People's Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research

University of Ahmed DRAIA Adrar

Faculty of Material Sciences, mathematics & Computer science

Department of Material Sciences

COURSE HANDOUT:

Experimental Techniques in Fluid Mechanics

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Introduction

The study of how fluids behave and interact with different forces and boundaries is called fluid mechanics. This field of science has many applications in engineering, science, and everyday life. However, the study of fluid behavior represents a challenge in terms of analysis and modeling, especially turbulent, compressible or multiphase flows. For this reason, experimental measurement methods and techniques in fluid mechanics are essential to complete fluid analysis. It is possible to provide results, validate our hypotheses, and improve our understanding of fluid phenomena.
The main objective of using experimental techniques in fluid mechanics is to **measure the properties of flowing fluids.** Measurements are used to understand how the fluid-containing system operates and then to apply this knowledge to designing improved systems and predicting their future operation. They are also used to monitor and control the physical process, therefore ensuring efficient and safe operation of the system.

This course is intended for first-year master's students in energy physics and renewable energies deals with the experimental techniques in Fluid Mechanics. It focuses on different techniques and challenges associated with measuring flow characteristics such as pressure, temperature, flow rate, speed and vacuum rate.

Teaching objectives: Acquire knowledge of the different measurement techniques used in fluid mechanics.

Recommended prior knowledge: Basic Concepts in Fluid Mechanics

Course content:

1. Pressure measurements
2. Flow measurements
3. Velocity measurements
4. Temperature measurements
5. Vacuum rate measurements

Chapter 1:
Generalities on measurements in physics

1.1 Definition

Measurement refers to the act of ascertaining the length, size, or amount of a substance. Throughout history, various techniques have been employed to gauge length. To measure a physical quantity, such as length, it must be referenced against a specific fixed quantity. This fixed quantity, which serves as a reference point for measurement, is known as A unit. Units function as standards for measurement. In ancient times, individuals utilized various parts of their bodies, such as hand spans, cubits, and fathoms, to determine length.

- Understanding how to assess the attributes of actual flow fields, such as pressure, velocity, and temperature, is essential.
- Flow measurement serves as the fundamental basis of experimental fluid mechanics. It not only offers insights into the characteristics of observed flows but also aids in assessing the alignment of theoretical models with real-world phenomena.

1.2 Background of flow measurement

The following terms provide the foundational knowledge necessary for understanding fluid flow measurement and should be comprehended prior to the selection of a flow measurement system. The definitions of "fluid," "flow," and "measurement" can be found in Webster's New Collegiate Dictionary:

Fluid: 1. having particles that easily move and change their relative position without separation of the mass and that easily yield to pressure; 2. a substance (as a liquid or a gas) tending to flow or conform to the outline of its container.

Flow: 1. to issue or move in a stream; 2. to move with a continual change of place among the consistent particles; 3. To proceed smoothly and readily; 4. to have a smooth, uninterrupted continuity.

Measurement: 1. the act or process of measuring; 2. a figure, extent, or amount obtained by measuring. Combining these into one definition for fluid flow measurement yields:

Fluid flow measurement involves assessing the movement of particles that travel smoothly and conform to the piping system in a continuous stream, allowing for the determination of the flow quantity. Certain constraints necessitate that the fluids exhibit a relatively stable mass flow, remain clean, homogeneous, Newtonian, and maintain a stable single-phase profile without swirling, adhering to specific limits of Reynolds number, which vary depending on the measurement device used. If any of these conditions are not satisfied, the accuracy of the measurements may be compromised, and in some instances, it may be advisable to refrain from measurement until the issues are resolved. These challenges must be addressed, as the anticipated accuracy will not be realized until the fluid is adequately prepared for measurement. Conversely, the expenses associated with preparing the fluid and/or the flow may, at times, exceed the benefits derived from the flow measurement, leading to a situation where lower accuracy is deemed acceptable.

1.3 Terms definition

Absolute Viscosity (mu) The absolute viscosity (mu) is the measure of a fluid's intermolecular cohesive force's resistance to shear per unit of time.

Accuracy The ability of a flow measuring system to indicate values closely, approximating the true value of the quantity measured.

Ambient Conditions The conditions (pressure, temperature, humidity, etc.) externally surrounding a meter, instrument, transducer, etc.

Ambient Pressure/Temperature The pressure/temperature of the medium surrounding a flow meter and its transducing or recording equipment.

Analysis A test to define the components of the flowing fluid sample.

Base Conditions The conditions of temperature and pressure to which measured volumes are to be corrected (alternatively known as reference or standard conditions). The base conditions for the flow measurement of fluids, such as crude petroleum and its liquid products, having a vapor pressure equal to or less than atmospheric pressure at base temperature are:

In the United States:

Pressure: 14.696 psia (101.325 kPa)

Temperature: 60F (15.56C)

The International Standards Organization:

Pressure: 14.696 psia (101.325 kPa)

Temperature: 59F (15C)

For fluids like liquid hydrocarbons that exhibit a vapor pressure exceeding atmospheric pressure at the base temperature, the base pressure is typically referred to as the equilibrium vapor pressure at that temperature.

The base conditions for the flow measurement of natural gases are (in the USA):

Pressure: 14.73 psia (101.560 kPa)

Temperature: 60F (15.56C)

The International Standards Organization:

Pressure: 14.696 psia (101.325 kPa)

Temperature: 59F (15C)

The base conditions for liquid and gas applications may vary across different countries, states, or industries. Consequently, it is essential to establish the base conditions for what constitutes "standard" volumetric flow measurement.

Calibration of an Instrument or Meter The process or procedure of adjusting an instrument or a meter so that its indication or registration is in close agreement with a referenced standard.

Certified Equipment Equipment with test and evaluations with a written certificate attesting to the device’s accuracy.

Compressibility The change in volume per unit of volume of a fluid caused by a change in pressure at constant temperature.

Critical Flow Prover A test nozzle that is used to test the throughput of a gas meter where the linear velocity in the throat reaches the sonic velocity of the gas.

Critical Point That state at which the densities of the gas and liquid phases and all other properties become identical. This is an important correlating parameter for predicting fluid behavior.

Critical Pressure The pressure at which the critical point occurs.

Critical Temperature The temperature above which the fluid cannot exist as a liquid

Density The density of a quantity of homogeneous fluid is the ratio of its mass to its volume. The density varies with temperature and pressure, and is therefore generally expressed as mass per unit volume at a specified temperature and pressure.

