11. Flow Visualization

Most fluids, gaseous or liquid, are transparent media, and their motion remains invisible to the human eye during direct observation. Techniques allowing visualization of the flow, usually referred to as *flow visualization*, are discussed in this chapter. A great variety of such methods is known that enable one to make fluid flows visible, in the fluid mechanical laboratory, in industrial environments, and for field experiments. These methods rely mostly on the addition of a tracer material to the flowing fluid, e.g. dye or smoke, and what is then observable is merely the motion of the tracer. Differences between the motion of the tracer and that of the fluid are aimed at being minimal. Presented in this chapter are surveys of available tracer materials, techniques of introducing the tracer to the flow, techniques of proper illumination of the flow scene, methods of providing optical access to the flow, and recording of the observable information. Some of the flow visualization methods provide qualitative information on particular flow patterns, others allow to measure the flow velocity quantitatively.

11.1 **Aims and Principles of Flow Visualization** 857

11.2 **Visualizations of Flow Structures and Flow Direction** 859
- 11.2.1 The Addition of Tracer Materials as Initial Condition 859
- 11.2.2 Dye Lines and Contours in Liquid Flow 860
- 11.2.3 Smoke Visualization in Air Flows 862
- 11.2.4 Hardware for Flow Visualization Experiments: Illumination, Recording, Confinements of the Flow Regime .. 863
- 11.2.5 Enhancement of Image Quality: Fluorescence, Image Processing 865
- 11.2.6 Direct Visualizations of Velocity Profiles 866

11.3 **Visualization of Free Surface Flows** 868

References 869

11.1 Aims and Principles of Flow Visualization

Flow visualization is a tool in experimental fluid mechanics that renders certain properties of a flow field directly accessible to visual perception. It has always been believed that observation of a process pattern facilitates the development of an understanding and the subsequent analysis of such a *phenomenon*; it is unnecessary to mention that this term indicates the process' visibility. In general and under normal circumstances, most fluids, gaseous or liquid, are transparent media, and their motion must remain invisible to the human eye during direct observation, unless a technique allowing visualization of the flow is applied. A great variety of methods has been reported that enable one to make fluid flows visible, in the fluid mechanical laboratory, in industrial environments, and for field experiments. A reader might argue that he or she has experienced seeing a flowing fluid in nature, e.g., wind, or water waves, or a flowing river. Closer inspection of what is seen in these cases shows that these flows become visible due to the natural occurrence of means equivalent to the experimental methods of flow visualization described herein.

Although the physical principles of many flow visualization methods are rather simple, a number of important discoveries were made with these techniques. A prominent example is the discovery of the existence of coherent structures in turbulent flows, which lead H. W. Liepmann to the conclusion: "It is ironical that coherent structures . . . were all found by the most primitive of experimental methods: flow visualization" [11.1].

Visualization of a flow requires illumination of the flow scene, and the visibility of the flow can thus be regarded as the result of the interaction of light and the flowing fluid. The light is modified due to this interaction and carries information on the state of the flow. Information on this interactive process can be obtained in two different ways (Fig. 11.1).

- One can record the light transmitted through the fluid and compare its properties with those of the incident light. The obtainable information is integrated along the whole path of the light in the fluid (*line-of-sight methods*). The properties of a light wave that are most commonly used for this way of visualization are optical phase and the direction of propagation, which change due to variations of the fluid's refractive index caused by the flow. Typical visualization methods that fall into this category are optical interferometry, schlieren, and shadowgraphy, which are discussed in Chap. 6.
- One may record the light that is scattered from a certain position in the fluid flow. A general assumption is that this light carries information on the state of the flow at the position where this light is scattered from, and that this light is not changed during its further passage through the fluid. Therefore, the recorded information is local, which is of importance if the fluid flow is three-dimensional. The intensity of the scattered light is much lower than that of the transmitted light. Visualization discussed in this chapter is based on light scattering.

The portion of light that is not transmitted further through the fluid (i. e., that is *extincted*) is reflected or scattered from the fluid particles. The intensity of light scattered from molecules is rather weak; in order to generate an intensity sufficient to be visible and recorded by *normal* means, the fluid can be seeded with tracer particles that are much bigger than the fluid molecules. What is then seen is the motion of the tracers, and particular attention must be given to whether this motion is identical to that of the fluid.

Flow visualization by means of observing the light scattered from tracer materials is mainly a qualitative method. If one resolves the light scattered from single tracer particles, the visualization becomes quantitative and allows measurement of the velocity of the scatterers. Such quantitative tracer-based techniques, sometimes

Fig. 11.1 Interaction of a light wave with a flowing fluid

referred to as *quantitative flow visualization*, are treated in Sect. 5.3. Many technical processes are governed by the interaction of a fluid flow and a solid body, and in these cases it is of great interest to know the state of the flow close to a solid wall. The interaction of the flow and the solid surface can be mechanical, thermal, or chemical; visualization methods for near-wall regimes have been developed in which the wall is coated with a material that undergoes a visible change when it interacts with the flowing fluid. Such methods for the visualization of surface flows are discussed in Chap. 7.

