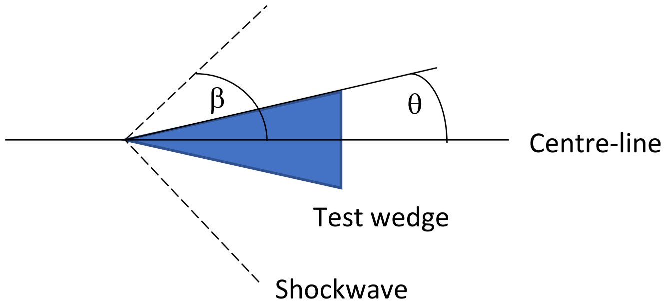
Instrumentation

Simple instrumentation (easiest to most complex)

1. **Test wedge (speed)**

   Putting a test wedge of known half-angle θ into a stream allows us to find the Mach number M by measuring the angle of the shockwave β. The result may be read off the θ-β-M graph: [ObliqueShockAngleRelation - Oblique shock - Wikipedia]

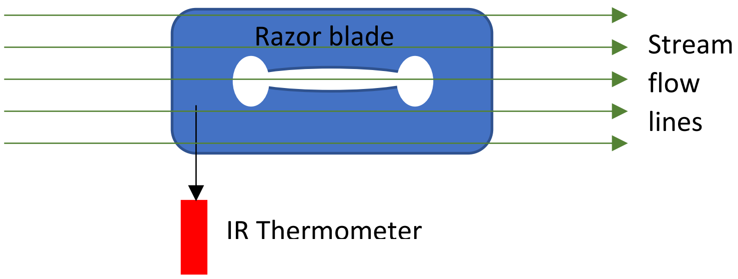


2. **Tracers (flow pattern / speed)**

   Foreign bodies can be introduced into the flow as tracers. The progress of these can be followed in video, photographs or ultrasonic equipment. Possible tracers might be pellets themselves, beads, smoke, fine particles / powder or glitter.

3. **Passive temperature measurement**

   A very thin piece of metal (like a razor-blade) can be introduced into the flow. If this is edge on, the disturbance to the flow is minimal. The temperature can be measured with an IR temperature gun. Flow needs to be present long enough for metal to reach thermal equilibrium.



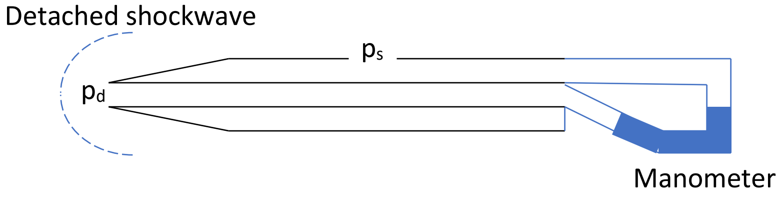
If two out the three parameters of P, T or ρ are known or can be measured, the other can be calculated from the gas equation:

$$P = \rho RT$$

P is pressure in Pa, T temperature in K, ρ density in Kg/m^3 and R is the Specific gas constant (287 J/Kg K for air).

4. **Supersonic pitot tube (pressure)**

This is a trickier to design and get working than the simple devices above – you need to look at some detailed designs in the literature before attempting to fabricate one. The general layout is shown below:

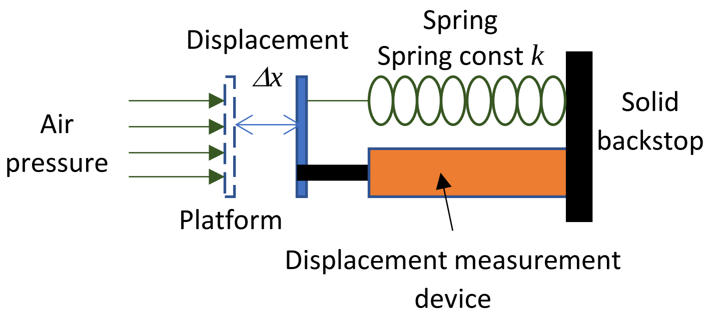


Obviously, you don't have to use a manometer to measure pressure.

$$\frac{p_d}{p_s} = \frac{1-\gamma+2\gamma M^2}{\gamma+1}\left[\frac{(\gamma+1)^2M^2}{4\gamma M^2-2(\gamma-1)}\right]^{\frac{\gamma}{\gamma-1}}$$