Density, Base The mass per unit volume of the fluid being measured at base conditions (Tb, Pb).

Density, Relative (Gas) The ratio of the specific weight of gas to the specific weight of air at the same conditions of pressure and temperature. (This term replaces the term “specific gravity” for a gas.)

Density, Relative (Liquid) The ratio of a liquid’s density at a given temperature to the density of pure water at a specific base temperature. (This term replaces the term “specific gravity” for a liquid.)

Diameter Ratio (Beta) The calculated orifice plate bore diameter (d) divided by the calculated meter tube internal diameter (D).

Differential Pressure The drop in pressure across a head device at specified pressure tap locations. It is normally measured in inches or millimeters of water.

Discharge Coefficients The ratio of the true flow to the theoretical flow. It corrects the theoretical equation for the influence of velocity profile, tap location, and the assumption of no energy loss with a flow area between 0.023 to 0.56 percent of the geometric area of the inlet pipe.

Empirical Tests Tests based on data observed in experiments.

Manometer A device that measures the height (head) of liquid in a tube at the point of measurement

Multiphase Flow Two or more phases (solid, liquid, gas, vapor) in the stream.

Newtonian Liquids Liquids that follow Newton's second law, which relates force, mass, length, and time. The flow meters covered in this book measure Newtonian fluids.

Nozzle A flow device with an inlet profile that is elliptical along its centerline and made to a specified standard; they are usually used for high-velocity flows. They are resistant to erosion because of their shape.

Pressure The following terms pertain to different categories of pressure.

Pressure, Ambient The pressure of the surrounding atmosphere.

Pressure, Atmospheric The atmospheric pressure or pressure of one atmosphere. The normal atmosphere (atm) is 101.325 kPa (14.696 psia); the technical atmosphere (at) is 98,066.5 Pa (14.222 psia).

Pressure, Absolute The static pressure plus atmospheric pressure. (Note: calculations use absolute pressure values to determine flow.)

Pressure, Back, Turbine Meter The pressure measured at specified pipe diameters downstream from the turbine flow meter under operating conditions.

Pressure, Differential (dP) The static pressure difference measured between the upstream and the downstream flange taps.

1.4 Steady versus unsteady measurements

Nearly all observed fluid flows exhibit inherent unsteadiness due to factors such as turbulence, wave motion, and instabilities. When assessing fluid flow characteristics, the measurements may display slight unsteadiness, even when the system boundaries are in a steady state. Nevertheless, for numerous applications, our primary interest lies in determining the mean or average flow properties at a specific location or across a surface. In most of the discussions within this lesson, we will concentrate on measurements designed for steady-state analysis, which consequently reflect a mean value (Figure 1.1). Additionally, we will explore a few techniques that involve measuring flow unsteadiness, necessitating a system capable of recording and logging the temporal history of the flow variable.

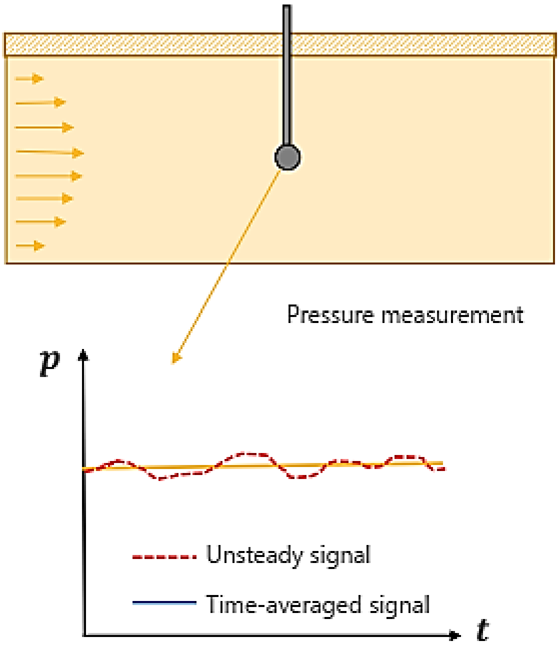


Figure 1.1: Difference between steady &unsteady measurements

Chapter 2:
Pressure measurements

2.1 Introduction

Pressure serves as a crucial parameter across a wide range of fields, including thermodynamics, aerodynamics, acoustics, fluid mechanics, soil mechanics, and biophysics. A pertinent example of the significance of pressure measurement can be found in power engineering. Various plants, such as hydroelectric, thermal, nuclear, and wind facilities that produce mechanical, thermal, or electrical energy, necessitate continuous monitoring and regulation of pressure levels. Excessive pressure can lead to the degradation of enclosures or drainage systems, potentially resulting in substantial damage.

As a vital factor, pressure plays a key role in the management and functioning of both automated manufacturing units and those operated by human personnel. In the realm of robotics, pressure measurement is utilized not only in control systems but also as an alternative to tactile feedback, such as in artificial skin applications, for pattern recognition, or for assessing grip strength. All these processes depend on a series of instruments, beginning with the pressure sensor, which provides data regarding the pressure of compressed air, gases, vapors, oils, or other fluids, thereby ensuring the proper functioning of machines or systems .

2.2. The pressure

In the subsequent sections, we will examine the various physical attributes essential for comprehending pressure sensors. This includes an exploration of pressure as a physical quantity, along with an overview of different sensor models, such as absolute, relative, and differential pressure sensors. Additionally, we will provide a concise review of the physical properties of fluids.

2.2.1. Pressure as a physical quantity

2.2.1.1. Static pressure

From a phenomenological perspective, pressure, denoted as p, is characterized as a macroscopic parameter that originates from the differential force dF applied perpendicularly to a differential surface area dA of the wall, as exerted by the fluid within the container:

$$p = dF / dA$$

The element of force dF caused by pressure p is perpendicular to the element of surface dA For pressure p inside the fluid with free surface we may write:

$$p = p_0 + \rho g h$$

p_0: atmospheric pressure

ρgh: hydrostatic pressure

ρ: density

g: acceleration of gravity at the place of measurement

h: distance from the free surface

Table 2.1: Units of pressure

	pascal (Pa)	**bar** (bar)	**atmosphere (Atm)**	**Comments**
1 pascal	1	10^{-5}	$9.869\ 10^{-6}$	Standard International Unit
1 bar	10^{5}	1	$9.869\ 10^{-1}$	1 Bar is standard atmospheric pressure
1 kg/cm^2	$9.8039\ 10^{4}$	$9.803\ 10^{-1}$	$9.86\ 10^{-1}$	Old Unit
1 atmosphere	$1.013\ 25\ 10^{5}$	1.0133	1	Normal Atmospheric Pressure
1 cm of water	98.04	$9.80\ 10^{-4}$	$9.68\ 10^{-4}$	
1 mm of Hg	$1.33\ 10^{2}$	$1.333\ 10^{-3}$	$1.316\ 10^{-3}$	For an Hg density of 13.59593 kg/ dm^3. 1 mmHg is also called Torr
1 inch Hg	$3{,}386\ 10^{3}$	$3{,}386\ 10^{-2}$	$3{,}342\ 10^{-2}$	
1 psi	$6.890\ 10^{3}$	$6.89\ 10^{-2}$	$6.89\ 10^{-2}$	Pound per Square Inch