With the advancement of computational fluid mechanics the term *flow visualization* is also used for the visual presentation of numerical data. This kind of visualization is the result of progress made with methods that facilitate the perception of large amounts of data values, either from computation or probe measurements. In contrast to its use in these fields, the term *flow visualization* in this chapter refers to physical experimentation.

In the following information will be given on tracer materials, equipment for illumination and image recording; methods will be discussed according to the information obtainable from their application; and a number of examples will be presented for various flow situations. Review literature on flow visualization is available in the form of books that discuss methods [11.2, 3] or just show flow scenes [11.4, 5], journals specializing on this subject, e.g., [11.6], and the state of the art is regularly screened at a number of symposia, among which the International Symposia on Flow Visualization have a long tradition.

11.2 Visualizations of Flow Structures and Flow Direction

11.2.1 The Addition of Tracer Materials as Initial Condition

As stated above, the addition of tracer material ensures that sufficient light is scattered for direct observation of the flow. The materials added to the flow differ principally for the flows of liquids and gases. In order to minimize the difference in the motion of fluid and tracer it is desirable to use a neutrally buoyant tracer material; this requirement can be met in a liquid, but almost never in a gas. The most common tracers are dye in a liquid flow, most often water, and smoke in the flow of a gas, which for the present considerations, is solely air. The addition and dispersion of tracer materials generate, in principle, a two-phase fluid, and what is visualized is the motion of the dispersed phase. Here, however, it is aimed at minimizing the difference between the two phases such that fluid and tracer can be regarded to form a continuum.

What can be seen in the visualization experiment depends strongly on how and where the tracer is added, i. e., on the initial condition of the subsequent motion of the tracer material. Tracer material, released into the flow only for a short instant of time, might be collected in a flow regime where the residence time of the fluid is high, while the rest of the material is carried away with the main flow; in this way, flow structures such as vortices and regimes of separated flow become visible

Fig. 11.2 Smoke visualization of axisymmetric wall jets issuing in an upward direction from three different ring-shaped openings (width 7.5 mm, 3 mm, 1 mm) and at two exit velocities (8 m/s, 42 m/s). Illumination is by laser light sheet. The air jets are adjacent to the wall of a vertical cylinder (courtesy of Prof. Franz Peters, Ruhr-Universität Bochum, Germany)

Fig. 11.3 Smoke visualization of the flow separated on the back of a car. Smoke is injected with a smoke pipe into the separated flow regime (courtesy of Volkswagen AG, Wolfsburg, Germany)

(Figs. 11.2, 3). If the material is continuously released at a particular point in the flow, the tracer pattern visible downstream from this position will be a streamline, if the flow is stationary, and thus the flow direction can be detected (Fig. 11.4). In unsteady flow, the visible line formed by the tracers is called a streakline or filament line; this is the instantaneous locus of all fluid particles that have passed through a particular fixed point of the flow field, here the position of the tracer source. If one observes, e.g., with a long-time exposure, the trajectory that a single particle traverses in the flow field as a function of time, the result is called a particle path. Thus, the particle path contains the integrated time history of the motion of the single particle. The three curves, steamline, streakline, and particle path, coincide in steady

Fig. 11.4 Smoke line visualization of the flow over a car body in a full-scale wind tunnel (courtesy Volkswagen AG, Wolfsburg, Germany)

Fig. 11.5 A two-dimensional water flow model of an artificial heart valve; the length of the streaks is a measure of the local velocity of the tracer particles (courtesy Aerodynamisches Institut, RWTH Aachen, Germany)

flow. Particular attention must be paid to the interpretation of the visible curve pattern if the observer is not at rest with respect to the coordinate system of the flow field, i. e., if relative motion exists between the object and the observer [11.2].

In such a visualization of flow structures and flow lines or direction, the tracer material can be regarded as a continuum, and the motion of individual tracer particles is not observed. At low values of tracer particle concentration in the flow, it may be possible to identify the individual moving particles, e.g., by a time exposure, and to measure their local velocity (Fig. 11.5). Apart from the possibility of producing visible flow patterns and quick surveys of the velocity distribution in an extended flow regime, this way of quantitative visualization has currently lost ground to the methods presented in Sect. 5.3.

11.2.2 Dye Lines and Contours in Liquid Flow

The marking of flow lines and contours in the flow of a liquid by means of dye can be achieved by introducing the dye into the liquid from outside (*direct injection*), or by generating the dye with an appropriate chemical reaction in the liquid. In the second case it is required that the liquid carries respective chemicals in solution, and that the dye-producing reaction is initiated at the correct position in the flow.

