# FLOWMETRY



## FLOWMETRY. FLUID-FLOW MEASUREMENT AND VISUALISATION

Diagnostics in thermo-fluid science and engineering is always based on measuring fluid velocity, in addition to measuring pressure, temperature and concentration fields (the latter mainly in physicochemical processes). Here we deal with the measurement of fluid velocity, momentum, and their integrals across some control surfaces (pipe and duct cross-sections). We distinguish between flow rate and flux, the latter being the flow-rate per unit normal area at a control surface.

The word flowmetry (not in dictionaries) means the measurement of flow. There are many flow magnitudes: fluid flow, mass flow (fluid or solid), heat flow, momentum flow, electromagnetic flow... We only deal here with fluid flow and the following associated measurable items:

- Mass flow rate, $\dot{m}$ .
- Volume flow rate, $\dot{V}$ .
- Speed (basically linear averaged speed, $u$, but also three-dimensional fields, $\vec{v}$ ).

- Flow and drag on solids.
- Flow and pressure difference.

Notice that all the above flowmetry magnitudes are derived SI-units, and thus must be calibrated with at least two basic patrons, namely mass and time for $\dot{m}$, length and time for $\vec{v}$, and so on (see Piezometry too). Besides, because the derived magnitudes are derivatives, to minimise uncertainty in the differentiation process, absolute mass-flow-rate calibrations are usually performed on self-regulated constant-pressure-difference test rigs: an overflowing liquid tank (Fig. 1a) or a Mariotte flask for liquids, and a free-floating gasometer for gases (Fig. 1b).

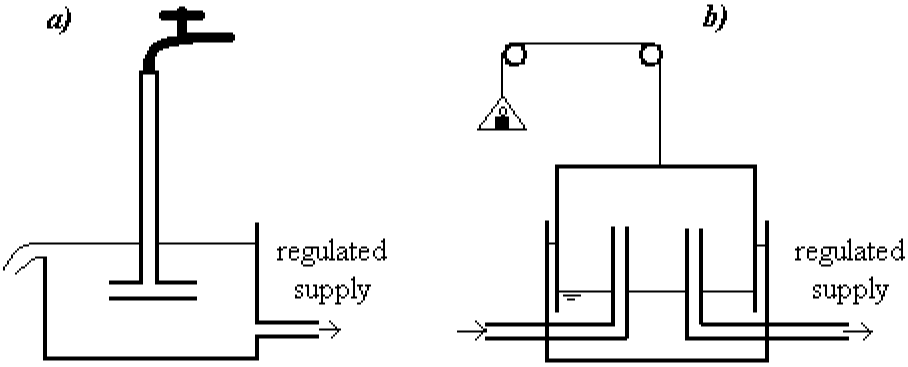

Fig. 1. Flow rate regulation.

Most of what follows refers to the flow of single-phase fluid flow, with some mention to open-channel flow, but no mention of the difficulties associated to multi-phase flow.

The purpose of fluid flow measurement can be just for knowledge of this process important variable (e.g. for accounting and taxation), or for flow regulation and control.

The variety of flow sensors is large and growing, because there is not one best solution for all applications. Most common devices are of venturi type or derivatives (the standard symbol for a flowmeter is also a kind of pipe necking), closely followed in applications by turbine flowmeters, magnetic flowmeters, thermal mass-flowmeters, and so. Most common flowmeters require clean fluids (free of suspensions) for proper operation; magnetic flowmeters and Coriolis flowmeters are used for slurries and particulate matter. Like most instruments, flow sensors are electrically conditioned to yield a standard signal range, most of the time the 4-20 mA current standard, or a standard voltage range like 0-5 V, or a digital counting (a pulse output signal with a K-factor usually in pulses/litre).

## Measuring mass flow-rate

Several methods can be used to measure flow rate, from the primary ones like accumulative weighting or positive-displacement meters, to indirect ones like drag-force or pressure-difference measurements. The trend is towards non-invasive flow sensors.

