Fluid Flow Measurement

Fluid Kinematics – Lesson 5

Introduction

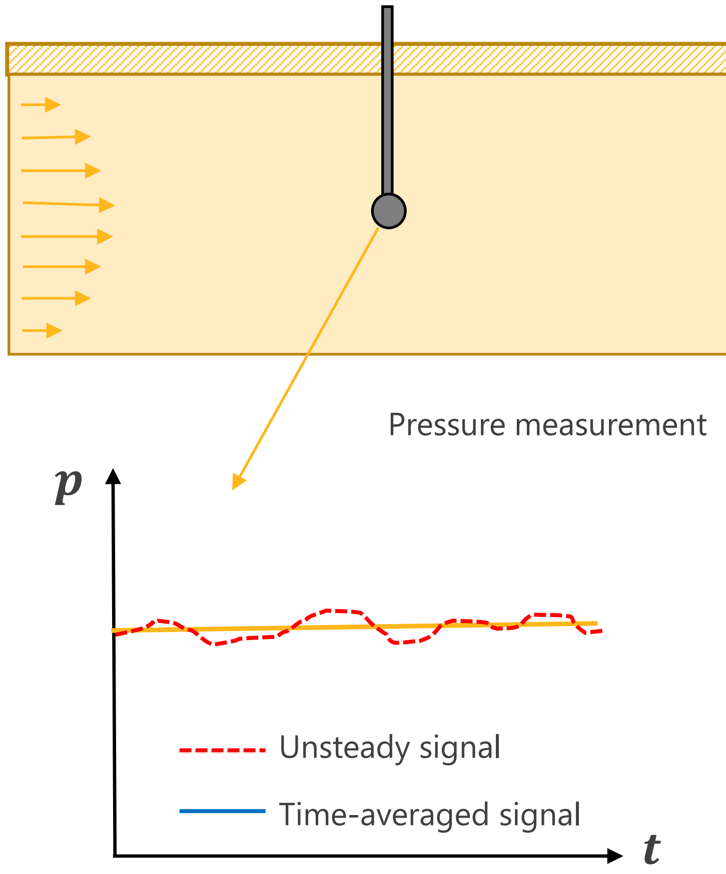
- As we explore the science of fluid mechanics, it is important to understand how we can measure the characteristics of real flow fields — pressure, velocity, temperature, etc.

- Flow measurement is the cornerstone of experimental fluid mechanics. It not only provides us with information about the flows observed but enables us to determine how well our theories match up to the real world.

- In this lesson we will highlight some of the important methods and measurement techniques for three key flow parameters:
  - Pressure
  - Velocity
  - Temperature

Steady Versus Unsteady Measurements

- Nearly all fluid flows we observe are inherently unsteady due to turbulence, wave motion and instabilities.
- When we measure fluid flow properties, the readings may in fact be mildly unsteady even if the system boundaries are at steady conditions.
- However, for many applications, we merely wish to know the mean or average flow properties at a point in space or spatially averaged on a surface.
- For most of the descriptions in this lesson, we will focus on measurements intended for steady-state analysis and therefore represent a mean value.
- However, we will also look at a few methods where the flow unsteadiness is measured, thus requiring a system which can record and log the time history of the flow variable.