2.2.2. Absolute, relative and differential sensors

An absolute pressure sensor measures static, dynamic or total pressure with reference to a vacuum (Figure 2.1).

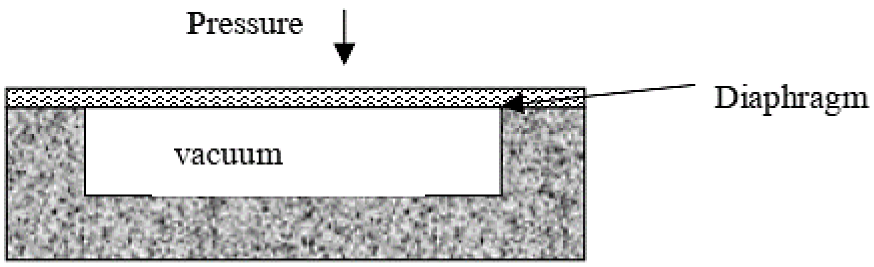


Figure 2.1: Absolute pressure sensor

A relative pressure sensor measures static, dynamic or total pressure with reference to ambient atmospheric pressure (Figure 2.2).

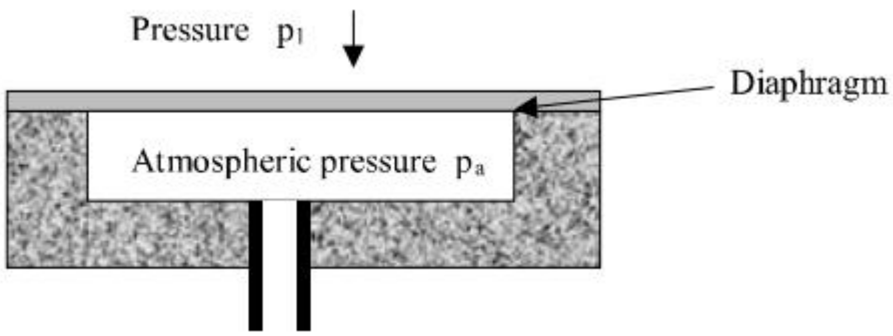


Figure 2.2: Relative pressure sensor

A sealed relative pressure sensor measures static, dynamic or total pressure with reference to ambient atmospheric pressure, sealed at the time of manufacture of the sensor (Figure 2.3).

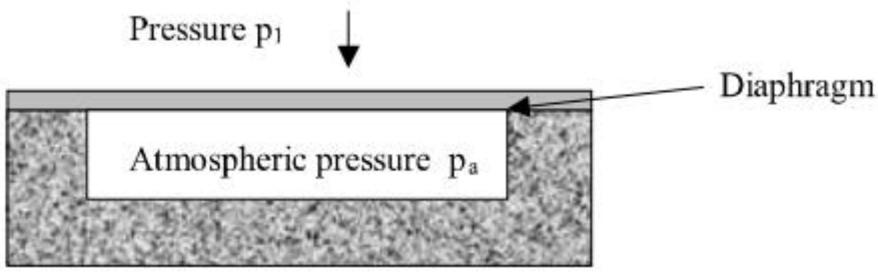


Figure 2.3: Sealed Relative pressure sensor

A differential pressure sensor measures a static, dynamic or total pressure with reference to an unspecified variable pressure p_2 (Figure 2.4).

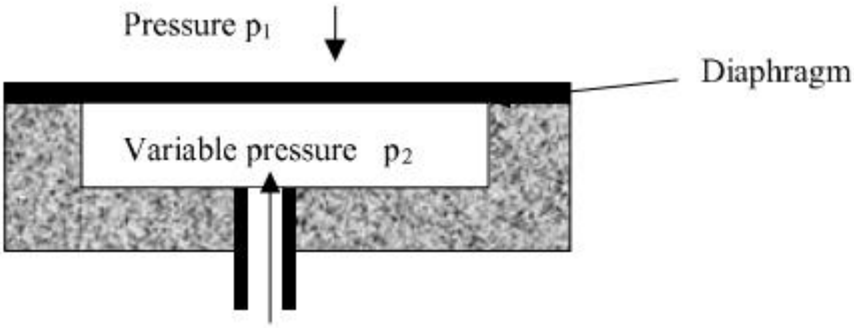


Figure 2.4: Differential pressure sensor

2.2.3. Fluid physical properties

In static liquids, the pressure force F exerted on the surface is solely a result of the random kinetic energy of the molecules. Conversely, in dynamic fluids, the force F is derived from the random yet directed kinetic energy of the particles. Overall, there are two primary categories of fluids: gases and liquids.

Liquids

The total pressure is comprised of the static pressure, the pressure resulting from external forces, and the dynamic pressure. For a fluid that is moving horizontally—characterized as incompressible and having negligible viscosity, such as liquids—this total pressure remains constant at all points, in accordance with Bernoulli's theorem:

$$p_t = p_s + p_d = p_s + \frac{1}{2}\rho v^2$$

with:

pt: total pressure

ps: static pressure

pd: dynamic pressure

v: local velocity

ρ: density

Gases

The pressure of a gas within a tank refers to the force applied by the gas against the tank's walls per unit area. In instances where a tank holds a mixture of gases, it is possible to establish a partial pressure for each individual gas. The total pressure is the cumulative sum of these partial pressures. The relationship governing an ideal gas is expressed by the following equation:

$$pV = nk_BT$$

p: pressure

n: number of molecules

T: temperature

V: volume

k_B: Boltzmann constant

2.3 Pressure sensors

A manometer, also known as a pressure sensor, is a device designed to measure the pressure of fluids, whether in liquid or gaseous form. The measurement of pressure can be conducted through various principles, including:

- The application of a known weight to assess the impact of pressure on a specified area (manometric balances).

