Modern methods of flow visualization

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Our everyday life is surrounded by flows, either natural or engineered. Examples of the former category include the flow of air breathed in and out of our lungs, and examples of the latter include the flows of fuel and air injected into the combustion chambers of vehicles. However, the fundamental physics of flows remains poorly understood in the so-called turbulent regime, the regime that attracts practically all the interest from researchers and engineers. As experience teaches us, a good first step toward solving a problem is usually to “see” the problem. Flow visualization is the art and science of making flow patterns visible so that researchers can “see the flow,” providing a starting point for further study and understanding.

Visualization techniques

Most of us developed our first impressions and intuitions of flows via visualization techniques provided by nature without actually realizing it. For instance, even though air is invisible (or transparent) to our eyes, we developed an intuitive feeling of air flows by making everyday observations, ranging from the buffeting leaves in the wind to the smoke rising from a cigarette. These two examples illustrate two categories of flow visualization techniques. In the first example, the leaves act as probes to help visualize the wind flow. In the second example, the smoke particles, tiny black particles generated by the burning of the cigarette (Fig. 1a), visualize the air flow around the cigarette by both tracking the flow and scattering light so that we can see them.
These seemingly simple and completely natural examples actually illuminate the underlying principles of flow visualization techniques actively used in the most advanced flow studies. In the terminology of flow visualization, techniques that involve sticking probes (the buffeting leaves) into the flow are categorized as intrusive techniques, and those that do not are
Researchers have invented, and are still inventing, a variety of flow probes to visualize different aspects of flows. And engineers still use smoke guns to visualize the flow around a vehicle to understand the aerodynamics of its body and to make it more “streamlined,” so that drag can be reduced and mileage improved.

The disadvantage of intrusive techniques, as the name suggests, is that the probe itself disturbs the flow to be visualized. Consider the buffeting leaves again: What we see from the motions of the leaves is actually a convoluted result produced by the interactions between the wind flow and the leaves. As beautiful as such motions are, researchers often want to see just the wind flow, that is, its pattern without interference from the leaves. Such research needs motivate the search for nonintrusive techniques, which aim at visualizing the target flow pattern without the use of probes.

The cigarette example mentioned above illustrates the key concept of nonintrusive techniques. These techniques require a tracer that can both track the flow and be detected optically. The smoke particles happen to meet both requirements in the cigarette example (and also in smoke gun applications). These particles are small in size: typically smaller than a few micrometers (in comparison, the diameter of a human hair ranges from 20 to 200 μm). Consequently, these particles are light in weight and can float in air and track the motions of the target air flow faithfully. Furthermore, the optical refractive index of these particles is significantly different from that of air, so they scatter light and we can see them. Should the smoke particles have the same refractive index as air, they would just be invisible and transparent to our eyes, like air. Hence, in some sense, nonintrusive techniques use the tracer particle and light (usually generated by a laser in research) as the flow probe, in contrast to the physical probes used in intrusive techniques.

It is not always easy (it is actually very challenging in many applications) to find a flow tracer that can meet both of these requirements. For example, many practical flows have high temperatures, or they are corrosive (for example, combustion flows in energy-generating devices), and finding a tracer that can survive in the flow itself is challenging.

**Light scattering**

The remainder of this article focuses on nonintrusive techniques. As already mentioned, optical detection of the flow tracer is necessary in these techniques, and such detection is often accomplished by light scattered by the tracer. Therefore, the scattering of light will now be discussed.

The smoke particle introduced in the earlier discussion is actually quite complex (Fig. 1a). These particles are the result of the aggregation of many smaller particles (so-called primary particles) in complicated ways. Because of their complicated structure and geometry, the explanation of how these particles scatter light is quite involved. A simpler explanation of light scattering uses an ideal spherical particle (Fig. 1b). Some flow tracers (for example, glass beads used as flow tracers to visualize water flows) do have an approximately spherical shape. Whenever there is a mismatch in refractive index between the particles (for example, smoke particles or glass beads) and their surrounding media (for example, air or water), the particles will scatter light (a collection of photons). Light will reflect and refract at the interface of the particles and their surrounding media according to the basic laws of optics (Fig. 1b). Such reflection and refraction redistributes the photons in the incident light (that is, the light used to illuminate the particles) in various directions. We will be able to see the particle if some of the scattered photons reach our eye or camera.