5. **Force balances**

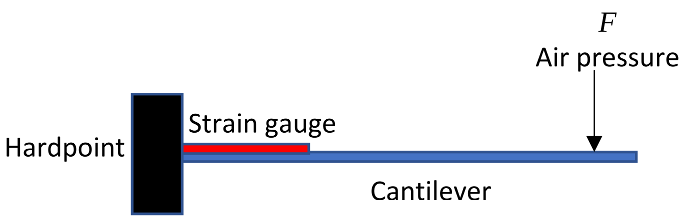
Force balances measure aerodynamic forces. There are several different ways to do this. One is to use a spring of known spring constant and measure its displacement:



The force is then:

$$F = k\Delta x$$

You can also use a cantilever and either use displacement as above or a strain-gauge:



The equations for the cantilever are slightly more involved - but can be found in any suitable reference book.

With some thought, it is often possible to use very simple force-measurement systems in setups – for example, commercial weighing scales.

6. **Ultrasonic doppler and time-of-flight (velocity of tracers and pellets)**

   Ultrasonic sound can be used to measure distance and/or speed parameters. It may be used in either time-of-flight mode (for distance) or by measuring doppler frequency shift (for speed). If two distance measurements are taken, then velocity can be calculated. In doppler mode the frequency shift Δf is**:**

$$\Delta f = \frac{2vf}{c}$$

   Where v is the speed, we're trying to measure, f is the unshifted source frequency and c is the speed of sound. You can find suitable circuits on-line.

7. **Hot wire anemometry (velocity)**

   This is a useful and versatile technique (and can also give fast readings in a changing flow or even, in a more complex multiwire form, image a flow-field). It consists of a fine wire, heated by a current flow. As the airstream flows past, it carries heat from the wire, cooling it. However, the wire's resistance changes with its temperature, so if we can measure resistance, we can calculate airflow speed from this. There are several different approaches to design and so it's recommended that specialised literature be consulted.

8. **Other devices**

   Other professional speed measurement devices are available. These include ultrasonic, laser and microwave measurement devices employed in a variety of industries. Examples include the vehicle speed measurement devices used by the police and instruments used to set up machines at the correct speed.

   Apparatus for the speed measurement of ammunition is widely and cheaply available. It usually works by timing the projectile as it sequentially breaks two light beams. This may perhaps be modified to measure pellet speed. Generally, such equipment works over a speed range of 0 – 999m/s.

Photography

1. **High speed video**

   A high-speed camera would be the ideal way to obtain results about the dynamics of moving objects (like pellets) in a supersonic flow. However, there is a problem.

   Consider the filming an object moving at Mach 1. In normal sea-level, room-temperature air, this is a speed of around 340 m/s. So, if we pointed a typical HD DSLR camera with a standard frame-rate of 60 frames-per-second (fps) at this, the object would have moved 5.7 m between frames – not much use in a short experimental test setup. Even at 100 fps the object would have moved 3.4 m.

If we wanted to get a resolution of 1 cm between frames, we'd need a camera capable of 34,000 fps or 340,000 fps for 1 mm resolution (and this is only at Mach 1).

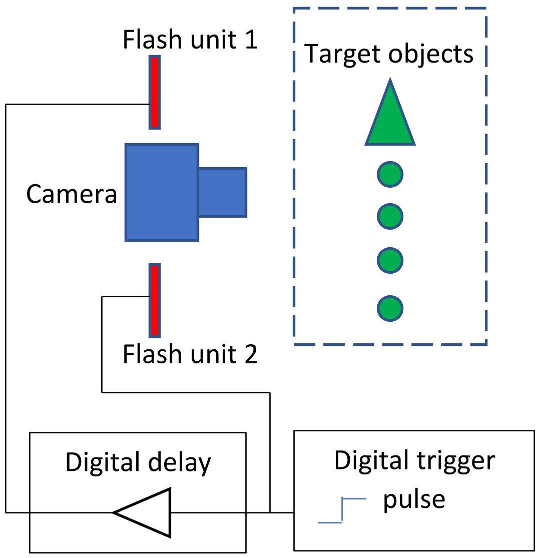
Such cameras are available (in fact up to 1,000,000 fps or more) but they are horrendously expensive: [Phantom Ultrahigh-Speed (phantomhighspeed.com)] Prices range from a few thousand pounds for lower rate cameras to hundreds of thousands of pounds for the highest speeds. Having said this, it is possible to rent such cameras – but this is still expensive and so you'd need to perfect experimental setup first.