- The alteration in the height of a liquid as a result of pressure (liquid pressure gauge).

- The observation of the deformation of a sensitive component in response to pressure:

- ✓ Bourdon tube.
- ✓ Pressure sensors with metal gauges,
- ✓ Pressure sensors with piezoresistive gauges,
- ✓ Pressure sensors by variation of inductances,
- ✓ Piezoelectric pressure sensors.

2.3.1 Hydrostatic sensors (manometers)

The manometer, recognized as one of the earliest devices for measuring pressure, demonstrates high accuracy when utilized correctly. The National Institute of Standards and Technology (NIST) acknowledges the U tube manometer (Figure 2.5) as a primary standard, attributing this status to its intrinsic accuracy and ease of use. Notably, manometers are devoid of moving components that could be affected by wear, aging, or fatigue. These instruments function based on the Hydrostatic Balance Principle, whereby a liquid column of a specified height generates a corresponding pressure determined by the liquid's weight per unit volume. The essential relationship governing pressure as indicated by a liquid column is as follows.

$$P = P_1 - P_2 = \rho g h$$

p = differential pressure

P 1 = pressure at the low pressure connection

P2 = pressure at the high pressure connection

ρ: density of the liquid

g: acceleration of gravity

h: height of the liquid column

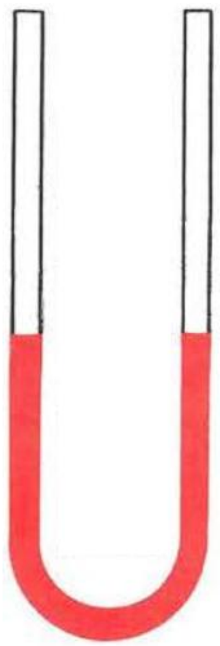


Figure 2.5: U Tube

2.3.1.1 U Tube manometer

The concepts of manometry are most effectively illustrated using the U-tube manometer. This device consists of a glass tube shaped into a U and partially filled with a liquid. When both ends of the tube are exposed to atmospheric pressure or are subjected to identical pressures, the liquid remains at the same level, establishing a zero reference point. When pressure is exerted on the left side of the manometer, the liquid level in the left leg decreases while it rises in the right leg. The fluid continues to move until the unit weight of the liquid, represented by H, precisely counterbalances the applied pressure. This phenomenon is referred to as hydrostatic balance (Figure 2.6). The difference in height of the liquid between the two surfaces represents the actual height of the liquid opposing the pressure.

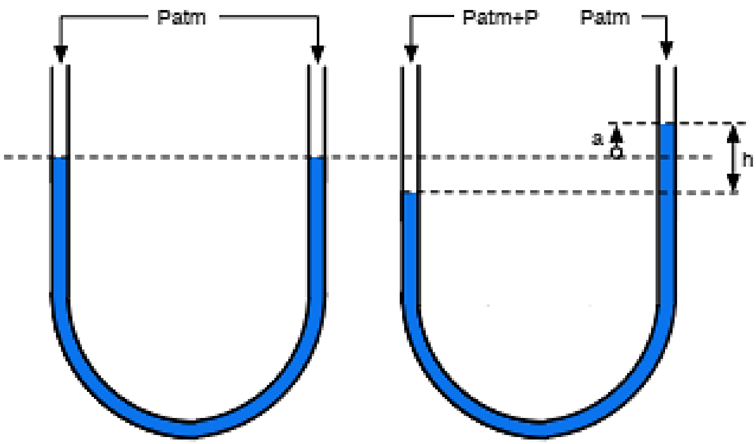


Figure 2.6: U tube manometer, Hydrostatic Balance Principle

2.3.1.2 Single-liquid manometers

They are essentially made up of a U-shaped tube containing a liquid of which one branch is connected to the pressure P_A to be measured and the other in communication with the pressure P_B (figure 2.7).

The most used liquids are:

- Mercury for high pressures:
- Water for low pressures.

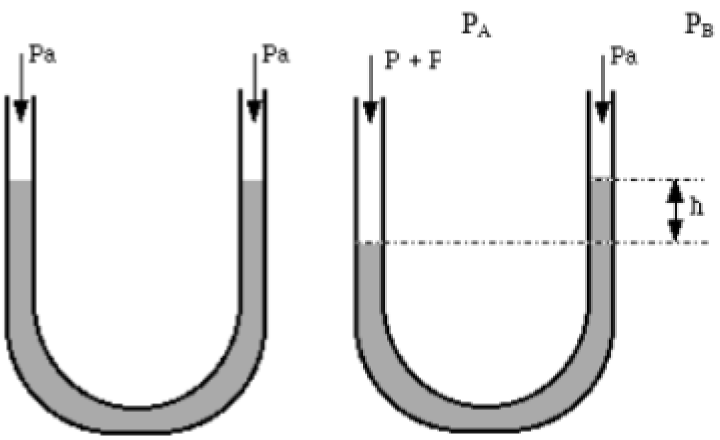


Figure 2.7: Single-liquid U-Manometer

PA - PB = ρgh

With **PB = Patm**

Single liquid manometer with reservoir

To increase the accuracy of measurements, a variation of the reservoir manometer is used, which involves tilting the tube. Then we measure the length (L).

$$L = \frac{h}{\cos\alpha} \qquad \text{Or} \quad \cos\alpha < 1 \quad \text{donc} \quad L > h$$