## Accumulative weighting

Liquid mass flow-rate can be directly measured with a balance and a stop-watch, using $\dot{m} = \Delta m / \Delta t$, by diverting the flow towards a suitable container. Problems may arise when the flow diversion changes the flow rate, or with volatile or toxic liquids. This method is not used for gases because of their low weight (they should be collected in an evacuated air-tight container).

## Thermal mass flow-meter

Two different approaches can be followed to measure mass flow-rate by means of a thermal disturbance (the whole, or a small bypass, of the fluid is electrically heated a little):

- Energy balance method. Some energy-deposition at the wall or the interior of the flow, and the measurement of the temperature jump achieved, assuming no heat losses, is used to compute $\dot{m} = \dot{Q} / (c\Delta T)$.
- Energy imbalance method. A very small energy-pulse deposition at the wall or the interior of the flow, and the measurement of the time-lag between two thermocouples or RTDs at each side along the flow, as explained in Fig. 2, is used to find the mass flow-rate. Notice that, when using immersion probes, this method really gives the convection speed around the resistor.

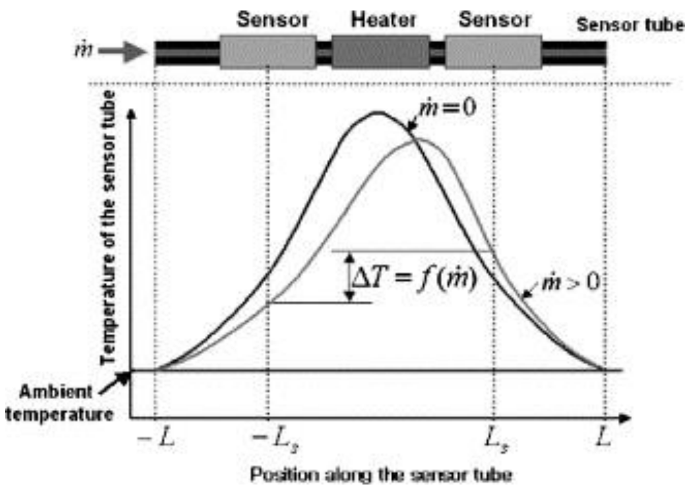


Fig. 2. Working concept of a thermal mass-flow-rate meter.

## Coriolis flowmeter

In the Coriolis-probe method, a vibrating elastic bend is inserted in series or bypass in the flow. The bend vibrates symmetrically if there is no flow, but oscillates azimuthally under flow (i.e. twists); the time delay between the twisting amplitudes (optically or magnetically measured) is $\Delta t = (8R^2/K)\dot{m}$, where $\dot{m}$ is the mass-flow-rate, $R$ the bend radius, and $K$ a rigidity constant that can be computed from tube-material properties and geometry. This is one of the bests flow metering solutions, very accurate, reliable and without restrictions on type of fluid or flow, but it is very expensive (and the bent tube, which cannot be large, is subject to fouling).

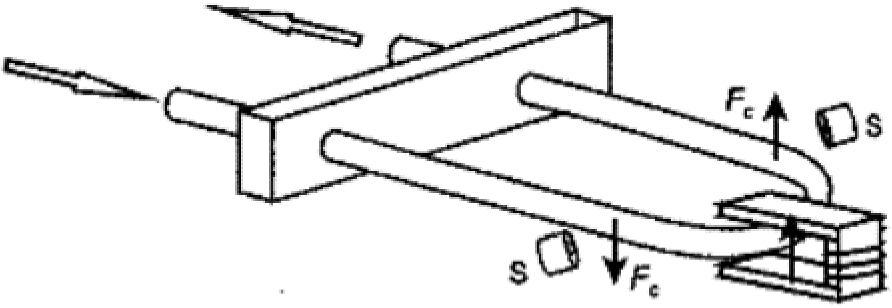


Fig. 3. Coriolis flowmeter: bent tube, vibrator, Coriolis force ($F_c$) and twist-angle sensors (S).