Fortunately, because the pellets have inertia, they are not initially travelling at anywhere like this speed (in fact this point is essential to the engine operating as planned) and so it may be possible to get useful images at much lower speeds – however, this has yet to be verified in practice (but will be one of the main experimental results).

2. **Double (or multiple) flash techniques**

Another, much cheaper technique would be to use either two cameras synchronised to take pictures in rapid succession – or alternatively two high-speed flashes timed to go off one after the other in a darkened space. This second option is probably easier and more accurate. Such high-speed flashes are available much more cheaply than high-speed cameras: [The Vela One is 100x Faster than Conventional Strobes, Can Stop a Bullet In Its Tracks | PetaPixel].

The unit above can produce a flash lasting a 2 millionth of a second – which corresponds to a distance travelled of 0.17 mm at Mach 1. Two of them could be triggered in rapid succession using the propagation delay of a simple logic circuit as shown below (a stop/start crystal-controlled counter could be used for timing calibration).



To avoid having to synchronise a single initial event (like a pellet drop) with the trigger pulse, a system to stream continuous subjects (like pellets) into the setup would be necessary.

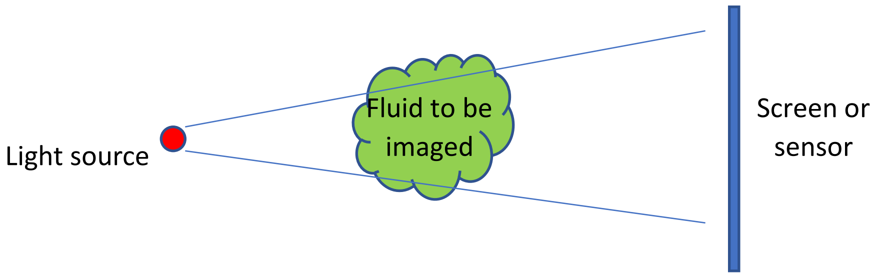
Optical flow visualisation and imaging techniques (easiest to most complex)

Many of the approaches described above also depend on being able to see details in the flow patterns around the test objects. Therefore, the optical techniques described below are essential components of most of the experiments. You should note that there are many ways to set up these systems – some of which are demonstrated quite well in Youtube videos. All the techniques work because different densities of fluid refract the light by different amounts.

1. **Shadowgraph**

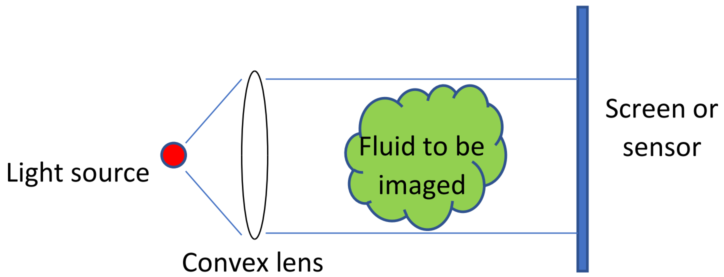
   The shadowgraph is the simplest method. It can be done using a simple point source of light. However, lens or mirrors can improve the image. Some setups are shown below:

   a) Simple point light source

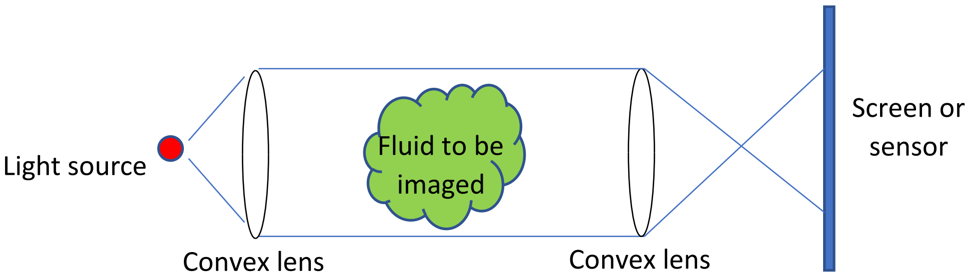


   You can also replace the point light source with a collimated beam (like a packaged laser) and use a concave lens to make this divergent – producing the same light pattern as shown above (a telescope eyepiece works well). This trick applies to all the setups.