Directly injected dye is released either from a small ejector tube placed at the desired position in the flow or from small orifices provided in the wall of a model un-

der investigation. In order to minimize disturbances in the flow, the ejector tube should be small and must be placed far enough upstream of the flow regime of interest. Tubes that normally serve as Pitot probes in air flows, hypodermic tubes, and syringes, with outer diameters of 1 mm or less, are often used as dye injectors. The rate at which the dye is released has to be matched to the average velocity of the liquid; formation of a dye jet at too high a release velocity must be avoided. Dyes used for flow visualization should fulfill several requirements: Besides some general properties such as being nontoxic, noncorrosive, etc., desired properties are neutral buoyancy, high stability against mixing, and good visibility.

Popular dyes for flow experiments in water are food coloring and ink. Optimal conditions can be met by arranging complete dilution of the dye in the working fluid, whose specific weight can be matched by the addition of alcohol. The undesired mixing of the dye with water, particularly if the aim is to visualize flow lines, increases with Reynolds number. Therefore, application of the method is restricted to laminar or low-Reynolds-number flows (Fig. 11.6). A number of recipes are known for stabilizing the dye filaments against mixing in such flows. Most effective is the addition of milk; the fattiness of milk apparently retards diffusion of the dye solution into the main bulk of water, and at the same time, the high reflectivity of the milk particles provides high visibility [11.8]. Another way of ensuring high optical contrast and good visibility is the use of fluorescent tracers. While ordinary dyes such as food coloring and ink require no specific provisions for illumination, fluorescent dyes should be illuminated with the appropriate wavelengths that initiate the fluorescence. It appears that no systematic investigations on the optimization of selection of dyes and illumination have been carried out. Information on these experimental parameters is available in numerous laboratory reports and various publications. For a choice of dyes the reader is referred to Table 11.1 in [11.2].

Fig. 11.6 Dye lines in the vortex flow behind a yawed cylindrical model. The fluid is water, the dye is a mixture of ink, milk, and alcohol (courtesy of Deutsch-Französisches Forschungsinstitut, ISL, St.Louis, France)

Generating a dye without mechanically disturbing the flow using an injector is possible for the purpose of marking the contour or shear layer between two different flows that begin mixing downstream of a given position. Use is made of a dye-producing chemical reaction at the interface of the two flows. Most suitable for such a procedure is the application of pH indica-

Table 11.1 Refractive-index-matching fluids (After [11.7]); n = refractive index; ρ = density; μ = viscosity; ρ_0 and μ_0 are the corresponding values of water at 20 °C; see [11.2] for detailed references

Aqueous solutions of	n	ρ/ρ_0	μ/μ_0
Glycerin	1.33–1.47	1.0–1.26	1.0–1490
Zinc iodide	1.33–1.62		
Sodium iodide (60%)	1.5		
Sodium thiocyanate	1.33–1.48	1.0–1.34	1.0–7.5
Potassium thiocyanate	1.33–1.49	1.0–1.39	1.0–2.4
Ammonium thiocyanate	1.33–1.50	1.0–1.15	1.0–2.1
Organic liquids			
Kerosene	1.45	0.82	
Silicone oil mixture	1.47	1.03	190
Paraffin oil	1.48	0.85	
Turpentine	1.47	0.87	1.49
Soybean oil	1.47	0.93	69
Olive oil	1.47	0.92	84
Castor oil	1.48	0.96	986

Fig. 11.7 Shear layer separating two mixing flows, visualized by means of a pH indicator reaction (courtesy Prof. R. E. Breidenthal, University of Washington, Seattle, USA; see also [11.9])

tors that can be dissolved in water and that change color upon a specific change of the pH value. The pH indicator is dissolved into one of the two streams, and the fluids in the two streams are given different pH values, below and above the critical value where the color change takes place. The mixing zone of the two fluids is visualized by the dye-producing reaction, and the structures formed in the mixing layer become visible [11.9] (Fig. 11.7).

Other dye-producing chemical reactions have been reported that are initiated along a given straight line in the flow, thus allowing the visualization of velocity profiles. These methods are discussed in section Sect. 11.2.

11.2.3 Smoke Visualization in Air Flows

The technique of marking flow lines or structures in an airstream by means of smoke is, in principle, the same as visualizing the flow pattern of a liquid by the injection of dye. Although its application is not restricted to wind tunnels, smoke visualization is a standard experimental tool for these facilities, and its technical advancement is closely related to the history of wind tunnels [11.10]. The term *smoke* is not well defined, and it can be used here in a wide sense, not only restricted to combustion products; it can also include steam, vapor, aerosols, mist. These substances cannot fulfill the requirement of being neutrally buoyant tracers, since the densities of these tracer materials are order of magnitude larger than the density of air. However, the solid or liquid particles of these materials have diameters smaller than 1 μm, thus making buoyancy effects, to a first-order approximation, negligible. The mentioned properties desired for a tracer, neutral buoyancy, stability against mixing, etc., are more difficult to meet than in the case of dyes. The basic types of producing smoke are burning or smoldering tobacco, wood, or straw; vaporizing mineral oils; producing mist as the result of the reaction of various chemical substances; and condensing steam to form a visible fog.