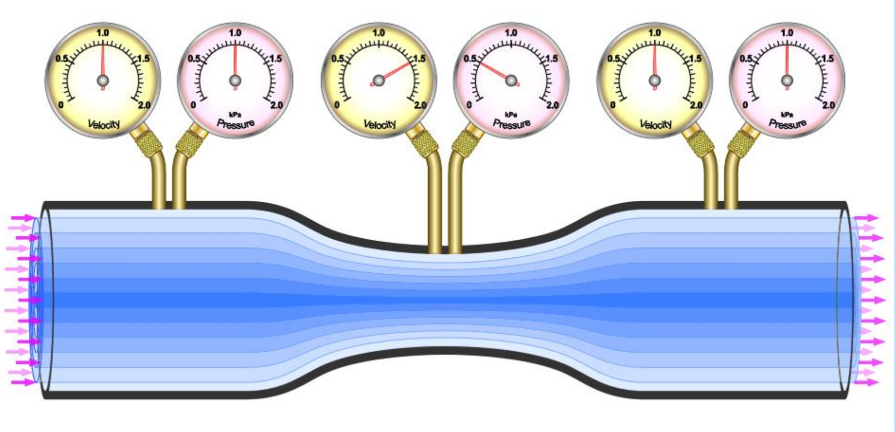


Pressure Measurement Methods

- Fluid pressure is a key variable in all fluid flows.
- The pressure variation on surfaces wetted by fluids gives rise to forces and moments which mechanically impact the bodies associated with those surfaces. For example:
  - Lift forces on an aircraft wing
  - Pressure drop in a gas pipeline
  - Drag force on a race car
  - Torque and power on the blades of a wind turbine
- Two devices commonly used for measuring pressure are the manometer and the barometer. These rely on the effect the pressure has on the height of a liquid in a tube situated in the earth's gravitational field.
- We will now look at examples of other methods of measuring pressure.

Static Pressure Taps

- Relating to the manometer, it is important to understand how pressure measurements are set up in a real-world flow system.
- One of the most common ways of sensing pressure is to install a static pressure tap.
- The static pressure tap is a hole drilled into the wall of a flow system such as a pipe. A manometer or other pressure sensor is connected at this point.
- The pressure tap allows the pressure of the fluid at a specific point on the wall to be measured and recorded (usually with an electronic data logger).

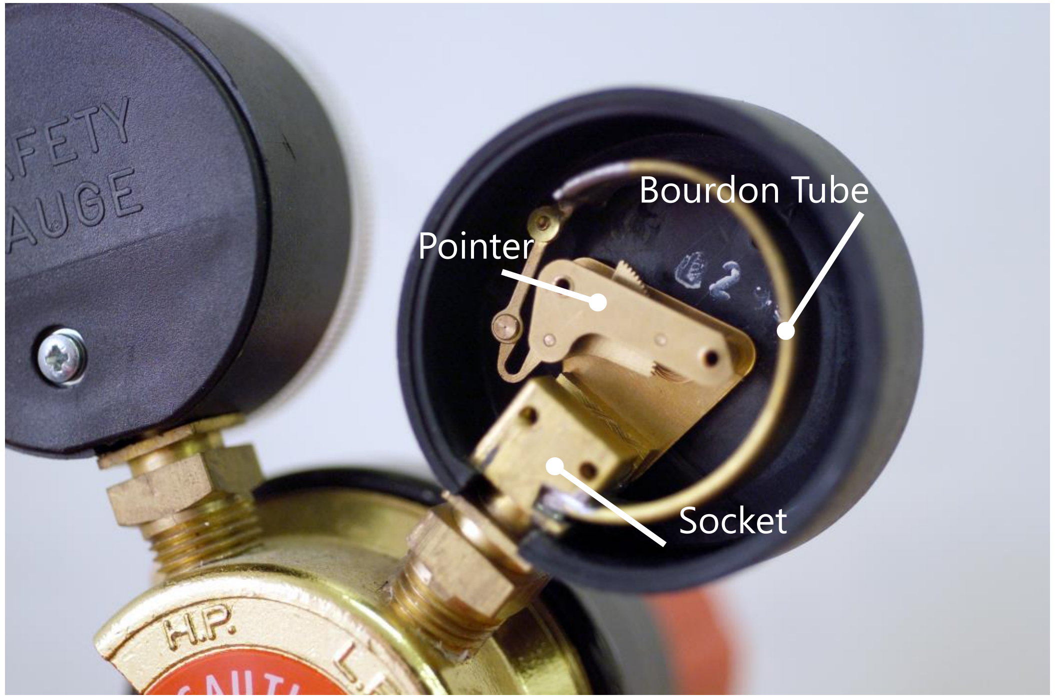


Pressure taps installed on the wall

The Bourdon Tube Pressure Gage

- A Bourdon Tube pressure gauge is a device consisting of a curved tube, with one end closed and the other connected to the pressure measurement source.
- When fluid pressure is imposed on the open end of the tube, an elastic deformation of the tube occurs. The amount of deflection is measured by a spring-loaded needle, which points to a calibrated scale to indicate the pressure.
- This type of gauge is often used for measuring pressures in closed tanks, tires, pressurized vessels and similar systems.

Bourdon Pressure Gage



Bourdon Pressure Gage – Working Principle

Velocity and Flowrate Measurement Methods

- Along with pressure and velocity, flowrate measurements are essential in understanding the state of a fluid flow in real systems.
- Flowrate measurements are concerned with measuring the volume or mass flow rates, usually in a bulk sense (e.g., flow passing through a pipe with a given cross-sectional area).
- Velocity measurements attempt to determine the magnitude and direction of the local velocity.
  - In some cases, only velocity magnitude can be readily determined.
  - More sophisticated measurements can obtain both magnitude and direction.