### Choked flow

The phenomenon of choked flow occurs with compressible fluids when the flow becomes supersonic at a flow constriction, because further pressure-changes downstream (below the choked value) have no effect on the mass flow-rate, which only depends on the upstream conditions. This is not a proper flow meter but a flow regulator, but allows quantifying the flow.

## Measuring volume flow-rate

We use $\dot{V}$ for the volume flow-rate because our interest is in thermo-fluid science, where $Q$ is always used for heat, but the usual symbol in Fluid Mechanics for volume flow-rate is $Q$.

### Accumulative filling

Liquid volume flow-rate can be directly measured with a burette (or graduated tank) and a stop-watch, using $\dot{V} = \Delta V / \Delta t$, by diverting the flow towards a suitable container. Problems may arise when the flow diversion changes the flow rate, or with volatile or toxic liquids. This method is not used for gases because they should be collected in an evacuated air-tight container at constant pressure (a gasmeter).

### Positive displacement meters

In a positive-displacement meter, a cavity of fixed size (or a number of cavities in a turn) is filled with flowing fluid and discharged downstream, so that the cavity size times the turns per second, yields the volumetric flow rate. Reciprocating, rotary, or nutating devices have been developed for the purpose; see Fig. 4. If an active device is used, it is called metering pump instead of flowmeter.

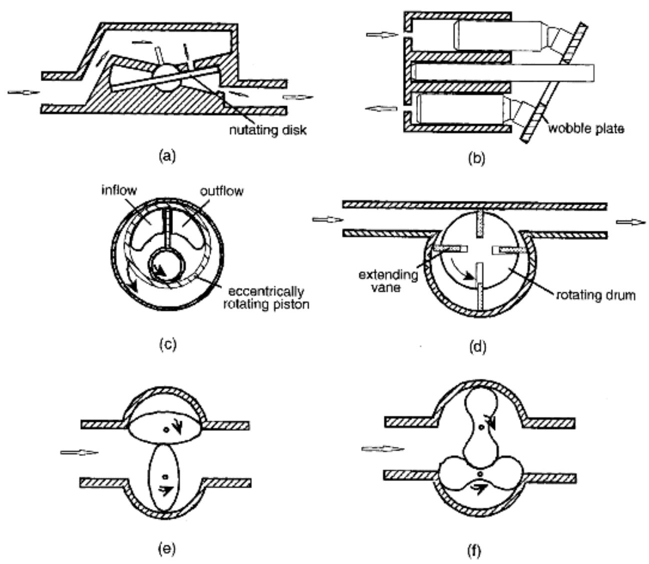


Fig. 4. Some example of positive-displacement concepts.

### Weirs

A weir is a low dam placed on an open-surface liquid stream to regulate the flow. The height of the flowing liquid over a given weir can be directly correlated to the volume flow-rate.

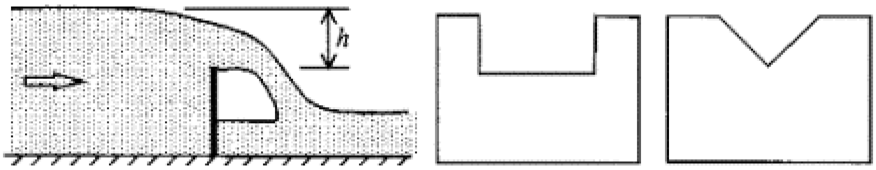


Fig. 5. Weir concept.

## Measuring speed

Measuring speed, $v$, directly or by means of momentum, may allow the computation of the flow rate through a cross-section area $A$. Notice that we here focus on one-directional velocity fields. If the bulk speed is measured, then $\dot{m}=\rho vA$; however, in most circumstances, only local speed can be measured, either with multiple probes or an scanning probe, and then some integration $\dot{m}=\rho\int v\mathrm{d}A$ is required. When air speed is measured, velocimeters are named anemometers.

