Introduction to Flow Visualization

Flow visualization is frequently a very important (and sometimes essential) component of a fluid flow experiment. It is particularly important during the process of interpreting other fluid measurements. Indeed the possibility of incorporating flow visualization should always be considered when planning a flow experiment. There are many different techniques for flow visualization including but not confined to

[A] **Flow tracers**: As we described in section (Kdb) there are a number of ways of introducing visible tracers into a flow in order to visualize pathlines in the flow. These include the introduction of smoke or mist into a gas flow or the introduction of dye or small bubbles into a liquid flow. These methods are described in section (Kdbb).

[B] **Tufts**: Often it is important to determine the point of flow separation from a solid surface in a flow since the forces on a object in a flow are often very dependent on the location(s) of flow separation. One common way to achieve this is to either attach numerous threads (or tufts) to the surface of an object such as an airplane or automobile model. When tested in a wind or water tunnel these tufts will indicate the local directions of the flow over the surface of the model and the line along which that direction changes will visualize the line of flow separation. Sometimes the tufts will flutter indicating a locally turbulent boundary layer rather than a laminar boundary layer. An alternative technique that is sometimes used is to place spots of very viscous paint on the surface of the model prior to installing it in the wind or water tunnel. The tunnel is then run for a brief period and the model is then removed and inspected. The local direction of the surface flow can then be gauged from the direction in which the spots of paint have been smeared by the flow.

[C] **Schlieren and Shadowgraph Techniques**: Another set of optical flow visualization techniques is based on the property that the refractive index of a fluid can vary with the local fluid temperature. These come in various levels of sophistication, the commonest being shadowgraph and Schlieren techniques. These are described in section (Kdbd).

[D] **Particle Image Velocimetry**: A modern, quantitative flow visualization technique is known as Particle Image Velocimetry or PIV for short. This involves digitizing a moving image of a flow seeded with particle tracers. The first developments of this technique focussed on two-dimensional images, but, as greater computational power became available, three-dimensional, holographic PIV became practical. The basics of PIV are described in section (Kdbc).

[E] **Liquid Crystal Techniques**: A variety of fluid visualization techniques have been developed that deploy liquid crystals to measure temperature and therefore related fluid flow properties such as the shear stress at a surface. Ireland and Jones (2000) present a excellent, detailed description of some of these techniques which can only be very briefly outlined here. The techniques are based on the molecular and optical properties of liquid crystals which change with temperature (within a particular but adjustable range of temperature). Techniques have been developed for use in both gas and liquid flows but they are most suited to gas flows in which there are significant temperature differences. The pertinent optical properties change within a transitional temperature range that may be broad (about $20°C$) or narrow (about $1°C$) and therefore can be adjusted to yield a gradual or sharp cut-off temperature presentation. The mostly commonly used form in which the liquid crystals are prepared is in a micro-encapsulated form (tiny $20\mu m$ spherical capsules) which are glued to the surface of a test object using an adhesive known as the binder. Care needs to be taken to choose liquid crystals whose transitional temperature range coincides with the range of fluid temperatures of interest in the experiment. A typical example of a multichrome image is shown in Figure 1, which records the shear stress under a turbulent spot in the process of developing and traveling downstream.

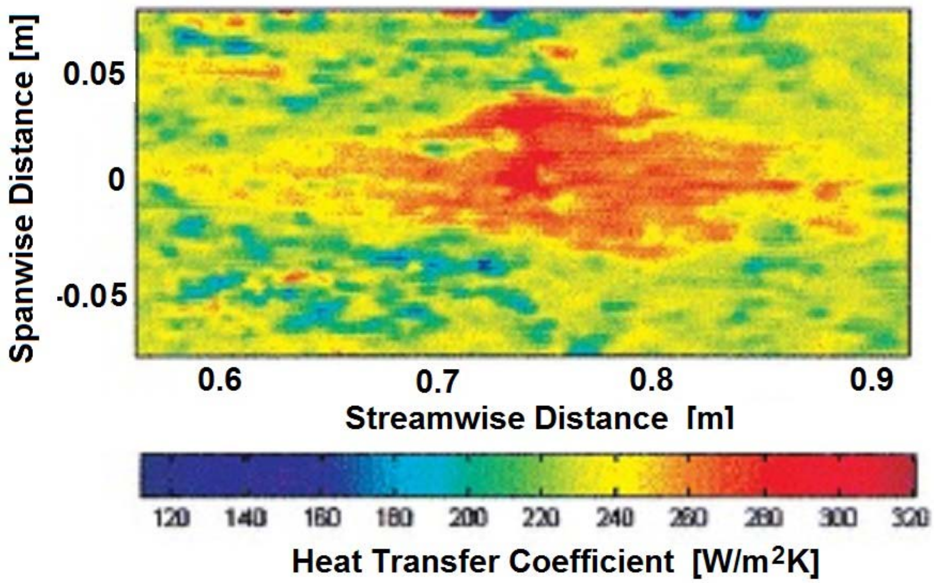

Figure 1: Liquid crystal visualization of the heat transfer and therefore the shear stress under a turbulent spot. Photograph by Guo *et al.* (2000).