The generation and the use of smoke for visualization purposes is more an art than a technology, and many laboratories have developed their own recipes and equipment. Smoke and aerosol generators are also commercially available, most of them not designed primarily for laboratory experiments but for entertainment and show (*nebulisers*). The majority of smoke generators are based on the vaporization of hydrocarbon oils, particularly kerosene. A kerosene mist (smoke) generator mainly consists of a heating facility and a device in which the kerosene vapor is mixed with an airstream to form the appropriate mist [11.2]. In order to form and visualize smoke lines (Fig. 11.8), the smoke is introduced into the flow by a pipe that should be oriented parallel to the main flow. For wind-tunnel experiments it is preferable to release the smoke at the inlet of the contraction section so that the smoke lines are stabilized during acceleration of the flow in this section [11.10]. In a closed-circuit wind tunnel the smoke would soon accumulate in the tunnel system and, therefore, typical *smoke tunnels* exhaust the air into the outside, and also have high contraction ratios of the nozzle in order to keep the turbulence level low and prevent the smoke from mixing early in the airstream.

Since most wind tunnels are of the closed-circuit type, there has always been interest in using steam as the visualizing tracer material. The idea is that steam in combination with a cooling agent is introduced into the air flow, where the mixture produces a visible fog. After heat exchange with the surrounding air, the fog will disappear, thus leaving the main airstream clean in the recirculating system [11.2]. In na-

Fig. 11.8 Smoke lines around a model airfoil in a low-Reynolds-number wind-tunnel flow (courtesy of Prof. T. J. Mueller, University of Notre Dame, USA)

Fig. 11.9 Karman vortex street formed in the wind downstream of the island of Jan Mayen in the North Atlantic Sea, visible in the formation of clouds (courtesy of Sternwarte Bochum, Germany)

ture, clouds as an accumulation of mist are the tracer material by which the motion of air can becomes visible (Fig. 11.9).

A frequently used chemical method for producing a dense white mist is based on the reaction of titanium tetrachloride, $TiCl_4$, with water. The result of the reaction is titanium dioxide, TiO_2, a white mist or smoke of high optical reflectivity. This mist can be produced in a smoke generator, and also inside the wind tunnel, i. e., without the need to introduce a smoke pipe, by depositing drops of $TiCl_4$ on the surface of a test model, which then reacts with the humidity in the air. Aerosol generators are also of great importance for velocity measurements with laser anemometers and imaging methods, on which information should be found, e.g., in Sect. 5.3.

Fig. 11.10 Open field experiment: smoke visualization of vortex formation during the start of an airplane (courtesy Prof. Cam Tropea, Technische Universität Darmstadt, Germany)

Fig. 11.11 Moist air rises along the slopes of Lanai Island (Hawaii), cools down with increasing height where the moisture condenses, forming a fog that visualizes the wake flow in the steady wind, here from *right* to *left* (W. Merzkirch)

11.2.4 Hardware for Flow Visualization Experiments: Illumination, Recording, Confinements of the Flow Regime

The source, duration and form of illumination must be chosen for an experiment. Front light illumination with ordinary lamps or spot lights may be sufficient for many *simple* flow visualization studies. This situation, with the sun as the source, is also given in open field experiments (Fig. 11.10), or when observing a naturally occurring flow (Fig. 11.11). Time control of the source, either in form of slow-motion, high-speed, or stroboscopic illumination, is required if it is desired to provide information on the velocity in the flow, and it must be adjusted to the expected magnitude of the flow velocity.

In order to provide certain local information on flow structures within the flow field, illumination in the form of a light sheet has been developed and has become the most common way of illuminating the flow scene of interest. A laser is required as the light source. The laser beam is expanded to form a light sheet that defines the plane within which the flow structures are visualized. Expansion can be done with a cylinder lens or a simple glass rod, as indicated in Fig. 11.12. The thickness of the sheet is then approximately equal to the diameter of the beam emitted by the laser, i. e., approximately 1 mm. The laser beam has a Gaussian intensity profile, and in many references, where number values for the light sheet thickness are given, this thickness is not precisely defined. A very thin light sheet might be desirable for improving the spatial resolution if visual-