Velocimetry may be based on tracking single particles (applicable to large tracers in low concentration, say larger than 10 μm and less than 1 particle/mm$^3$), or on a more sophisticated speckle analysis using very small tracers (less then 10 μm) in a large concentration (more than 1 particle/mm$^3$). Speckles are granular diffraction patterns observed when a diffuse (or diffusing) object is illuminated with coherent light; the change with time of the speckle pattern of an image gives a precise measurement of the whole two-dimensional velocity field in the illuminated plane.

### Tracer-particle tracking

Visualising small particles naturally encountered in the flow, or artificially seeded for the purpose, allows the measurement of the local speed of the flow (provided there is no drift of the particles).This method is commonly known as particle image velocimetry (PIV).

### Hot wires or hot plates

Hot wires are based on heat convection correlations; e.g. for a typical hot-wire anemometer, a simple correlation, $Nu_D=\left(2+\sqrt{Re_D}\right)/3$, relates the heat flow (electrical power dissipation, $\dot{Q}=\pi DL\left(T_w-T_\infty\right)kNu_D/D$), with the flow speed $v=\nu Re_D/D$, based on wire diameter and length, $D$ and $L$, thermal conductivity and kinematic viscosity of the gas $k$ and $\nu$, and temperatures of wire and bulk fluid, $T_w$ and $T_\infty$. The energy balance for the hot wire can be also written as $\dot{Q}=VI=I^2R=I^2R_0\left(1+\beta\Delta T\right)=hA\Delta T=\left(h_0+h_1\sqrt{v}\right)A\Delta T$, where $\beta$ is the wire-resistivity variation with temperature, and the convection coefficient $h$ has been modelled with the square-root of the velocity, as said before. Two approaches may be applied: either keep a constant intensity (power) and measure the change of electrical-resistance versus speed, or keep a constant temperature and measure the electrical-intensity required versus speed. Most thermal velocimeters operate in the constant-temperature mode, correlating the power demand against the flow speed.

Hot wires are minute items with unsurpassed spatial and temporal resolutions. Handheld probes are usually mounted on telescopic masts, what allows an easy way to scan across jets and plumes to get the velocity profile. The hot-wire method was developed in 1914 by King, and was the first method to allow very quick velocity measurements, required for turbulence analysis.

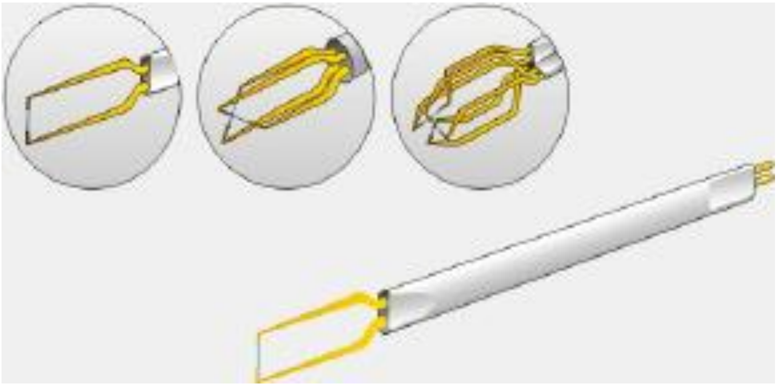

Fig. 6. Some hot-wire sensors and a mounting probe.

## Laser doppler velocimetry

There are several laser methods used in fluid flow measurement:

- Laser doppler velocimetry (LDV, or LDA because of anemometry application), developed in 1970s.
- Laser speckle velocimetry. Gives a two-dimensional velocity field, but requires coherent light and heavily-seeded fluids (little use).
- Laser-induced velocimetry. Does not require additional markers; the fluid own molecules are excited and serve as tracers.

