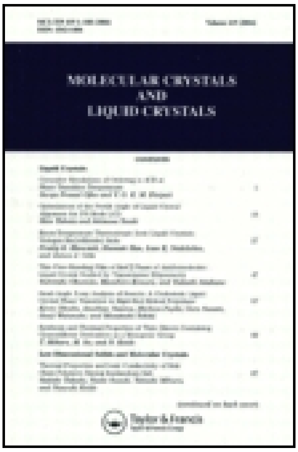

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FLOW FIELD VISUALIZATION BY PHOTOCHROMIC COLORING *

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Abstract The visualization of the velocity field in fluid flows is discussed on the basis of the nearly disturbance-free method of photochromic coloring. Several examples are given which show that other methods of visualization would fail to get insight into the flow behavior. For nonpolar organic liquids the photochromic material 1,3,3-trimethyl-6'-nitroindoline-2- spiro-2'-benzpyran was used. Stationary and non stationary motions of liquids are investigated, and the application to two-phase flows is pointed out. Especially the use of UV-laser light is shown to be profitable for generating colored patterns in the flow field which allow the determination of the velocity profile and the velocity gradient in the flow field. Recent research in the field of water soluble photochromic material has led to the application of the laser induced photochromic coloring even in large scale experiments.

INTRODUCTION

Flow field visualization in Fluid Mechanics is used to get a quick and reliable picture of the overall behavior of the flow field. It is of main interest to detect in the flow field 'secondary flows' which can be observed in planes perpendicular to the main flow. So, flow visualization should lead to a detailed picture of the structure of the flow field. An example of such a three-dimensional motion is the secondary flow in a nozzle or in a wind tunnel which develops in planes perpendicular to the main flow direction. This type of flow has vortical character. When pipe flows are considered, any curvature in the wall geometry leads also to secondary flows which play an important role e.g. for pumping systems. Those secondary motions are typically of vortical character, and vortices are the most important entities in a flow field and responsable for the stability of the flow.

Visualization techniques and measurements of the velocity field in fluid flows can roughly be devided into two groups: One group contains all those methods which cause disturbances in the flow field on a macroscopic level. The other group comprises all the other methods which are nearly disturbance-free and which interact only on the submicroscopic level with the fluid, which means on the molecular scale by an interaction with the electromagnetic field.

It is evident, that any measurement of a field quantity has to interact with the fluid to get information from the system about the velocity field. The scale on which such an interaction of the observer with the physical system may take place is depending on the geometrical dimensions of the flow field and of the character of the

* **Animation relating to this article is included in the 1997 CD-ROM edition of *Molecular Crystals and Liquid Crystals Science and Technology, Section A: Molecular Crystals and Liquid Crystals.***

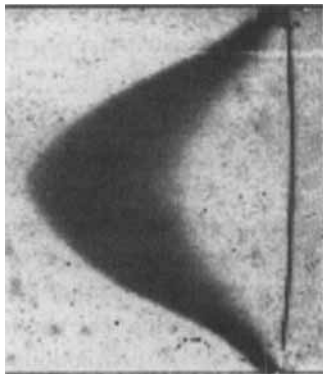

Figure 1: Coloring of the flow by an electrolytic reaction of thymol blue in water

phenomenon which is to be analysed. An example of the visualization of the pipe flow by an electrolytic color reaction in the liquid using a thin wire is shown in Fig.1. The dark blue coloring near the cathode stems from the locally high OH^- ion concentration. This experiment shows the time evolution of one time line which was released at some moment before the photography was taken. For that kind of visualization one has to span a metal wire through the pipe which causes several severe disturbances in the flow field: The wire acts like a small cylinder perpendicular to the main stream in the pipe, and gives raise to large disturbances near the wall (horse shoe vortices). Depending on the Reynolds number of the flow, vortices may be created periodically in the downstream direction of the flow (Kármán vortex street). By the short current pulse through the wire, the wire is heated and releases heat to the fluid around. This leads to buoyancy effects of the environmental liquid. As the diameter of the wire is not very small, the area of the pipe at the point of the measurement is diminished by the cross section of the wire. If the heating effect should be avoided, one has to construct the metal body as a thin hollow cylinder through which a cooling liquid has to be pumped, to balance the heating effect. This represents a very complicated experimental setup. If one wants to measure the velocity profile at several positions in the pipe, the disturbances will accumulate and destroy the original character of the flow. From those disturbances it seems evident that any macroscopic impact on a flow volume inevitably prevents the experimentator to observe the phenomenon he wants to study. Under special circumstances it may be allowed to forget about the disturbances which are introduced by the analysing system. In any case the fluid dynamicist has to decide whether the method of investigation will affect essentially the observations or not.