Fig. 11.12 Expansion of a laser beam by a glass rod (cylindrical lens) for forming a light sheet. The thickness of the sheet is controlled by a second lens

ization is quantitative with the aim of measuring flow velocities. This requires more-refined light sheet optics than a simple glass rod. A so-called telescopic arrangement consists of two spherical lenses combined with a cylinder lens [11.11]. The area of the sheet to be used effectively for the measurement and the sheet thickness can be controlled easily with one lens of the telescope. A thickness of 0.1 mm can be realized in this way. Making the sheet parallel, i. e., not expanding, by means of a large-diameter lens or a spherical mirror provides a uniform illumination intensity in the field of view. A new approach, which is particularly suitable for visualization studies of flows in microsystems, is the use of diffractive optical elements (DOE) that replace conventional optical lenses in the light sheet optics and allow the light sheet to be tailored to the specific microflow conditions [11.12]. By moving the light sheet normal to its plane one can scan the volume of the flow field and generate a kind of tomographic resolution of the three-dimensional flow structures [11.13]. This kind of *tomography* should not be confused with *optical tomography*, which is essential for resolving three-dimensional flows with varying fluid density (Chaps. 3 and 25). Light sheet optics is an essential element of setups for particle image velocimetry and related imaging systems for velocity measurements, information on which can be found in the corresponding sections, e.g., Sect. 5.3.2.

Scanning the three-dimensional (3-D) flow field with a light sheet in order to obtain 3-D information on spatial structures requires the flow to be steady during the scanning period. If this is not the case, the solution can be to use holography with single-pulse laser illumination; in this way, complete 3-D information is frozen in the hologram and can be scanned upon reconstruction of the object. Such a hologram also provides a direct 3-D view of the flow structures; see, e.g., the hologram of a jet flow in [11.15]. An alternative for producing visible 3-D information on a flow is stereo photography. This method, which employs two cameras to obtain percep-

Fig. 11.13 **(a)** Optical setup for confocal laser scanning microscopy (CLSM). **(b)** Particle images taken in two different y-planes by the CLSM (*left column*), and by the conventional epi-fluorescence microscopy (*right column*), courtesy Prof. K. D. Kihm, University of Tennessee, USA, see also [11.14]

tion of optical depth, has been in use for several decades in various engineering applications. Such stereoscopic systems record two simultaneous, but different, views of the object. The two views are then combined, and a mathematical algorithm provides the reconstruction of the three-dimensional object field. Stereoscopic systems are of great importance for determining the three velocity components in 3-D flows by means of velocimetric imaging methods; more-detailed information is available in Sect. 5.3.2.

Confocal microscopy combined with spatial filtering and excitation of fluorescence is becoming an important means for reconstructing 3-D structures under microflow conditions [11.14]. The basic *confocal* concept is a point scanning of the laser excitation and a spatially filtered fluorescence signal emitting from the focal point onto the confocal point (Fig. 11.13a). The pinhole aperture, located at the confocal point, allows the emitted fluorescent light exclusively from the focal point (solid rays in Fig. 11.13a) to pass through the detector, and filters out the fluorescent light emitted from outside the focal point (dashed rays). This spatial filtering is the key principle behind optical-resolution enhancement by depth-wise optical slicing. The illuminating laser can scan rapidly from point to point on a single focal plane, in a synchronized way with the aperture, to complete a full-field image on the detector. The scan is repeated for multiple focal planes to reconstruct three-dimensional images. Tracer particle images obtained with confocal laser scanning microscopy (CLSM) are shown in Fig. 11.13b, compared with results of conventional epifluorescence microscopy. The raw PIV images (40 X, 0.75 NA) are shown for two selected planes of $y/R = 0$ at the center plane, and $y/R = 0.98$ near the top end of the inner surface of a 99 μm-ID microtube. The confocal microscopic images demonstrate optically sliced images with clear image definition of individual particles located within the slice thickness [11.14].

Any visualization experiment requires optical access to the flow, i. e., transparent walls for flows bounded by walls. To relate the visible information to the local position in the flow correctly it may be necessary to account for refraction of light by the viewing window. This correction is easy for a plane window, but the problem is more difficult to solve for curved optical boundaries. The problem does not exist if the refractive indices of the wall and fluid are equal. A number of liquids have been found whose refractive indices can be matched with those of glass or Plexiglas, approximately 1.5; (Table 11.1 [11.7]). Not all of these liquids are pleasant to work with, some are unstable or even unsafe, and the values of their viscosity might not be appropriate for a specific experiment. However, the number of such liquids that have tolerable properties is increasing, as a result of the growing interest in flows in porous media [11.16].

11.2.5 Enhancement of Image Quality: Fluorescence, Image Processing

Rapid diffusion of a dye into the ambient water deteriorates the image quality and makes it difficult to detect flow structures. Improvement of the imaging quality might also be desirable for flows in complex geometries, e.g., porous media. Enhancement of the visibility of flow contours can be obtained by using a fluorescent tracer. Fluorescence is induced by the corresponding light from a laser source [*laser-induced fluorescence* (LIF)] or an ultraviolet (UV) lamp, and the fluorescent radiation emitted by the tracer, at a wavelength different from that of the inducing radiation, can be isolated from the background and other disturbing light by using an optical filter in the wavelength range of the fluorescence. In this way, use is made of the inelastic scattering from the fluorescent tracer, instead of elastic scattering from *normal* tracer materials (Sect. 7.4).