Another technique that is sometimes employed to visualize the streamlines in a flow uses the phenomenon of birefringence. Birefringence is the optical property of a medium in which the refractive index depends on the polarization and propagation direction of the light. When a beam of unpolarized light shines through region of that medium the light that is polarized in one direction is more deflected than the light polarized in the perpendicular direction. By adding a dilute suspension of bentonite to the water of a water tunnel and adjusting an illuminating light beam, the streamlines of the flow can be observed in a manner not dissimilar to the shadowgraph/schlieren techniques described in section (Kdbd). The disadvantage of such a method arises when the bentonite solution must be cleaned from the facility.

[F] **Tomographic Techniques**: Tomography refers to imaging through the use of any kind of penetrating wave. A region of flow in which a fluid flow property (such as the volume fraction of a multiphase flow) is to be evaluated is identified. We denote that property by $\alpha(\overline{x})$ where $\overline{x}$ is a position vector within the region. The region is also partitioned into K different sub-regions and the object of the tomographic process is to estimate average values of α in each of these regions, α_k, $k = 1 \rightarrow K$. Instrumentation is set up around the whole region in order to measure total attenuation, a, of the wave amplitude along many different trajectories through the region. We denote the number of different trajectories by J. The object of the tomographic process is to determine the values of α_k, $k = 1 \rightarrow K$ that best fit the data a_j, $j = 1 \rightarrow J$. Clearly it is necessary for $J > K$ and better results are obtained for $J \gg K$. Often the matrix inversion needed to find α_k, $k = 1 \rightarrow K$ from a_j, $j = 1 \rightarrow J$ is very computationally intensive especially when high resolution results are desired and a three-dimensional result is needed. It is self-evident that the process is simpler when the wave trajectories are straight lines and so most tomographic procedures use waves, such as gamma rays or x-rays, that are not significantly diverted by the medium (flow) through which they are passing. Light waves or electromagnetic waves which are deflected can only be deployed in quite restrictive circumstances. However, electric resistance and electric capacitance tomography have both been developed. They have the advantage of being inexpensive but the disadvantage of being much more difficult to process mathematically.

Figure 2 depicts a typical tomographic arrangement using a single radiation source and an array of detectors. For example, such devices have been used with a gamma-ray source to measure the time-averaged void fraction within cylindrical tube.

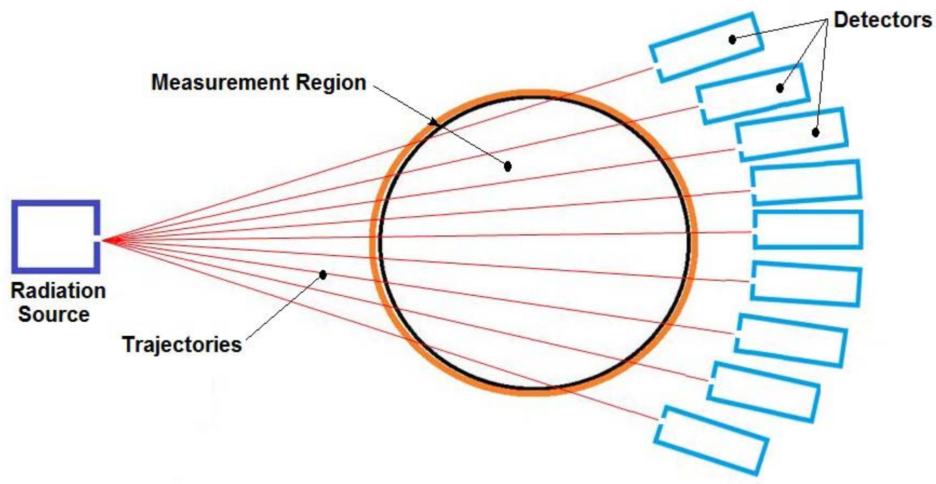

Figure 2: Schematic of a single source, tomographic arrangement deployed around a tube containing a flow.