In Fluid Dynamics all kind of flows can be devided according to the geometry of their boundaries into the following main groups: Flows around bodies, flows through pipes and nozzles, and flows in closed volumes. In all the cases the use of photochromic coloring is possible and useful. In some cases only the photochromic coloring method is applicable, and this method is much simpler than any other method. If the very neighbourhood of the rigid walls in a duct or the boundary layer around an immersed body is to be analysed, no other method can compete.

COLORING METHODS FOR LIQUIDS IN MOTION AND AT REST

In order to describe a fluid flow qualitatively by visualization, the following terms are used: A stationary flow field can be characterized either by its 'streamlines' or by its 'path lines' which coincide with the former, because of the stationary character of the flow. Such line patterns can easily be created by a permanent coloring process at one point in the flow field. This kind of lines are named 'streaklines'. By projecting a point pattern into the liquid under motion, streaklines or streaksurfaces can easily be created by photochromic coloring.

If the flow field has a time dependent character, those three types of lines do not coincide necessarily. For time dependent flows the use of 'time lines' can also give some information of the structure of the flow field. Creating time lines is equivalent with the process of giving names to the fluid particles at a special moment of time. This naming of some fluid particles can be done by photochromic coloring to distinguish them from their environment.

The visualization method by photochromic coloring can also be used for a quantitative measurement of the velocity field. Then special care must be taken for the patterns which are projected into the liquid. If it is possible to project a system of grid lines into the liquid[1,2,3], by recording the deformation of the grid, not only velocities, but also velocity gradients can be calculated directly from the experimental data. In this respect the photochromic coloring method gives more information about the flow field than any other method.

From the geometrical point of view one can create different shapes of the tracers. Tracers can have the form of colored points, lines or surfaces in a liquid, which keep their individual character during a long time interval. The lifetime of such patterns can be long because the back reaction time of the molecules is a strong function of the temperature.

Assume that the flow will start from rest, one can create colored small volumes in the liquid by a single glass fiber which can be positioned at any point in the liquid. If the UV-laser is pulsed, small colored dots are created. While moving the glass fiber through the liquid a linear array of dark points is left in the fluid before starting the motion of the body. In the transient regime of the motion one can trace the colored fluid particles and derive some information about the velocity field.[4] If in a special flow situation one can not enter the fluid volume by any glass fiber, it is possible to transmit the transparent walls by UV-laser light and create e.g. crossed time lines in the liquid.

USE OF HIGH CONCENTRATIONS

The fluid dynamicist is often interested in the behavior of those fluid layers which are situated close to the walls of the flow field, and which are called 'boundary layers'. The importance of that part of the flow field comes from the fact, that at rigid walls the gradient of the velocity field is very high and therefore responsible for the drag of the body which is moving through the fluid (Prandtl's boundary layer theory). Vortices in the flow field have their origin also in the boundary layer close to the wall. In addition to that information about the flow field, it is necessary to know whether the flow around three-dimensional bodies will detach from the wall or even separate.

All known methods of velocity measurements and most of the flow visualization techniques are suffering from the fact, that they have to seed the fluid by small tracer particles, to get a light signal out of the fluid for a pointwise determination of the velocity. But those particles with diameters of about 5-50 μm can principally never approach very closely the wall, because of the Magnus-effect which prevents them to enter the shear layers by autorotation.

If a high concentration of phochromic material is used, the absorption length of the UV-laser light which is transmitting the transparent wall material is very short, and by using a mask of tiny holes an array of colored liquid spots in the boundary layer can be created. The deformation of these spots under the motion of the liquid gives simultaneously information about the velocity field in the boundary layer.[5]

USE OF LOW CONCENTRATION

The use of a low concentration of the photochromic compound is necessary, if one wants to create extended time lines in the flow field by irradiation from outside through the wall. Also for the projection of any grid pattern into the liquid, the concentration of the photochromic compound must be low.

If the contrast of the optical signals is not large enough, a postprocessing of the data on the computer leads to a better quality of the pictures for interpretation of the flow field. working at low concentration does not affect in a measureable degree the viscosity of the liquid, which is profitable, because the similarity parameters (Reynoldsnumber, Prandtl number, etc.) of the flow are not changed by adding a small amount of photochromic molecules.