A number of fluorescent dyes that can be solved in water have been described and investigated. It appears that Fluorescein is the most appropriate material to work with [11.17]. Fluorescein is highly soluble in water and has a high quantum yield of approximately 85%. The fluorescent radiation can also be used for quantitative measurements, e.g., concentration, which is not the main focus of this section. For these quantitative purposes, stability of the dye properties is desirable. Fluorescein has a weak temperature dependence; but the emitted radiation depends strongly on the pH value, which ought to be controlled and kept constant during an experiment. The absorption peak of this dye is near 490 nm, which is conveniently close to the 488 nm wavelength of an argon-ion laser, which may therefore serve as the light source for illumination. The fluorescence intensity from a dye solution is observed to diminish with time, perhaps as a result of oxidation processes. Experiments using a fluorescent dye are particularly suitable for the study of mixing processes, e.g., one fluid stream that is supposed to mix with a second stream is seeded with the dye such that the structure of the mixing zone becomes clearly visible.

Fluorescent species used for visualization experiments in gas flows are either seeded as tracers into the flow, e.g., biacetyl, O_2, I_2, NO, or are radicals produced as a result of a chemical reaction, e.g., CH, OH, C_2, CO in combustion processes. The illuminating laser must be

Fig. 11.14 NMR image of the heart of a patient suffering from mitral stenosis. *Top*: anatomical configuration, 1 – left auricle of increased volume, 2 – left ventricle, 3 – right auricle, 4 – right ventricle. Stenosis causes a decreased throat area when opening of the mitral valve allows the blood to flow from the left auricle to the left ventricle. *Bottom*: NMR is applied such that velocities higher than a selected threshold value appear dark, while those lower than the threshold are bright. The dark area in the left ventricle visualizes the velocity increase due to the reduced throat area (courtesy of Dr. M. Montag, Krupp-Krankenhaus, Essen, Germany)

tuned to the absorption wavelengths of the respective species, while the optical filter, which allows only the wavelength emitted from the fluorescent tracer to pass through, eliminates all the radiation generated by the combustion process. Details of reacting flows can thus be observed [11.18].

A hardware tool for the enhancement of image quality at low illumination intensity, though expensive, is the use of an image intensifier camera [11.19]. A great variety of software tools are available for improving the image quality, e.g., filtering algorithms, but it is recommended to control the physical significance of those phenomena that become visible with their application in order to avoid misinterpretation of possible numerical artifacts. For detailed information on the application of filtering algorithms, see the literature on planar velocimetry where image-processing methods are needed for the generation and presentation of experimental results (Sect. 5.3.2).

The desired visualization of flows in porous media may require more-effective means than just the method of refractive index matching mentioned in Sect. 11.2.4. Magnetic resonance imaging (MRI) has been successfully used for this purpose; it is applicable even to flows in containments with nontransparent walls, and for this reason has found intensive application for in vivo measurements in medicine, where the technique was developed (Fig. 11.14). MRI is based on nuclear magnetic resonance (NMR), which measures relaxation-weighted proton density and can also yield information on fluid velocity and temperature [11.20]. The method makes use of the dynamics of the magnetic moment of hydrogen nuclei in an externally applied magnetic field. The information obtained with an MRI system is a planar distribution of greyscale values, from which one derives, in a first step, the interstitial space in the porous medium filled with water, and thereby the geometry of the medium. Special timing of the magnetic field allows one to generate a velocity map of the fluid.

11.2.6 Direct Visualizations of Velocity Profiles

If one produces instantaneously tracers along a straight line perpendicular to the main flow direction, one may visualize local velocity profiles by observing the distortion of the line in the flow. Methods for such direct visualization of velocity profiles are known for both water and air flows. They were developed prior to the general availability of planar velocimetric methods based on the recording of tracer particle patterns and subsequent evaluation by image processing (Sect. 5.3.2), they are still in use where the equipment is available, and they are particularly useful for tutorial purposes.

The hydrogen-bubble technique is the most popular representative in this group [11.2]. It is based on the electrolysis of water; a fine wire as the cathode defines the straight line where the tracers are produced upon application of a dc voltage. Hydrogen bubbles are formed at the cathode and oxygen bubbles at the anode that is placed somewhere else in the water flow, away from the region of interest. The hydrogen bubbles are used as tracers because they are much smaller than the

Fig. 11.15 Visualization of vortical structures in boundary layer flow by means of hydrogen-bubble time lines (courtesy Prof. C. R. Smith, Lehigh University, Bethlehem, PA, USA)

oxygen bubbles. A column-shaped row of bubbles, the instantaneous line of tracers, is formed along the wire when an electric pulse is generated; this row is carried away with the flow and deformed according to the local velocity profile. By pulsing the voltage at a constant frequency, one can produce several successive rows of bubbles, which mark the flow curves separated by a constant flow time. These curves are called time lines, and it is in this mode that the hydrogen-bubble technique is most frequently employed (Fig. 11.15).