## Ultrasonic flowmeters

Ultrasonic flowmeters are based on sound propagation at ultrasonic frequencies (typically 10 MHz). When used in air they are usually called sonic anemometers. Two different methods can be followed:

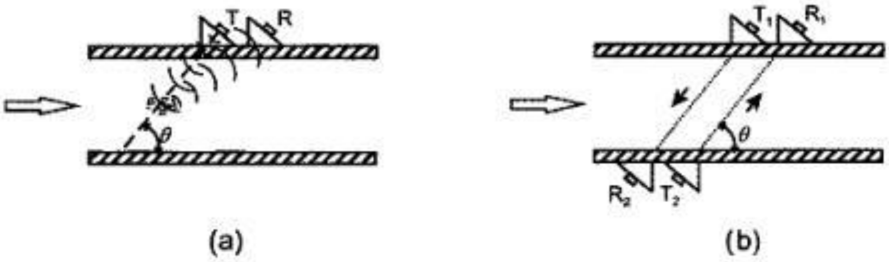


Fig. 7. Ultrasonic flowmeters: a) doppler concept, b) time-of-flight concept.

- Doppler effect. A transmitter-receiver probe at an angle $\theta$ to the flow, emits sound pulses and receives the echo from suspended particles. The receiver frequency-shift is $\Delta f=2fv\cos\theta/c$, where $v$ is flow speed and $c$ is the sound speed. Requires some solid particles or gas bubbles, for the reflexion.
- Time-of-flight effect. Two couples of opposite transmitter-receiver devices are set-up at an angle $\theta$ to the flow; one of the transmitters being triggered by its neighbour receiver, giving a difference in frequency of $\Delta f=2v\cos\theta/L$, where $L$ is the path. Notice that this ultrasonic method does not depend on the speed of sound, $c$ (i.e. on temperature).

## Vortex flowmeters

Vortex flowmeters are based on measuring the frequency of von Kármán's vortex street, a periodic shedding of eddies from alternating sides at an obstacle in the flow. Its range of applicability is not very wide, say $40<Re_D<150$ for a cylindrical probe of diameter $D$, i.e. not valid for slow flows.

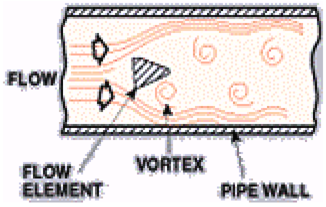


Fig. 8. Vortex velocimetry concept.

## Magnetic flowmeters

Electromagnetic flowmeters are based on Faraday induction in electrically-conducting fluids (e.g. water, but not organic liquids). A magnetic field, $B$, is applied to the metering tube (which must be electrically insulated from the fluid), what yields an electromotive force $E=KvBL$ perpendicular and proportional to the flow speed. Faraday tested it in 1832 to measure the seep in the Thames based on the Earth magnetic field but the electrical potential was too small for the time. Probes are expensive, but very accurate and without pressure loss; electrodes may foul with time.

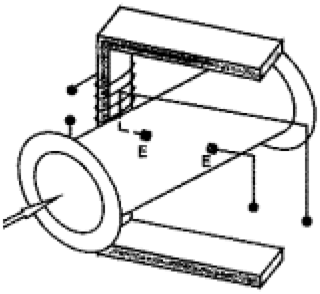


Fig. 9. Magnetic flowmeter concept: E, electrodes.

# Measuring drag effects

They usually require specific calibration. Several main types of drag-effect flowmeters can be distinguished, which may be classified in free-movers (turbines and weights) and elastic objects (spring-loaded and load-cells).

## Turbine flow-meter

The turbine flow-meter (and similar devices using vanes, caps, paddlewheels, or propellers), are forced by the flow drag to rotate at a rate proportional to the flow speed. Optical or magnetic counting of vane passes is used. They are accurate, but they introduce some pressure loss, are are prone to clogging (a filter is usually found upstream). Some types of turbine flow-meters may approach a positive-displacement device.

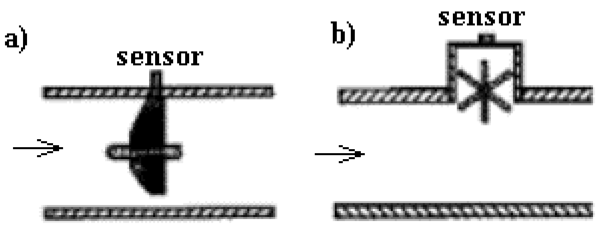


Fig. 10. Some drag-effect flowmeter concepts: a) turbine, b) paddlewheel..

