreign substance in this case is energy transferred to certain portions of the flow to increase the energy level (spark, electron beam and glow discharge methods) and make artificial density variations. Such portions of the flow have an altered density and can be visualized by the optical methods.

They are applied to visualize the rarefied gases that are for several reasons distinguished from the ordinary compressible flows [1]. The gas flow with extremely high level of kinetic energy becomes luminous in a stagnation point where the kinetic energy is transferred into heat. That heat exits electronic transition in the gas and the flow itself is visible (Fig.22).

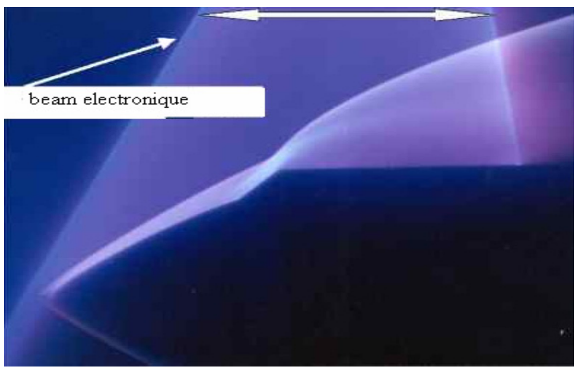



**Figure 22.** Flow visualization by electronic beam in hypersonic wind tunnel for $M = 10$ [9]

An intensive hot spot can be obtained by means of a spark discharge across two electrodes into a gas stream or using a giant pulse laser for producing the luminous plasma (Q-switched giant pulse ruby laser of 100 MW). Another way of artificially introducing density changes in a flow is to seed the flow with a foreign gas of different refractivity (benzene vapour, CO2).

Very often, methods mentioned as special techniques where the double refracting liquids, solutions or suspension of certain macromolecules in a neutral solvent are used for flow visualization. A transparent medium can be birefringent if it consists of optically anisentropic molecules. An incident light wave is separated into two linearly polarized components with the planes of polarization being perpendicular to one another. The birefringence in these solutions can be observed by means of a polariscope. With the isochromates and isoclines recorded on a photograph, a data field from which shear distribution in a two-dimensional flow field can be deduced and flow velocity calculated.

Analogous methods are of interest in the flow visualization technique. The hydraulic analogy has the widest application. For e.g., the formation of gravitational waves of long wavelengths on the free surface of a liquid is analogous to the pattern of pressure waves in an isentropic supersonic flow [2]. The hydraulic analogy has been used to investigate the wave pattern in the supersonic flow around models. Fig.23. shows the flow around a model in free surface water tunnel that is analogous with the supersonic flow $M_\infty = 4.1$.

For the purpose of flow visualization high speed photographic techniques are usually applied in connection with one of the visualizing methods. High speed cameras with exposure time of $10^{-6}$ to $10^{-9}$ s in connection with associated illumination systems can record the shock wave motion. If a single shot photograph is used, the synchronization between the unsteady flow pattern and the exposure of the photograph must be made. A high speed cinematographic system is also very suitable for visualizing application.

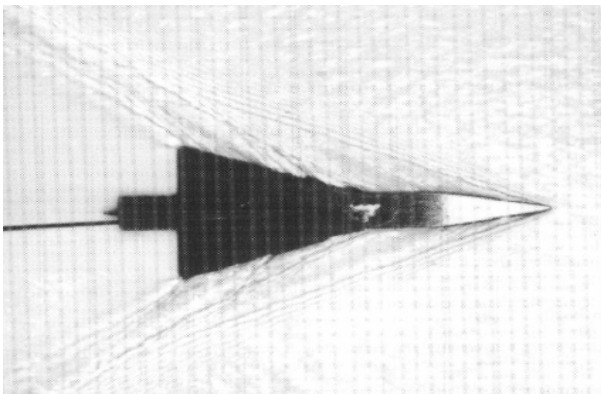


Figure 23. 2D model using the hydraulic analogy to simulate supersonic flow ( $M_\infty = 4.1$ ) [16]

## Conclusion

This paper presents an overview of techniques for flow visualization in different velocity regimes, except the optical methods. Flow visualization is an important topic in experimental aerodynamics and has been the subject of active research for many years in wind and water tunnels of VTI.