Normal tap water may serve as the electrolytic fluid; if the water is too soft, sodium sulfate can be added in order to increase the electrolytic conductivity. A rule of thumb is that the bubble size is of the order of the diameter of the generating cathode wire. Measurement systems for this method, particularly the electric supply and control system, are commercially available. Illumination with conventional lamps at an angle of 65° between the illumination and viewing directions has been found to be most suitable. The period of time during which the bubbles can be observed in the flow is limited by the dissolution of the hydrogen bubbles in the fluid. Diffusion of the bubbles increases with Reynolds number and is very rapid in turbulent flows. The method is therefore limited to low-speed flows, maximum velocities being of the order of 20–30 cm/s. However, great achievements have been made using the hydrogen-bubble technique to study unstable and transitional boundary-layer flows.

The hardware of the thymol blue method is similar to that of the hydrogen-bubble technique [11.2]. A thin cathode wire defines the line along which the visible tracer is produced instantaneously upon application of a voltage and as the result of a sudden change of the local pH value. The production of dyes by means of pH indicators was mentioned in Sect. 11.2.2. Here, the working fluid is an aqueous solution of thymol blue which is orange–yellow in an acidic environment and turns its color to blue if the the solution becomes alkaline. This change occurs close to the cathode wire; a thin line of liquid is marked blue in the otherwise yellow fluid and moves with the flow, being deformed by the local velocity as described for the row of hydrogen bubbles. In contrast to the latter method, the applied voltage here is low in order to avoid or minimize the formation of H_2 bubbles. While the bubbles are buoyant tracers, the tracer generated with the pH indicator is non-buoyant, and this makes the thymol blue method particularly attractive for studies of flow in liquids exhibiting a natural density stratification. Furthermore, the marked fluid has the same properties, particularly size of the tracer, as the unmarked fluid, and the method is therefore also suitable for experiments with rotating flows. The comment above about diffusion of the tracer

Fig. 11.16 Visualization of velocity profiles inside a growing drop by means of the photochromic dye technique (courtesy Prof. E. Marschall, University of California at Santa Barbara, USA)

Fig. 11.17a,b Smoke wire visualization of the velocity profile in the flow through a curved pipe **(a)**; this flow is known to exhibit a pair of counter-rotating vortices extending in the streamwise direction (*secondary flow*), as seen in the smoke visualization with the light sheet normal to the pipe axis **(b)**. (courtesy Prof. Y. Tanida, Tokai University, Japan)

into the bulk fluid at higher Reynolds numbers applies here as well.

These two methods suffer from the presence of a disturbing electrode wire in the flow field of interest. Such mechanical disturbances are avoided if one produces the desired dye or tracer material along a straight line by a photochemical reaction with a laser beam. Photochromic materials that can be used for this purpose are known; they have the disadvantage of not being well soluble in water, and a number of organic liquids are therefore used as solvents and working fluids [11.2]. The photochromic substance absorbs UV radiation provided by a laser and becomes opaque and thus visible, while it is transparent in the unexcited state. With a short laser pulse an instantaneous line of tracers is produced along the laser beam. The reaction is reversible. The reverse transition is spontaneous but slow, and the visible tracers disappear after a given period of time that, in addition to the reverse reaction being spontaneous, can be controlled by thermal energy. The photochromic dye is a true solution and thus non-buoyant. The excitation of the reaction by UV radiation requires the use of a quartz window to introduce the laser beam into the flow. The method is applied to the study of velocity profiles in near-wall flows, and also to visualize the internal flow in drops during their formation (Fig. 11.16).

Direct visualization of velocity profiles in air flows is more difficult due to the higher degree of diffusion of possible tracers (smoke) in the flow. A frequently used method is a smoke wire that spans the flow of interest and can be heated electrically [11.2]. The wire is coated with a thin layer of oil that evaporates when the wire is heated. Application of a short electric heating pulse produces a thin line of smoke (oil mist) along the length of the wire, similar to the tracer lines in the methods described for use in liquid flows. Again, the method has been found useful for the study of near-wall flows (Fig. 11.17).

A technique for producing tracer lines in an air flow without the need to use a mechanically disturbing wire is available: the *spark tracer method* [11.2]. A high-voltage electric discharge across the mean flow direction generates a thin channel of ionized luminescing molecules that is visible and deforms, like the tracer lines in the previous cases, with the flow profile. Application is restricted to high-speed air flows.