### Rotameters

Rotameters are based on balancing a levitating weight in a conical vertical pipe (diverging upwards), by the flow drag, i.e. they make use of a variable restriction and a constant pressure differential, rather than a constant restriction area and a variable pressure differential as in other drag-effect sensors. Rotameters have a small range, and require calibration, but are accurate, simple, and economic. An stimation of the calibration curve can be made based on the force balance of a mass $m_P$ floating in a conical tube of radius $R(z)=R_0+R'(z-z_0)$, where $R_0$ is the maximum diameter of the float. At steady state, the force balance is $m_P g\left(1-\rho/\rho_P\right)=A_P c_D \frac{1}{2}\rho v^2$, where $v$ is the undisturbed speed and $A_P$ the frontal projected area. Assuming the fluid density being much smaller than the load density, $\rho<<\rho_P$, the friction coefficient of order one, $c_D$=1, one gets $\dot{V}=v\pi R^2(z)=Cv\,\pi\left(R^2-R_0^2\right)=2Cv\pi R_0R_0^{'}(z-z_0)$, thus, the volume flow-rate varies linearly with the $z$-position of the float, and inversely proportional to the square of the fluid density (i.e. for the same float position, butane will have a volume flow-rate 1/sqrt(0.029/0.058)=0.7 times that of air; for diesel oil the volumetric flow-rate will be 1/sqrt(1000/840)=0.92 that of water). Actually, volume flow-rate increases more than linearly with weight height.

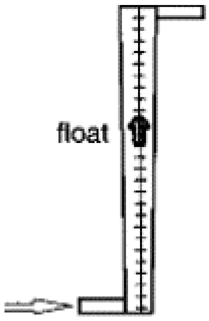


Fig. 11. Sketch of a rotameter flowmeter.

### Drag force meters

Drag force meters are based on measuring the force or deflection caused by the flow drag on a frontal disc or a sphere (load cell).

## Measuring differential pressure

Measuring differential pressure through or across a flow restriction (with or without significant pressure losses), can be used to find local or global flow speeds based on Bernoulli's equation.

Measuring differential pressure along a capillary tube, to guaranty laminar developed flow and apply Poiseuille law, $\dot{m}=\pi\rho R^4\Delta p/\left(8\mu L\right)$, can also be used to measure flow rates.

### Pitot

A pitot probe yields a local measurement of flow speed based on dynamic pressure, with insignificant pressure losses. More details can be found aside, in Piezometry.

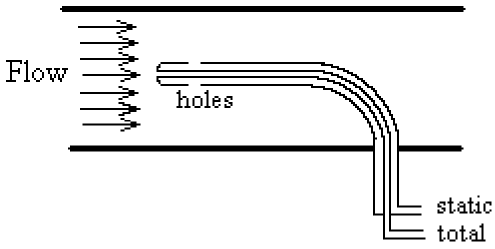


Fig. 12. Pitot probe.

### Venturi flowmeters

A venturi probe yields a global measurement of the volumetric flow-rate, based on dynamic pressure, with insignificant pressure losses. They are reliable accurate devices, most accurate in the range $10^5<Re<10^6$, but more expensive than flow-obstruction meters. More details can be found aside, in Piezometry.

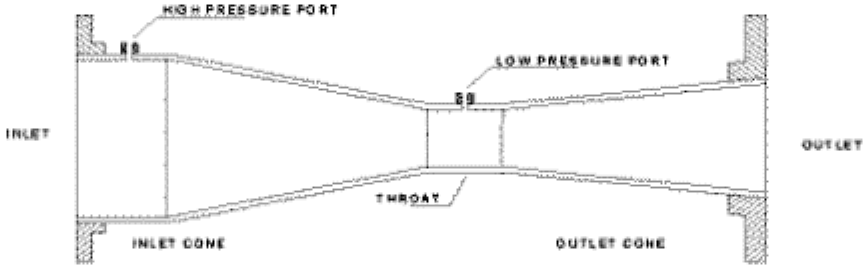


Fig. 13. Venturi flowmeter.