Bernoulli's Equation

- Many flow and velocity measurement methods infer the velocity (or mean velocity) from a pressure difference which can be measured (e. g., by a manometer). We can relate pressure differences to the velocity through various forms of Bernoulli's equation.
- One form defines the velocity in terms of a total and static pressure difference $(p_0 - p)$:

$$\bar{V} = \sqrt{\frac{2(p_0 - p)}{\rho}}$$

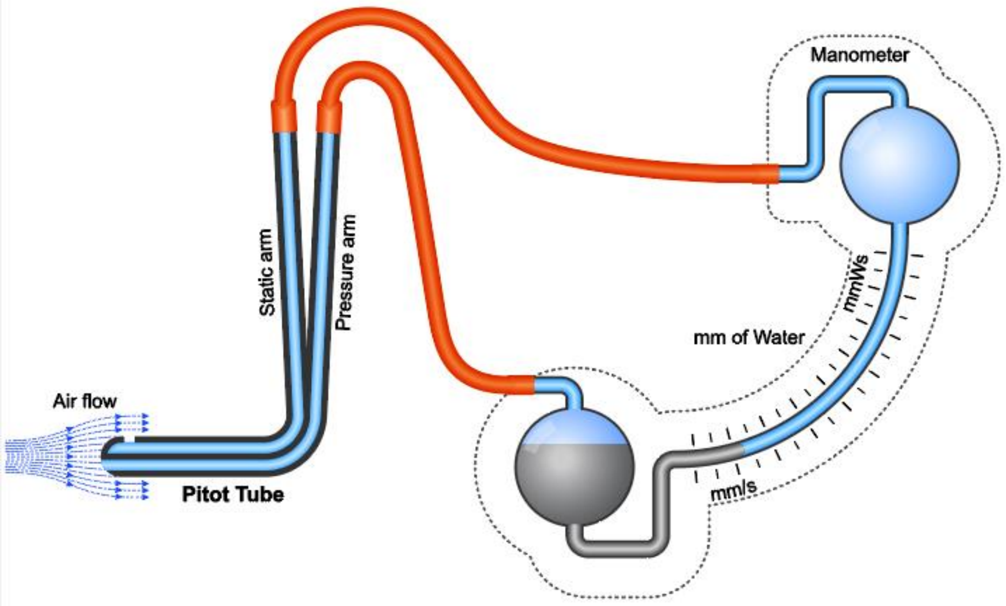
- Another form infers velocity from a static pressure difference $(p_2 - p_1)$ and a loss coefficient K :

$$\bar{V} = K\sqrt{\frac{2(p_2 - p_1)}{\rho}}$$

- In either case, these devices must be calibrated. That is, the loss coefficient is calibrated such that the pressures measured yield the correct flowrate.

The Pitot Tube

- The pitot tube is a device for measuring velocity at a point and has applications in experimental fluid mechanics (wind tunnels) and aviation (air velocity sensors).
- The device is a pointed tube with openings for pressure measurement at the tip and at the side of the tip.
- The tip pressure is the total (or stagnation) pressure, while the side opening is the static pressure. Both can be measured at once and the difference recorded.
- Using Bernoulli's equation (previous slide), we can determine the velocity knowing the fluid density.

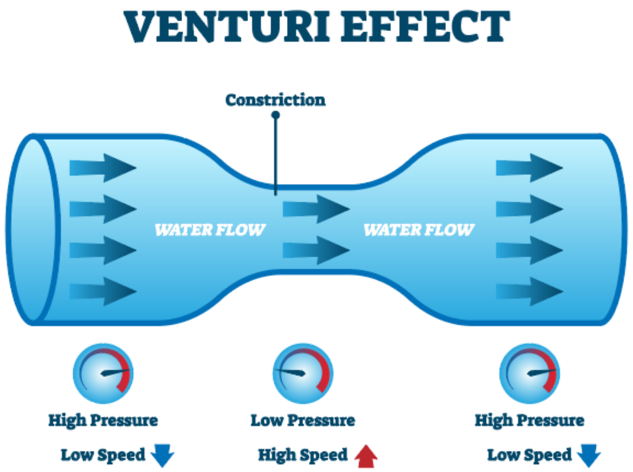


Pitot Tube – Working Principle

Pitot Tube

The Venturi Tube

- A Venturi tube is a device for measuring flowrate, again using two pressure measurements.
- The device is essentially a tube with a narrow constriction (or throat).