Molecules can also scatter photons. (Figure 1c illustrates the scattering of light by an oxygen molecule.) Although the mechanism of scattering by molecules is different from that by particles, the end result of relevance to optical detection is that this scattering also redistributes the photons in the incident light in various directions (Fig. 1c). So molecules also can be used as flow tracers.

**Particle image velocimetry (PIV)**
Now, we are ready to examine PIV, a representative flow visualization technique, in depth. The PIV technique visualizes (or measures) the flow velocity in a plane (Fig. 2). The technique involves seeding small particles (ranging from glass beads and oil droplets to metal powders) in the target flow. A laser is used to illuminate the particles, serving as the incident light (Fig. 1). The laser output is focused into a sheet (typically with a thickness less than 1 mm) to visualize a two-dimensional planar region in the flow. The laser generates two pulses (that is, two bursts of light), each with a duration of the order of nanoseconds. These two light pulses are generated consecutively at times $t$ and $t + \Delta t$, with $\Delta t$ being the delay of the second pulse relative to the first. In practice, $\Delta t$ can range from milliseconds to microseconds depending on the application ($1 \text{ ms} = 1000 \mu\text{s}$ and $1 \mu\text{s} = 1000 \text{ ns}$). As a result, the particles in the flow are illuminated twice; and each time, an image of the particles is recorded by a camera using the light scattered by the particles. Because these two images are taken at two different times ($t$ and $t + \Delta t$) and the particles are displaced by the flow during $\Delta t$, the positions of the particles will be different on these two images. The PIV technique determines such displacements of the particles by comparing the two images recorded. Once the displacement is obtained, velocity can be calculated by simply dividing the displacement by $\Delta t$.

In summary, the PIV technique, as its name suggests, visualizes the flow velocity by imaging seeded particles. Such visualization was accomplished without sticking any physical probes into the flow to be visualized.

The PIV technique has found application in a wide range of engineering and scientific disciplines. Two examples from the author's research group will be given to illustrate the range of applications. The first example is a velocity measurement in an artificial heart valve using PIV (Fig. 3). In this measurement, the arrows show the local direction of the flow and the colors show the local magnitude of the flow (red corresponding to the highest flow velocity and blue to the lowest flow velocity). As a second example, PIV is used to study high-speed flows encountered in air-propulsion engines. The design and optimization of these engines, which may have the potential to save billions of dollars of fuel costs in both civilian and military aircraft, involve some of the most intricate and challenging flow patterns at combustion temperature and high speeds, well beyond 100 m/s (224 mi/h). Such visualization techniques provide powerful insights into flow patterns, which are difficult to obtain otherwise, for researchers to understand fundamental flow physics and for engineers to design better devices.
Fig. 3 Example of a velocity measurement in an artificial heart valve.

See also: Aircraft propulsion (/content/aircraft-propulsion/019200); Fluid mechanics (/content/fluid-mechanics/262300); Laser (/content/laser/372100); Molecule (/content/molecule/431200); Photon (/content/photon/511100); Reflection of electromagnetic radiation (/content/reflection-of-electromagnetic-radiation/577100); Refraction of waves (/content/refraction-of-waves/577400); Scattering of electromagnetic radiation (/content/scattering-of-electromagnetic-radiation/605200); Schlieren photography (/content/schlieren-photography/606400); Turbulent flow (/content/turbulent-flow/716800); Velocimeter (/content/velocimeter/802710); Wind tunnel (/content/wind-tunnel/746800)

Bibliography


Additional Readings


Index to Hyperphysics, Atmospheric Optics (Georgia State University) (http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/atmoscon.html#c1)