### Flow obstruction meters

Flow obstruction meters measure the pressure loss through orifice plates and nozzles, based on static pressure, with insignificant pressure losses). They usually requires specific calibration: $\dot{V}=K\left(\pi D^2/4\right)\left(1-(d/D)^4\right)^{-1/2}\left(2\Delta p/\rho\right)^{1/2}$. More details can be found aside, in Piezometry.

Fig. 14. Nozzle and orifice flowmeters (pressure probes not shown).

## Flow visualization

It is rare that a fluid experiment does not involve some kind of visualisation. No matter how advanced the fluid management and diagnostic equipment may be, visualisation is invaluable at least during the setup phase. Image interpretation (pattern recognition) has always demanded the highly intelligent data reduction ability of human sight, but nowadays computerised image analysis is beginning to take over many routine duties, as in particle image velocimetry.

Flow visualization basically refers to transparent fluids; the flow of opaque fluids can only be visualised at their free surface (or otherwise using high-energy radiations, to which they become transparent).

## Interface optical diagnostics

In that basic photographic setup, an image is formed at the observer's eye-back or camera plane (both analogue and digital) with the visual radiation received from the object and the background, based on one of the following mechanisms:

- Reflection at the object, from an external light source, usually close to the viewing direction to avoid shadows (instead of a point source, a distributed light source may be used to smooth shadows). As most fluids are transparent, tufts, dyes, smoke, or suspended particles (either floating or being carried with negligible drift) are added.
- Own radiation emission. Due to hot or chemiluminiscent objects in the visible range, but present in all cases in the infrared range. In this case, the external source is not needed.
- Silhouette (obstruction by the object of the light coming from the background, either by reflection or transmission). Of interest in fluid experiments to locate interfaces very accurately.
- Reflection and scattering by small particles inside a transparent object. Normally only a plane in the object is illuminated to avoid ambiguity in depth location of particles. Of great use in fluid experiments to visualize internal motion and compute the velocity field in the illuminated plane. For proper light scattering measurements, monochromatic and collimated light is used.

Ambient lab illumination is seldom good enough to record fluid science experiments and a special lighting system is needed, the ambient lab illumination being then a nuisance because of unwanted reflections.

## Refractometry

Refractive index methods do not measure velocity but density changes, what can be a fluid-flow characteristic in compressible flows. Refractometry can be based on optical path deflection or retardation, namely:

- Ray intensity distortions measurement.
- Ray phase-shift distortions measurement.

Measurement ray distortions can be accomplished by suitable amplification phenomena (shadows in ray concentration, selective intensity-cutting in schlieren, phase interference, deformation of the image projected by an optical grating on a secondary grating (moiré technique), etc.

If a two-dimensional transparent object is placed in a collimated light beam, intensity non-uniformities can be seen and an image formed, shadowgraph, due to ray concentration changes (convergence or divergence), although the accuracy in the reconstruction is poor and that this method is only used for qualitative visualization (e.g. shape of shock waves, of mixing layers, etc.).

The schlieren effect is a reinforcement of the shadowgraph effect when a knife edge is interposed in the path. The knife cuts a fraction of the light-source image at the focal plane, obscuring the image on the screen in the average but also selectively, because ray pencils deflected sideway towards the knife is cut more than ray pencils deflected in the opposite direction.

Interferometry (classical, speckle, holographic,...) is based on phase-shift distortions caused by the fluid volume, which must be confined between parallel plates of optical quality. When two coherent collimated beams are superimposed on a screen, the possible phase shifts may give way to an interference pattern. Even with a constant refractive index medium, a fringe pattern with a regular spacing w will normally show up due to geometrical distortions.

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