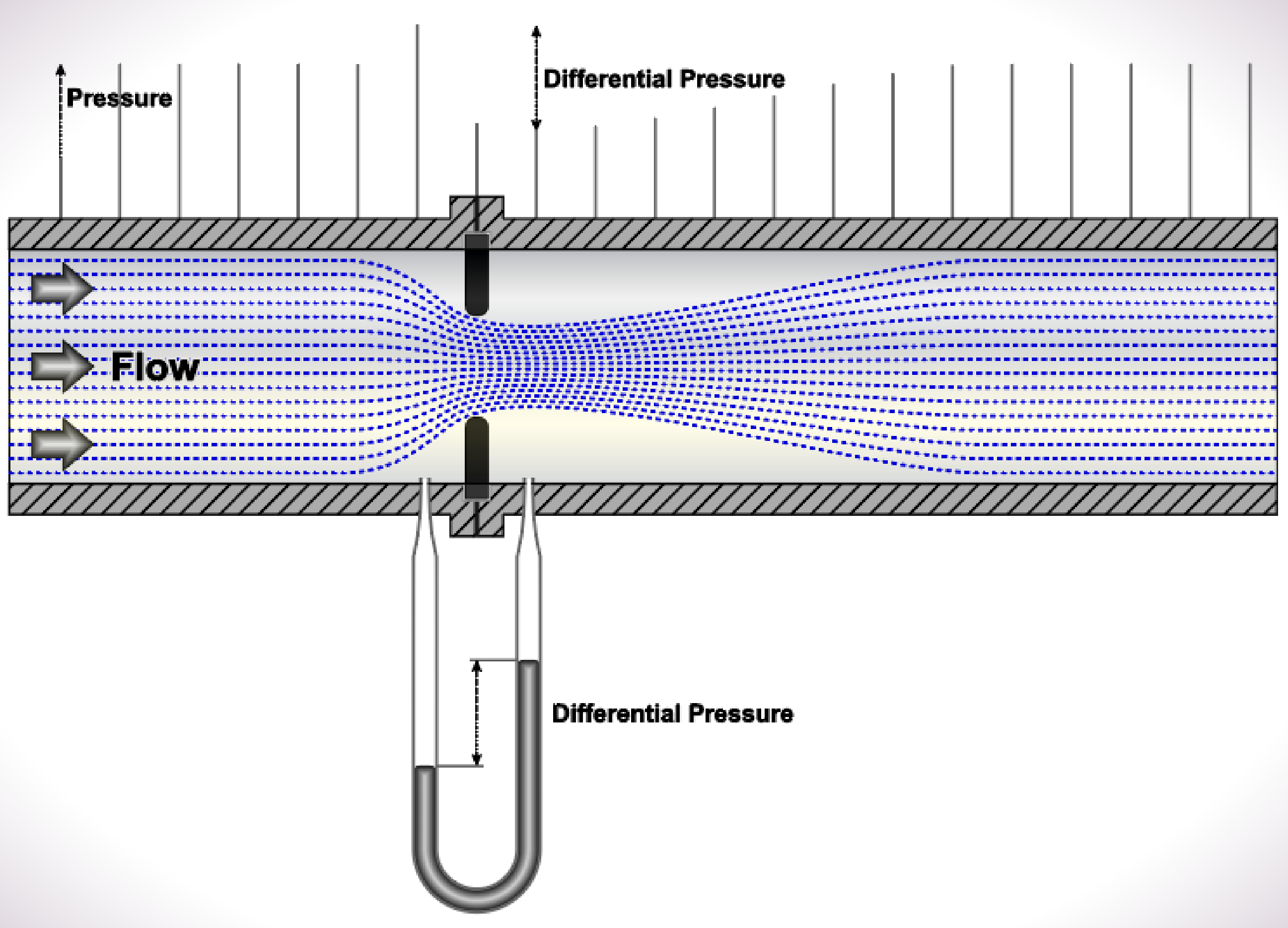
Venturi Tube

- As the flow passes from the upstream to the throat, the pressure drops. The level of pressure drop along with knowing the fluid density and area difference between the upstream pipe and throat allows us to determine the volume flow rate using the following equation:

$$Q = A_1 \sqrt{\frac{2(p_1 - p_2)}{\rho\left[\left(\frac{A_1}{A_2}\right)^2 - 1\right]}}$$