A brief introduction to experimental flow visualization methods is given. Every method is illustrated by photos of flow visualization effects. The advent of computer technique, new technology for illumination, modern and very powerful device for digital image recording and processing makes automatical analysis of the flow visualization effects and extracting qualitative and quantitative information possible which may not be readily available from conventional flow measurements. Experimental flow visualization is a starting point for numerical flow visualization of simulations using computer graphics.

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# Metode vizualizacije strujanja u aerotunelima Prvi deo: Neoptičke metode

**U radu je prikazan preged metoda koje se najčešće koriste za vizualizaciju struajnja. Prvi deo opisuje osnove i primena različitih (neoptičkih) metoda vizualizacije podzvučnog i nadzvučnog strujanja u aero i vodenim tunelima; metode s ubrizgavanjem čestica (dim, boje magla, različite male čestice), metode vizualizacije sa elektrolitičkom i fotohemiskom proizvodnjom boja, gasni i hidrogenski mehurići, specijalne tehnike, vizalizacija sa končićima, uljanim premazima, sa tečnim kristalima, boje osetljive na promenu temperature i pritiska.**
**Posebna pažnja je posvećena metodama vizualizacije koje se koriste u aero i vodenom tunelu VTI-a. Skoro sve fotografije, koje su prikazane, snimljene su laboratorijama VTI-a.**
**Optičke metode i njihova primena u vizualizaciji stišljivih fluida je data u drugom delu ovog rada.**

*Ključne reči*: **vizualizacija strujanja, aerodinamički tunel, hidrodinamički tunel, metoda ispitivanja.**

# Методы визуализации потока в аэродинамических трубах Часть первая: Неоптические методы

В настоящей работе приведен обзор методов, наиболее и наичаще использованных для визуализации потока. Первая часть описывает основы и применение различных (неоптических) методов визуализации дозвуковых и сверхзвуковых потоков в аэродинамических и в водяянных трубах; методы с инжекцией частиц (дым, краски, туман, различные мелкие частицы), методы визуализации с электролитным и фотохимическим производством красок, газовые и гидрогенические пузыри, специальные техники и способы; визуализация с нитками, с маслянными покрытиями, со жидкими кристаллами; краски реагирующие на изменение температуры и давления.
Особое внимание посвящено методам визуализации, пользуемых в аэродинамических и водяных трубах Военно-технического института (ВТИ). Почти все приведенные фотографии сделаны в лабораториях ВТИ.
Оптические методы и их применение в визуализации сжимаемых потоков приведены во второй части настоящей работы.

*Ключевые слова*: визуализация потока, аэродинамическая труба, гидродинамическая труба, методы исследования.

# Méthodes de la visualisation du courant dans les souffleries aérodynamiques Première partie: méthodes non-optiques

**Les méthodes utilisées le plus souvent pour la visualisation du courant font l'objet de ce travail. La première partie décrit les bases et l'application de différentes méthodes (non-optiques) de la visualisation du courant soubsonique et supersonique dans les souffléries aérodynamiques ainsi que dans les tunnels hydrodynamiques; méthodes à injection des particules (fumée, couleurs, brouillard, particules variées), méthodes de la visualisation avec la production,électrolitique ou photochimique, des couleurs, bulles de gaz ou à touffes, enduit d'huile, cristaux liquides, couleurs sensibles aux changements de la température ou de la pression. Une attention particulière est prêtée aux méthodes de la visualisation appliquée dans la soufflerie aérodynamique et dans le tunnel hydrodynamique qui sont situés à l'Institut militaire technique à Belgrade. La plupart des photos, publées dans ce papier, ont été prises aux laboratoires de cet Institut. Les méthodes optiques et leur utilisation dans la visualisation des fluides compressibles sont traités dans la seconde partie de ce travail.**

*Mots clés:* **visualisation du courant, soufflerie aérodynamique, tunnel hydrodynamique, méthode d'essai.**