So instead of observing a fairly small difference in level h, we will observe a larger difference in level of L

$$L = \frac{h}{\cos\alpha}$$

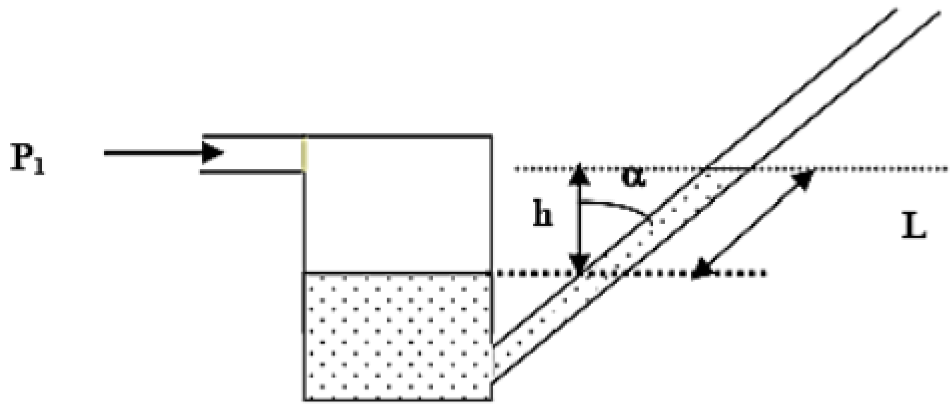


Figure 2.8: single liquid manometer with reservoir

2.3.1.3 Mercury Barometer

This device is used to measure the local atmospheric pressure, p_a. It is formed by inverting a glass tube filled with mercury into a mercury bath (Figure 2.9). At the top of the mercury column in the tube (point 3 in the sketch), the pressure is nearly a total vacuum. The pressure at point 1 is atmospheric, and this pressure holds the mercury column at some height h, as measured by a ruler. The hydrostatics equation can be used to solve for atmospheric pressure in terms of the known values of h, g, and the density of mercury:

$$p_{below} = p_{above} + \rho g|\Delta z|$$
$$p_2 = p_3 + \rho_{mercury} g h$$
$$p_a = 0 + \rho_{mercury} g h = \rho_{mercury} g h$$

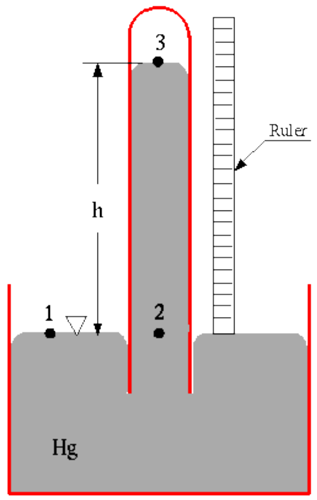


Figure 2.9: Mercury Barometer

Some typical numbers can be heard in weather reports. For example, the weatherman may say "…the barometer reads 29 inches of mercury." This means that h = 29. inches of mercury column in the barometer. By the way, h is called the "head," which is simply pressure expressed as an equivalent column height of fluid. Using the above equation, one can calculate atmospheric pressure in more standard pressure units, such as kPa:

2.3.1.4 Two-liquid manometer

In each branch of the tube, the liquid of density ρ is surmounted by another liquid of density ρ' (Figure 2.10).

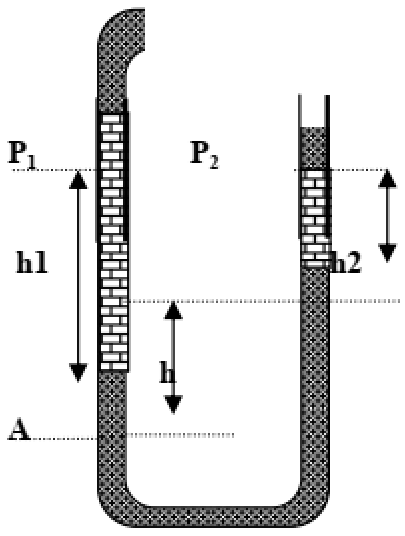


Figure 2.10: Two-liquid manometer

PA - PB = ρgh

Or $PA = P1 + \rho' gh1$

$PB = P2 + \rho' gh2$

$P1 - P2 = PA - PB + \rho' gh2 - \rho' gh1$

$P1 - P2 = \rho gh + \rho' gh2 - \rho' gh1 = \rho gh - \rho' g(h1-h2)$

$P1 - P2 = \rho gh - \rho' gh = (\rho - \rho')gh$

$P2 = Patm$

So, $P1 - Patm = (\rho - \rho')gh$, which is the relative pressure at point 1

1.3.1.5 Advantages and disadvantages of U Tube manometers

Liquid column manometers cover a range from 0 to 5×10^5 Pa for gas pressure measurement only.

Table 2.2: Advantages and disadvantages of U Tube manometers

Advantage	***Disadvantages***
- Good precision, they can exceed 0.1%; - Good stability; - Simple and inexpensive construction.	- Bulky and fragile; - They are sensitive to temperature and vibrations; - The tubes must be perfectly calibrated; - Viscous, dirty liquids and greasy tubes are causes of errors; - These devices do not translate the measured pressure into an analog signal usable in industrial regulation

Working field

- Measurement of absolute, relative or differential pressures up to two (2) bars;
- The column of liquid cannot exceed two meters;
- Reserved for laboratory use or as standard devices.

2.3.2 Manometer with elastic element

Pressure gauges, commonly referred to as manometers, are widely utilized in various technical applications for pressure measurement, owing to their durability and user-friendly design. These devices feature measuring elements that undergo elastic deformation when subjected to pressure. Mechanical pressure gauges are constructed using bourdon tubes, diaphragms, capsules, and spring elements, which serve to categorize them based on their design.

The measuring components are typically fabricated from copper alloys, alloyed steels, or specialized materials tailored for specific measurement needs. Pressure readings are only meaningful when compared to a reference pressure, with atmospheric pressure often serving this role. Consequently, the pressure gauge indicates the extent to which the measured pressure deviates from the atmospheric pressure, functioning as an overpressure measuring instrument.

Pressure is displayed within standard measuring ranges across a 270-degree arc on the dial. Liquid-filled pressure gauges provide enhanced protection against damage caused by high dynamic pressure fluctuations or vibrations, thanks to their damping properties. When paired with limit signal indicators, these gauges can facilitate switching operations, and when combined with transmitters, they can generate electrical output signals (e.g., 4 ... 20 mA) for use in industrial process automation.

2.3.2.1 Manometer with bourdon tube

Bourdon tubes are cylindrical devices characterized by an oval cross-section (Figure 2.11). When pressure is applied to the interior of the tube, the oval shape transforms towards a nearly circular form. This curvature induces hoop stresses that cause the tube to bend. The free end of the tube moves in response to this bending, providing a measurement of the pressure. The movement of the pointer reflects this change on the display. These circular tubes, typically bent at an angle of approximately 250°, are designed to handle pressures up to around 60 bar. For applications involving higher pressures, bourdon tubes may feature multiple superimposed coils of the same diameter (helical coils) or a single spiral-shaped coil (spiral springs) arranged in a single plane. It is important to note that bourdon tubes have limited capacity for overload protection. To address particularly demanding measurement requirements, a chemical seal can be installed upstream as a protective or separating mechanism. The pressure measurement ranges can vary from 0 to 0.6 bar up to 0 to 7000 bar, with reading accuracies (or classes) ranging from 0.1% to 4.0%.