11.3 Visualization of Free Surface Flows

The visualization of flow patterns on free water surfaces is of interest for many reasons. These flows, which include the formation and propagation of water waves, are associated with a deformation of the free surface, which is the key for a direct visualization and also quantitative measurements. It is appropriate to distinguish between large-scale deformation on the scale of water waves, and small-scale deformation or fine structure as caused, e.g., by turbulence. Water waves can be visualized by observing a regular grid immersed in the water, parallel to the free surface. To the observer, the grid pattern appears distorted as a result of the refraction of light at the wavy surface. The deformed grid pattern can be evaluated quantitatively, analogous to the application of moiré methods to the visualization of flows with varying refractive index (Chap. 6). An alternative is to observe and record the light reflected from the wavy surface, a method that makes water waves directly visible in nature (Fig. 11.18). The fine structure of such a surface, which can be caused by the interaction of the free surface with wind and turbulence, can be made visible in reflection with speckle methods that are also used for statistically analyzing turbulent tracer particle patterns [11.21]; see particularly Sect. 5.3.2.

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 gas flow, because these processes are governed by equations of equivalent mathematical form. This so-called

Fig. 11.18 System of waves produced by a ship moving into Seattle harbor (W. Merzkirch)

Fig. 11.19 Supercritical water flow around a wedge at zero angle of attack, visualizing a hydraulic analog of the oblique shock in supersonic flow (courtesy Prof. M. S. Wooldridge, University of Michigan, USA)

hydraulic analogy between *supercritical* flow in a water channel and supersonic gas flow enables one to visualize supersonic flow patterns in a water channel [11.2]. Although the analogy would be exact only for a gas having a ratio of specific heat of $\gamma = 2$ (which is not realistic), the method continues to attract interest, particularly for tutorial purposes [11.22] (Fig. 11.19).

References

11.1 H.W.Liepmann: The rise and fall of ideas in turbulence, Am. Scientist **67**, 221–228 (1979)

11.2 W.Merzkirch: *Flow Visualization*, 2nd edn. (Academic, Orlando 1987)

11.3 W.-J.Yang (Ed.): *Handbook of Flow Visualization* (Hemisphere, New York 1989)

11.4 M. Van Dyke: *An Album of Fluid Motion* (Parabolic, Stanford 1982)

11.5 Y. Nakayama, W.A. Woods, D.G. Clark (Eds.): *Visualized Flow* (Pergamon, Oxford 1988)

11.6 *J. Flow Visualization and Image Processing* (Begell House, New York since 1993)

11.7 R. Budwig: Refractive index matching methods for liquid flow investigations, Exp. Fluids **17**, 350–355 (1994)

11.8 H. Werle: Hydrodynamic flow visualization, Annu. Rev. Fluid Mech. **5**, 361–382 (1973)

11.9 R. Breidenthal: Structure in turbulent mixing layers and wakes using a chemical reaction, J. Fluid Mech. **109**, 1–24 (1981)

11.10 T.J. Mueller: On the historical development of apparatus and techniques for smoke visualization of subsonic and supersonic flow, AIAA Paper **80-0420-CP** (1980)

11.11 J.P. Prenel, Y. Bailly: Theoretical determination of light distributions in various laser light sheets for flow visualization, J. Flow Visual. Image Process. **5**, 211–224 (1998)

11.12 F. Peters, A. Grassmann, H.S. chimmel, B. Kley: Improving small laser light sheets by means of

a diffractive optical element, Exp. Fluids **35**, 4–7 (2003)
11.13 J.P. Prenel, Y. Bailly: Quantitative imagery of 3-D flows: From tomographic to volumic investigations, J. Flow Visual. Image Process. **8**, 189–202 (2001)
11.14 J.S. Park, C.K. Choi, K.D. Kihm: Optically sliced micro-PIV using confocal laser scanning microscopy (CLSM), Exp. Fluids **37**, 105–119 (2004)
11.15 L. Hesselink: Digital image processing in flow visualization, Annu. Rev. Fluid Mech. **20**, 421–485 (1988)
11.16 M. Stöhr, K. Roth, B.Jähne: Measurement of 3D pore-scale flow in index-matched porous media, Exp. Fluids **35**, 159–166 (2003)
11.17 D.A. Walker: A fluorescence technique of measurements of concentration in mixing liquids, J. Phys, E Sci. Instrum. **20**, 217–224 (1987)
11.18 G. Kychakoff, R.D. Howe, R.K. Hanson: Quantitative flow visualization technique for measurements in combustion gases, Appl. Opt. **23**, 704–712 (1984)
11.19 I. Grant, X. Wang: Directionally-unambiguous, digital particle image velocimetry studies using a image intensifier camera, Exp. Fluids **18**, 358–362 (1995)
11.20 M.D. Shattuck, R.P. Behringer, G.A. Johnson, J.G. Georgiadis: Convection and flow in porous media, J. Fluid Mech. **332**, 215–245 (1997)
11.21 D. Dabiri, M. Gharib: Simultaneous free-surface deformation and near-surface velocity measurements, Exp. Fluids **30**, 381–390 (2001)
11.22 S.L. Rani, M.S. Wooldridge: Quantitative flow visualization using the hydraulic analogy, Exp. Fluids **28**, 165–169 (2000)