Orifice Plates and Flow Nozzles

- Like a Venturi tube, orifice plates and flow nozzles infer flowrate from the measurement of pressure difference across an orifice opening or a flow nozzle.
- In both cases the orifice or nozzle is an obstruction to the flow which causes a pressure drop. The flowrate can be calculated knowing the density of the fluid and the pressure drop, assuming the geometry of the orifice or nozzle (and therefore the loss characteristics) is known.



Orifice Plate

Turbine Flowmeters

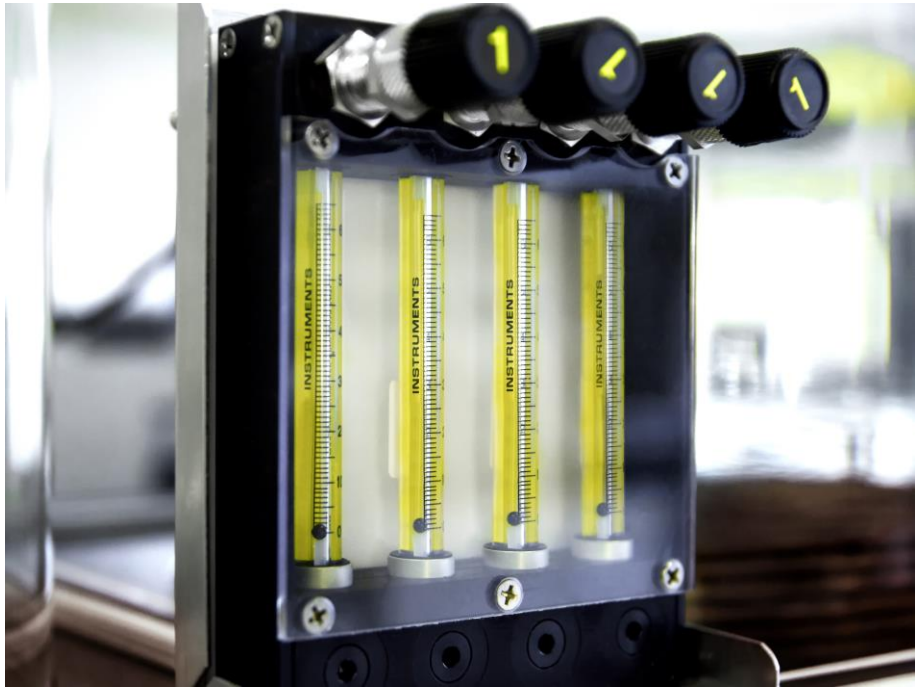
- Turbine flowmeters are based on the idea that a flowing fluid can turn a simple turbine rotor. Attaching the shaft of the rotor to an electric pulse detection sensor (to obtain the rotor RPM), we can calibrate the electrical signal thus produced with the fluid flowrate.

- With their rugged construction, turbine flowmeters are used in harsh environments for measuring flows (e. g., high pressures and temperatures).

The Rotameter

A rotameter is a flow measuring device that uses a float in a tube of varying cross section to determine volume flowrate.

The basic principle is that the tube, which is oriented vertically, directs the fluid flow around the float, which pushes the float upwards due to the drag force acting on the surface of the float. The weight of the float acts in the opposite direction. As a result, an equilibrium position is established. This position can be calibrated with flowrate and a scale created for the device based on the fluid properties.



Flow Rotameter

- Obviously, the orientation of the rotameter and calibration of the flowrate scale are important when applying it to specific measurement applications.