WALL MATERIAL

For the application of the photochromic coloring technique, the wall material has to be transparent, and therefore it consists mostly of perspex or glass. If nonpolar solvents are used, e.g. kerosene or cyclohexane, no special care is necessary for the choice of the wall material. This is the case if the walls of the fluid flow are plane such that the observation can be done in a direction perpendicular to the walls. Then for optical reasons perspex can be used as wall material without any adjustion of the index of refraction.

If the container has curved walls, it has to be surrounded by a boxlike volume with plane walls. to get the optical signals without any distortion out of the fluid volume. Still, distortion of the optical signals have to be taken into account because of the difference of the indices of refraction of the liquid and the wall material. This may force the experimentalist to look for a mixture of two organic solvents which could dissolve the perspex. To adjust the index of refraction of a pipe made from perspex, phthalic acid dibutyl ester is extremely useful, because it has exactly the same index of refraction as perspex. But the danger of a damage of the wall material is very likely. Therefore, one should better use glass for the construction of the experimental setup or cover the perspex wall with some material which is resistant against the solvent. As glass differs in the optical behavior from perspex, a mixture

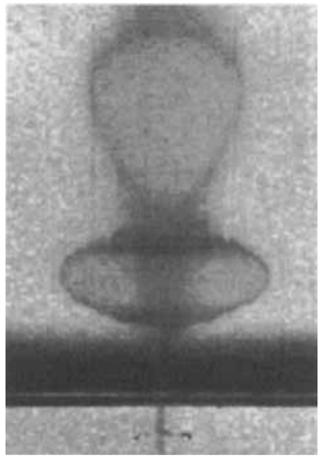

Figure 2: Zones of recirculation in a cylinder with rotating lid

of phthalic acid dibutyl ester with kerosene makes it possible to meet exactly the index of refraction of glass. This diminishes the risk of damaging those parts of the experimental setup which consists of perspex, because of the lower concentration of phthalic acid dibutyl ester.

STATIONARY FLOW FIELDS

Several stationary flows were investigated with the help of laser-induced photochromic coloring. Especially rotating flows near 'critical points', where the flow shows the tendency to follow the principle of exchange of stability and wants to reorganize to build up another flow pattern, were analysed by visualization of the velocity field creating streak lines or streak surfaces in the fluid. In Fig.2 two recirculating zones can be seen which develop in a circular cylinder when the lid rotates at a constant angular velocity. The UV-light transmits the bottom at the center part through a window of perspex. The streak surfaces have a very complex structure and indicate that the two recirculating zones interact with each other.

NON STATIONARY FLOW FIELDS

Most of the technical flows are of non stationary character. If one models those flows on a smaller scale in the laboratory, it is possible to observe the flow field as a whole. This means that wall effects and the behavior of the flow in the inner part of the liquid have to be studied together. For that purpose the photochromic coloring has many advantages compared with other methods which introduce macroscopic disturbances by using probes or rigid tracer particles. As one transmits the wall with the UV-laser light, simultaneously the boundary layer and the inner part of the flow field can be studied.

A special type of non stationarity is the periodicity of a flow field. A closed container filled with liquid and oscillating around one axis in space, induces a secondary motion of sometimes large values of the velocity. To see how the liquid close

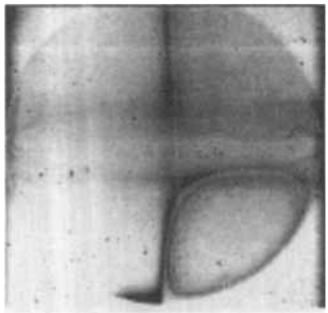

Figure 3: Secondary flow in a totally filled sphere oscillating around the horizontal axis

Figure 4: Secondary flow in the upper part of an eccentrical spherical gap

to the walls will be advected after e.g. a sudden spinup, the coloring of the liquid at the wall is performed by a flash light from outside. The fluid closely adjacent to the walls gets e.g. dark blue and can be followed during the reorganization in the fluid volume. Fig.3 shows the secondary flow in a hollow sphere which oscillates around the horizontal axis. The frequency of the oscillation is about 5 Hz. Another situation is represented in Fig.4. An excentrical inner sphere oscillates around the vertical axis and causes a vortical motion which is visualized by coloring only the upper part of the inner spherical surface. This is done by flash light from the inside of the oscillating inner sphere. It is clearly seen where the boundary layer material of the sphere is advected. There is a dividing stream surface in the flow field which separates the upper part from the lower part of the liquid which is set into motion. No mixing between upper and lower part is possible by this kind of induced flow.