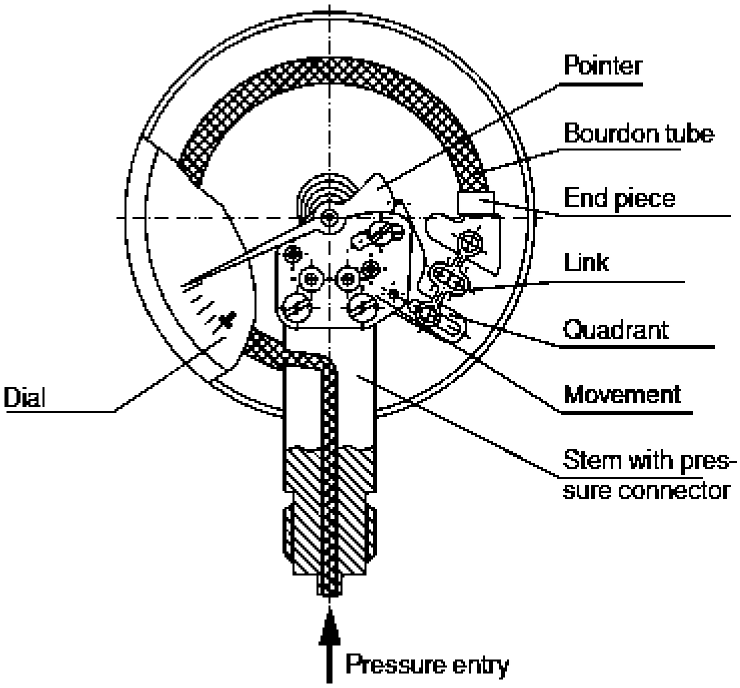


Figure 2.11: Manometer with bourdon tube

2.3.2.2 Manometers with diaphragm elements

Diaphragm elements consist of circular, corrugated membranes. They are typically secured around their edges between two flanges or welded in place, and they experience pressure from the media acting on one side. The resulting deflection serves as a measurement of the pressure, which is indicated by a pointer (Figure 2.12).

When compared to bourdon tubes, diaphragm elements exhibit a relatively high actuating force and are less sensitive to vibrations due to their annular clamping design.

These diaphragm elements can endure greater overloads when the diaphragm rests against the upper flange. Additionally, by applying a special coating or covering with a foil, the gauge can be safeguarded against highly corrosive substances.

For applications involving highly viscous, impure, or crystallizing media, it is possible to incorporate wide connection ports, open connection flanges, and purging capabilities. The pressure measurement ranges can vary from 0 to 16 mbar and from 0 to 40 bar, with accuracy classes ranging from 0.6 to 2.5.

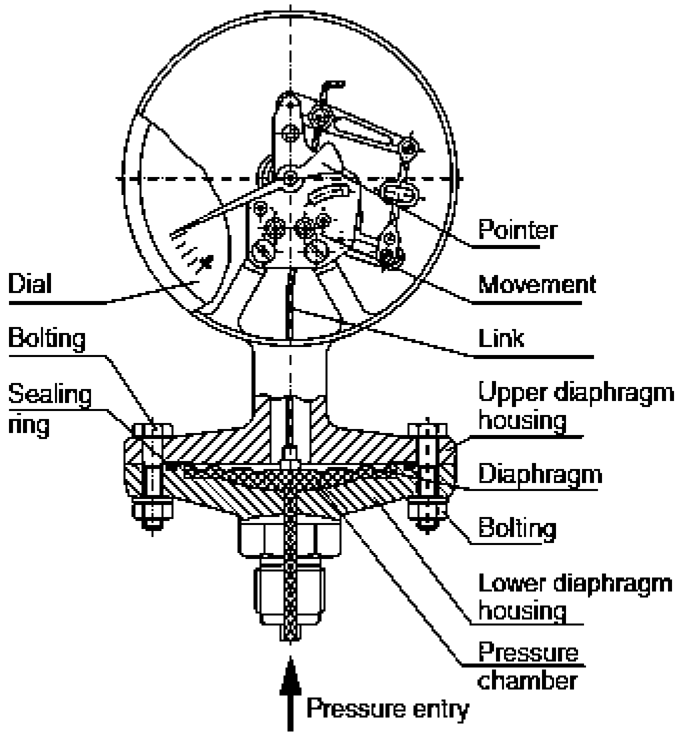


Figure 2.12: manometers with diaphragm elements

2.3.2.3 Manometers with capsule elements

The capsule component consists of two circular, corrugated membranes that are completely sealed along their edges. Internal pressure is applied to this capsule, and a pointer, serving as a pressure measurement (Figure 2.13), displays the resulting stroke movement. Pressure gauges utilizing capsule components are especially effective for gaseous substances and relatively low pressure levels. Overload protection can be implemented within specified limits. The actuating force is enhanced when multiple capsule components are mechanically linked in series, forming a "package" of capsule elements. The pressure measurement ranges from 0 to 2.5 mbar and from 0 to 0.6 bar, with accuracy classifications ranging from 0.1 to 2.5.

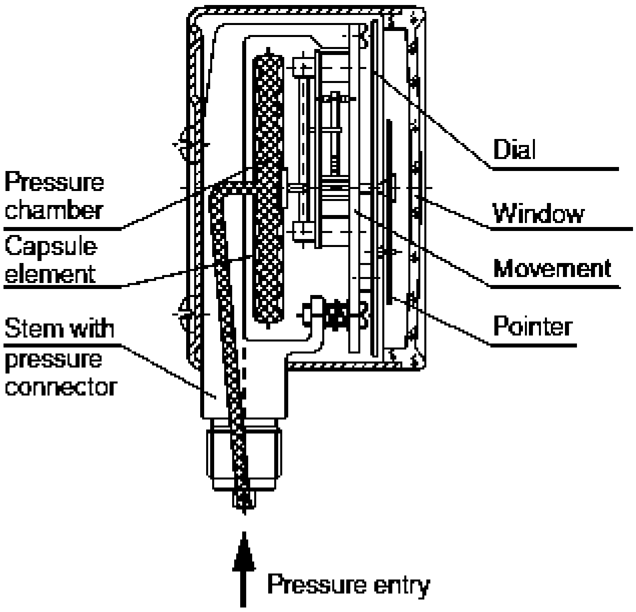


Figure 2.13: Manometer with capsule elements

2.3.2.4 Differential manometers

Differential pressure gauges directly measure the difference between two pressures and display this value. The measuring elements and principles previously discussed for overpressure gauges are applicable here as well.