Hot Wire Anemometers for Velocity Measurement

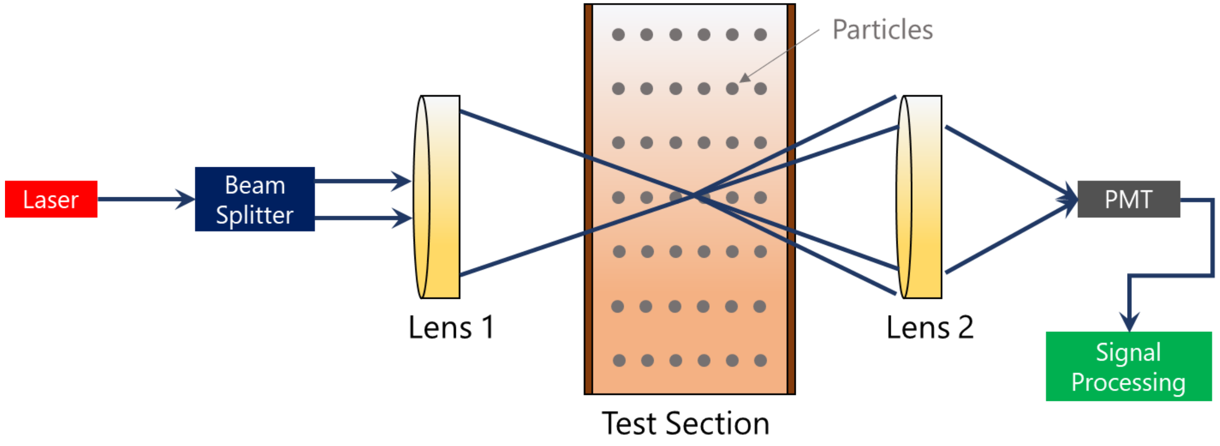
- A hot wire anemometer is a probe designed to sense velocity magnitude by measuring the heat transfer and temperature of an electrically heated thin wire which is immersed in the flow.
- The heat flux q'' from the wire can be expressed as a function of calibration parameters (a, b), local fluid velocity (u), freestream temperature (T_∞) and wire temperature (T_w) as follows:

$$q'' = (a + b\sqrt{u})(T_w - T_\infty)$$

- Since the wire is heated electrically, we can measure the electrical current through the wire and relate the heat flux with the wire resistance, temperature and calibration parameters. Thus, we can determine the fluid velocity from the equation above.
- Hot wire anemometers are very sensitive to change in velocity and thus are used for measuring rapidly fluctuating turbulent flow transients.

Laser Doppler Anemometer (LDA) Velocity Measurement

- One of the problems with the flow measurement devices discussed to this point is that they disturb the flow in some way (e.g., a flow nozzle is an obstruction in a pipe flow).
- If precise measurements of the undisturbed flow field are required, then optical methods must be used.
- The Laser Doppler Anemometer (LDA) (also called Laser Doppler Velocimetry - LDV) is an optical method with the precision to obtain quantitative measurements.

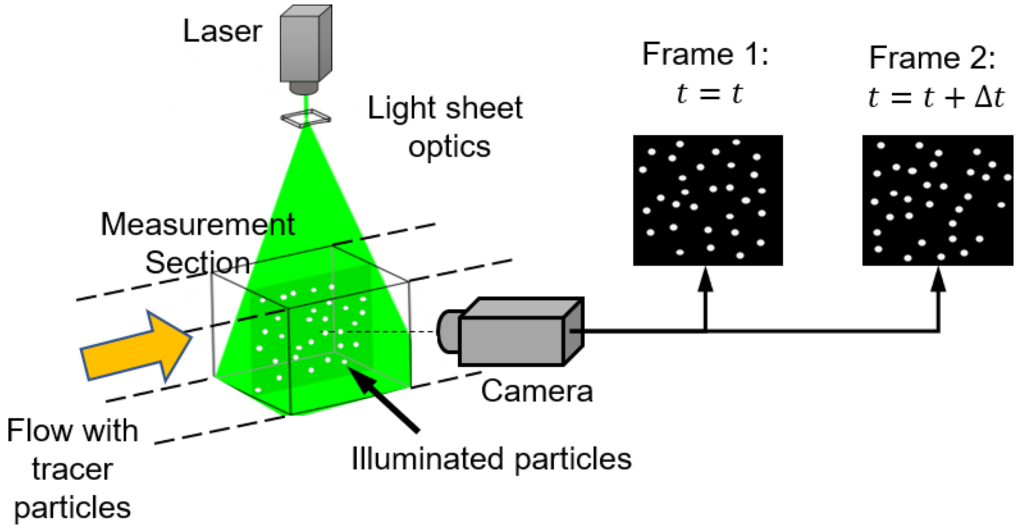


Laser Doppler Anemometer (LDA)

- Basically, the LDA works by focusing a laser beam on a point in a flow which is seeded with a low concentration of particles. The particles scatter the light such that a Doppler shift can be detected, which is related to the velocity of the fluid at the point of measurement.