A special application of the photochromic coloring is given in Fig.5 and Fig.6. The experiment shows the wake of a cylinder in a towing tank. The camerà and the deflecting mirror setup of the laser light are moving with the cylinder. In Fig.5 at a specific distance behind the cylinder time lines are created by longer laser pulses. The wake is cut by the time lines and its lateral extent can be recorded and measured directly. The Reynolds number of this motion is 40 which corresponds to a velocity of the cylinder of 5.58 mms^{-1} and to kerosene as liquid. Fig.6. shows the same cylinder at a velocity which is half the velocity of the previous motion, which leads to a smaller longitudinal extent of the wake. The laser light meets now exactly the free stagnation point of the wake. This is clearly seen from the fact that no colored fluid flow can approach the cylinder from behind. All colored fluid particles have a relative velocity which is directed off the cylinder downstream.

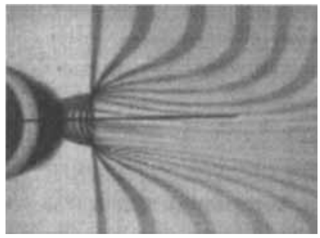

Figure 5: Time lines on the s wake of the moving cylinder

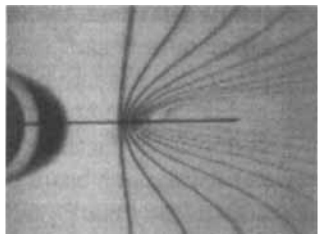

Figure 6: Time lines on the surface of the fluid in the backpart of the moving cylinder

WATER SOLUBLE COMPOUNDS

Sometimes it is not possible to scale down the experiments geometrically so that only a small amount of the organic liquids can be used. This is the case e.g. for experiments in a towing tank of large size. Under these circumstances it is not possible to use kerosene for such an experiment because of the danger, handling tons of an inflammable liquid. It is therefore appreciated very much that water soluble photochromic materials are available which act as additives to water at low concentrations. Such chemical compounds are available[6]. The concentration may be extremely small (1:3200 in vol. % gives signals of good quality). This is a great advantage and makes the use of that kind of chemical compound for photochromic coloring possible even for large volumes of water.

SUMMARY

Different types of flow were visualized by the use of photochromic materials. Especially rotating flows in spherical closed geometry were analysed and new phenomena were found. Vortical motions could be detected which otherwise never could be observed. For time-periodic motions the induced secondary flow could be visualized easily. Aperiodic motions during spinup or spindown could be investigated experimentally with a low cost experimental setup. The application to two-phase flows was tested under several different circumstances. As the coloring method can be characterized as a procedure to 'name' fluid particles, it is a convenient means to introduce Lagrangean coordinates into the fluid in motion or at rest. The tracers in the liquid are the small colored liquid volumes of the organic or aqueous phase which have the great advantage to be deformed under shear.[7] No other visualization method which uses rigid tracer particles can do the same. On the contrary, a rigid particle represents a massive disturbance of the flow field and may cause instabilities whilst a pure liquid would never change its stability.

The success of any photochromic technique depends strongly on the quality of the laser light which transmits the fluid or which is used to illuminate a mask. A low diverging light beam is necessary to get sharp optical signals from time lines.[8] As the color of a tracer in an organic or aqueous liquid depends strongly on the solvent and the photochromic compound which was chosen, one has the possibility to enhance the contrast for the photographic recording by a special choice of the substance. Valuable hints are found in the review article[9] on flow visualization which contains a summary of the application of this technique with respect to a variety of flow problems. If the motion of the liquid is fast, then a cine camera is necessary to record the tracers with a high resolution in time.[10]

Future development of synthesizing organic photochomic compounds should lead to systems which react to a double exposure to a two-photon process in the molecule. This could lead to a very elegant method to set point at any place in a fluid at rest or in motion by two crossing laser beam pulses of short time length to define a small fluid volume as tracer in the liquid.

Applications for two-phase flows have been reported recently[11] and show the wide range of problems in Fluid Dynamics for which the method of photochromic coloring is very important.

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