   b) Simple source and collimating lens

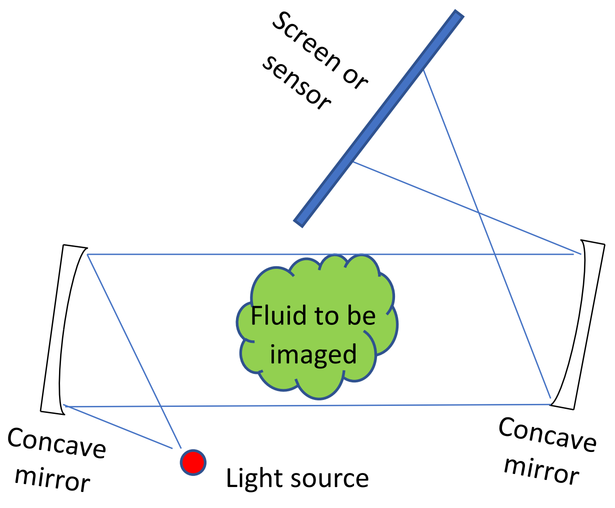


   c) Two convex collimating lenses



d) Two collimating parabolic mirrors

In all the examples above, the lens can be replaced by mirrors (it's much easier to get a very large mirror compared with a large lens). You can also use a single mirror like the schlieren version shown below.

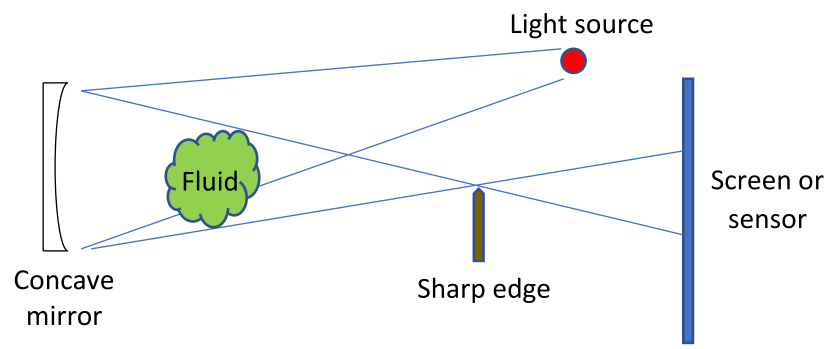


2. Schlieren

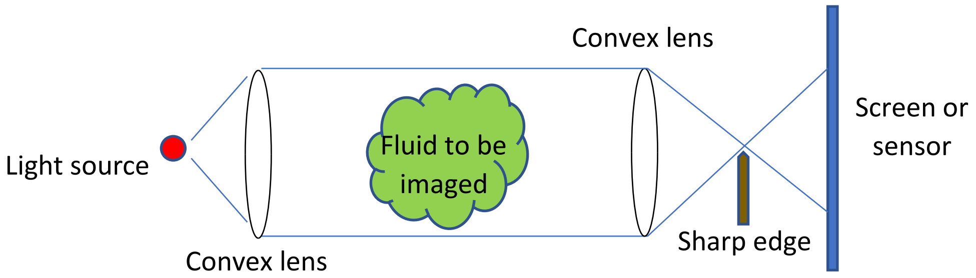
You can read about why schlieren techniques work on-line or in any suitable textbook. However, the main practical difference between this and the shadowgraph technique is the addition of a sharp edge (often a razorblade). This cuts out direct light from the source and only allows the refracted light through – so improving contrast and providing a better image than shadowgraph. Actual density values can be calculated from Schlieren images (unlike shadowgraph images). Two setup methods are shown below. Note however that, like the shadowgraph, there are many layouts and optical paths possible.

a) Single Parabolic mirror

This is perhaps the most popular of all optic fluid-imaging setups. A reflecting telescope mirror is suitable. Variations include the use of two mirrors to produce a parallel (collimated) beam through the fluid – as in the shadowgraph version.



b) Version with lenses



3. Interferometry

In interferometer setups, the light is split into two paths and then recombined at the end of the optical system. This is much more complex than either of the two methods shown above (and not as widely used). It also requires high quality research-grade light sources and glass components (accurate to within a few wavelengths of light). It does however offer some advantages including extreme detail (which you can read about in the literature). A common setup is known as the "Mach-Zehnder interferometer". The general idea is shown below.