Particle Image Velocimetry (PIV) Measurement

- Particle Image Velocimetry (PIV) is another optical method used to measure flow velocities.
- Unlike the LDA which measures the velocity at a point, the PIV produces two-dimensional or even three-dimensional velocity fields.
- The PIV process focuses two subsequent light pulses from a laser through a flow seeded with trace particles on a camera. This provides information for reconstructing a two-dimensional velocity field.
- The addition of the second camera enables stereoscopic imaging of the flow, resulting in a three-dimensional representation of the velocity field .



Particle Image Velocimetry (PIV)

Temperature Measurement Methods

Temperature is a very important flow parameter, particularly for compressible flows and flows with heat transfer.

There are many ways to measure temperature and most fall into three categories:

- Mechanical temperature measurement
- Electrical temperature measurement
- Radiation temperature measurement

We will briefly consider these three types of temperature measurements.

Mechanical Temperature Measurement

This temperature measurement method uses the change in size or dimension of a solid or fluid as an indication of temperature.

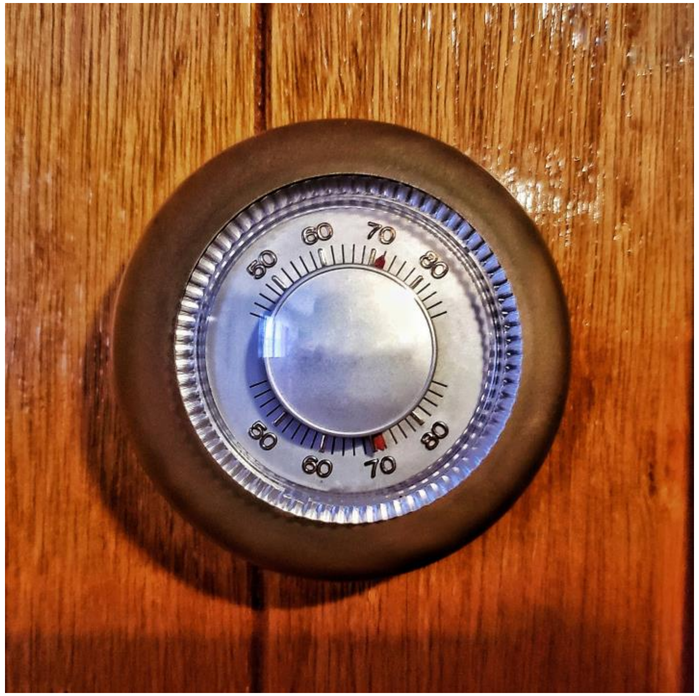
Mercury Liquid-in-Glass Thermometer

- Mercury expands/contracts in the tube in response to temperature.

Bimetallic Strip

- Two pieces of metal with different coefficients of thermal expansion are bonded together.
- The strip bends in two directions depending on the temperature.

Thermometer



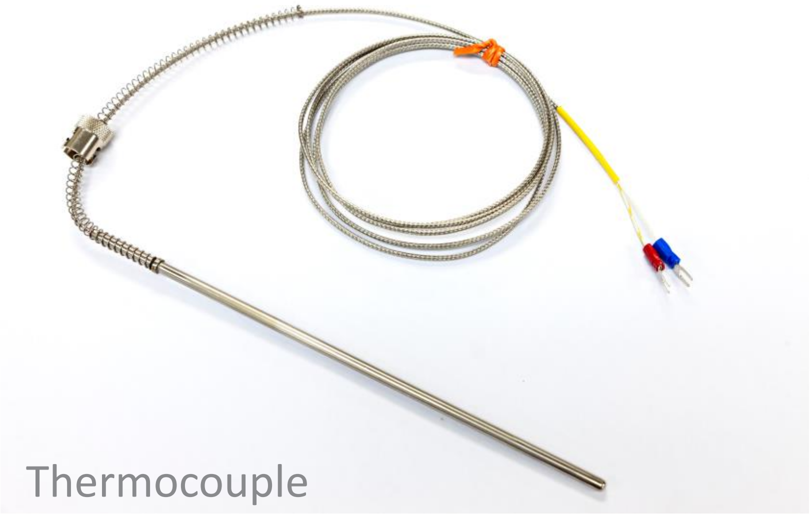
Bimetallic Strip Thermostat

Electrical Temperature Measurement

There are two main categories of electrical temperature measurement:

- Electrical resistance thermometer — This device consists of a resistance element of a known metal or a semiconductor. The electrical resistance of the material is a function of temperature and can be read precisely and converted to a calibrated temperature.