The measuring element is positioned between two sealed pressure media chambers. When both operating pressures are equal, the measuring element remains stationary, resulting in no pressure indication. A differential pressure reading is only produced when there is a disparity between the two pressures (Figure 2.14).

Even in the presence of high static pressures, it is possible to measure low differential pressures directly. Diaphragm elements provide a significant overload capability.

It is essential to adhere to the permissible static pressure and overload capacity on both the positive and negative sides. In most instances, the transmission of movement from the measuring element and the pressure indication occurs similarly to that of the previously mentioned overpressure gauges. The pressure ranges can vary from 0 to 16 mbar and from 0 to 40 bar, with accuracy classes ranging from 0.6 to 2.5.

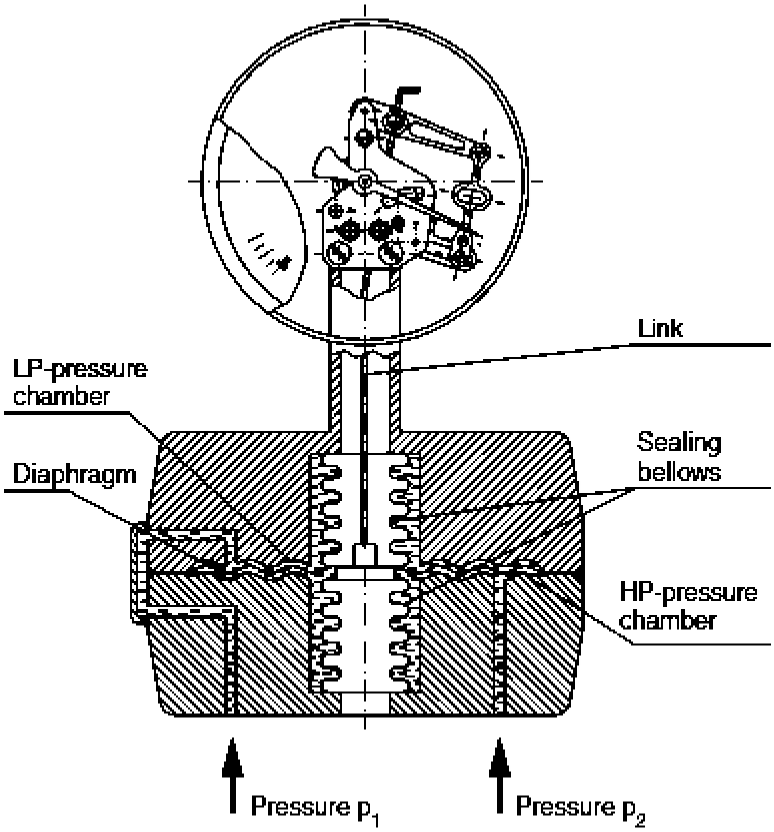


Figure 2.14: Differential Manometer

2.3.2.5 Sensing devices

In the context of pressure p, the sensing element is typically engineered to deliver the following outputs:

– a deformation followed by a displacement;

– a force;

– a strain.

The most commonly utilized sensing element is the welded diaphragm, characterized by an effective section S, which may be planar, corrugated, cylindrical, or take on a more intricate geometric shape, depending on the pressure range or the specific fluid being analyzed.

Examples of sensitive elements

- ✓ Embedded diaphragm
- ✓ Piston with spring

- ✓ Corrugated diaphragm
- ✓ Open manometric cell
- ✓ Closed manometric cell
- ✓ Biconical cell
- ✓ Bellows
- ✓ Bourdon tube
- ✓ Helical twisted tube
- ✓ One-eyed tube

The challenge associated with pressure sensors primarily revolves around finding the optimal balance among the following factors:

– Cost.

– Efficiency.

– Manufacturing techniques.

– Material selection.

Advancements in microelectronic technology tailored for micro systems facilitate innovative, highly integrated, and cost-effective designs. Furthermore, improvements in material quality and enhanced data processing capabilities enable a simplification of the sensing element's geometry. Consequently, the majority of contemporary pressure sensors employ cylindrical or planar sensing elements, such as diaphragms. The materials commonly utilized in the fabrication of these sensing elements include the following:

Examples of constructional materials for sensing elements

- ✓ Stainless steel 17-4 pH
- ✓ Stainless steel 316
- ✓ Hastelloy
- ✓ Monel
- ✓ Inconel
- ✓ Titanium
- ✓ Ni Span C
- ✓ Quartz
- ✓ Silicon
- ✓ Sapphire