- Thermocouples — When two dissimilar metals are joined, a voltage is created which is a function of temperature (this is known as the Seebeck Effect). This voltage can be read and converted to a calibrated temperature. Thermocouple circuits require special care in their installation and need compensation for other voltages that may arise due to connections away from the point of measurement.



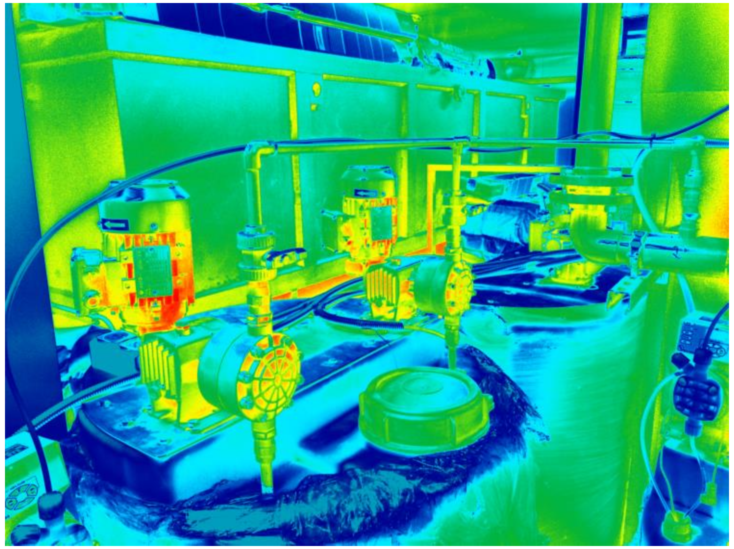
Ansys

Radiation Temperature Measurement

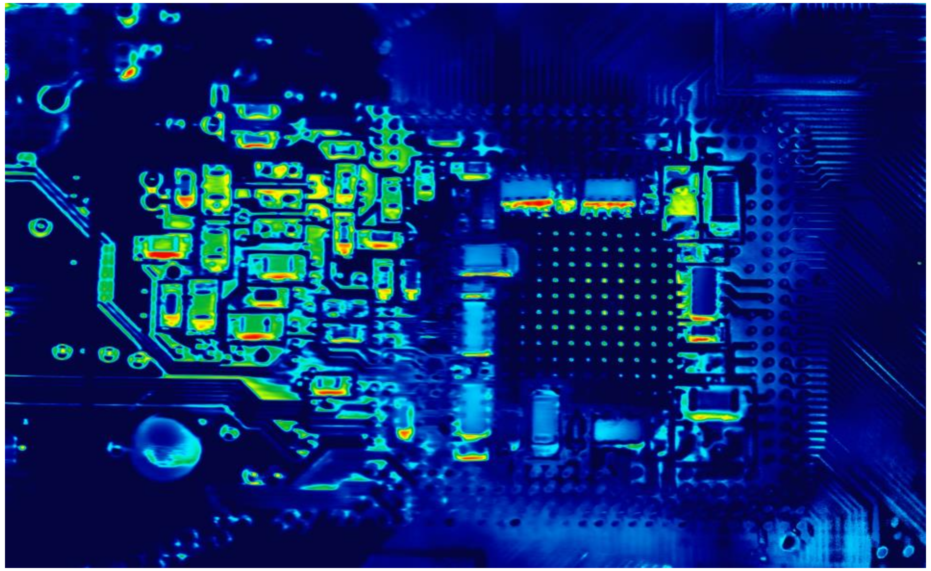
Mechanical and electrical devices for temperature measurement are somewhat intrusive as we need to insert the measurement element into the flow, thereby disturbing it.

There are optical methods which avoid this and infer temperature by sensing the infrared radiation emitted by the fluid.

It is beyond the scope of this lesson to explore this in detail, but it should be noted that infrared cameras have now become commonplace and can be used to qualitatively show regions of high and low temperature.



IR Image of an Engineering System



IR Image of an Electronic Printed Circuit Board

Summary

- This lesson described methods for measuring flow properties experimentally.
- Experimental data is highly valuable as the testing helps further our knowledge of fluid mechanics and provides reference information to assist in the development of numerical simulation methods.

Ansys

Ansys