The different geometries of sensing elements are summarized in figure 2.15

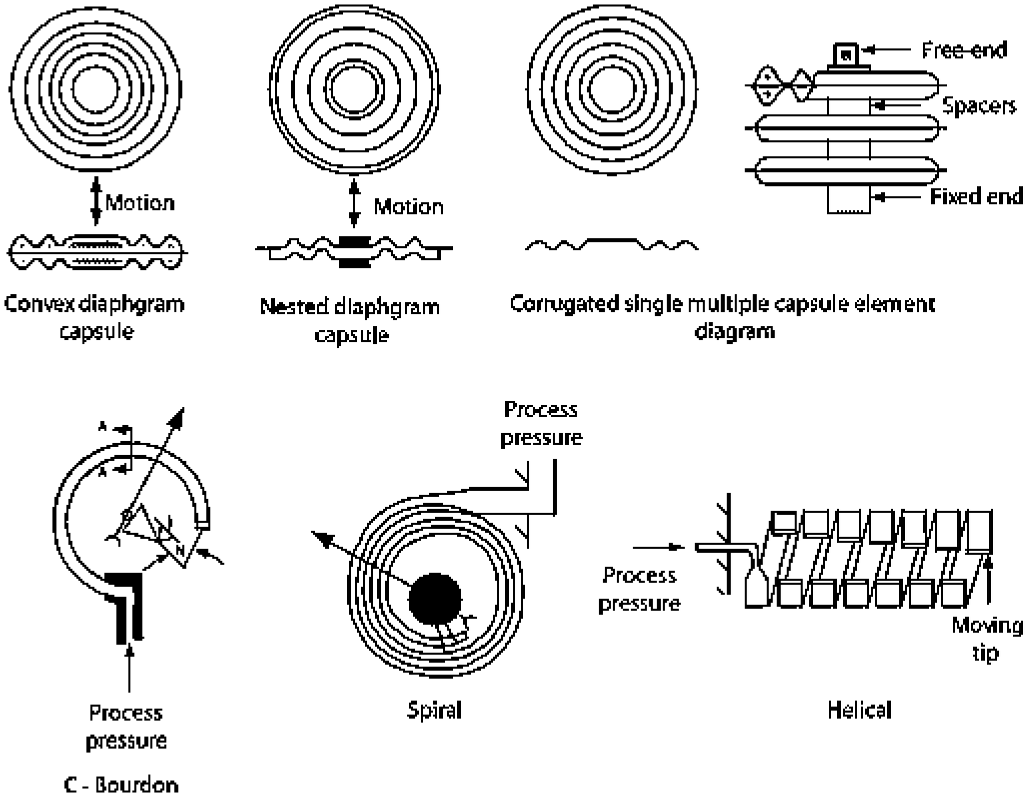


Figure 2.15: Different sensing element geometry

2.3.3 Conversion by resistance variation

2.3.3.1 Metal strain gauges

Foil-type (piezoresistive) strain gauges continue to be extensively utilized. A resistive grid is formed on a foil that is adhered to the sensing element. The pressure applied results in deformation, leading to a variation in resistance. When four of these sensors are appropriately arranged in a Wheatstone Bridge configuration, it allows for temperature compensation and enhanced sensitivity (see Figure 2.16). The inner gauges are responsible for measuring tangential strain, whereas the outer gauges assess radial stress, which exhibits an opposite polarity.

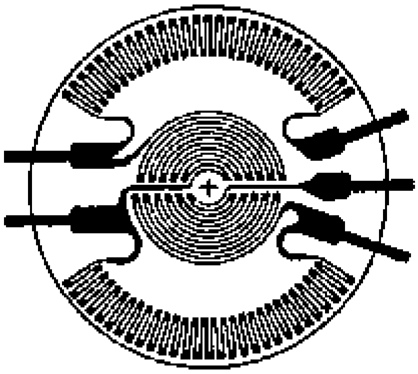


Figure 2.16: Metal strain gauge for pressure sensors

Table 2.3: Advantages and disadvantages of sensors with foil strain gauge

ADVANTAGES	DISADVANTAGES
– resistant to vibrations – low cost – great adaptability with various technology applications – simple to implement	– problems attaching the foil gauges to the sensing element – low gauge factor

2.3.3.2 Gauges with deposited film

In order to address the challenges associated with the support and attachment of the gauge, which contribute to instability, we apply a resistive layer directly onto the wall of the sensing element. This application is performed through sputtering techniques to create "thin layer" gauges or via screen-printing methods to produce "thick layer" gauges, as detailed in Table 2.4

Table 2.4: Characteristics of gauge and stability of various technologies

Technology	Gauge K factor	Long-term stability
Metallic thin layers	2 to 4	excellent
Resistive thick layers	10 to 20	very good
Semiconductor	100	poor

Table 2.5: Advantages and disadvantages of sensors with deposited screen

ADVANTAGES	DISADVANTAGES
– resistant to vibrations – good stability – low cost – relatively simple technology	– sensitive to electric overloads – average integration potential, especially for thick layer gauges

2.3.4 Conversion by capacitance variation

2.3.4.1 Pressure sensor with variable effective area

Typically, pressure sensors that operate on the principle of capacitance variation are characterized by their simplicity and robustness. In these sensors, one electrode of the capacitor is linked to a sensing element, such as a diaphragm. The effective area A of the capacitor plates can vary linearly with the displacement 'X. More commonly, the variable parameter is the distance d. Numerous production geometries are derived from this principle, with Figures 2.17 and 2.18 illustrating one such example.

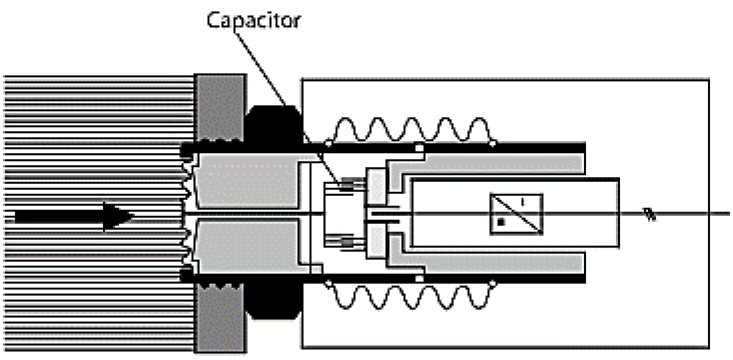


Figure 2.17: Pressure sensor with variable effective area

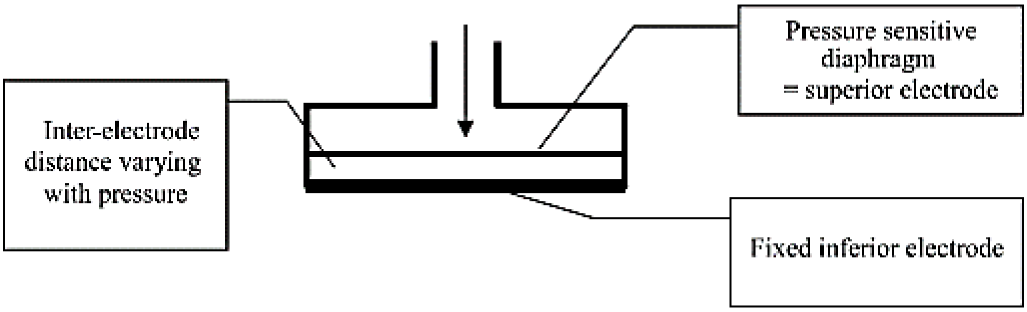


Figure 2.18: Diagram of a pressure sensor with capacitance conversion

2.3.4.2 Standard capacitive pressure sensors

Capacitance pressure transducers were initially designed for measuring vacuum levels. Illustrated in Figure 2.19, it is a conventional bridge circuit utilized for capacitance pressure sensors.

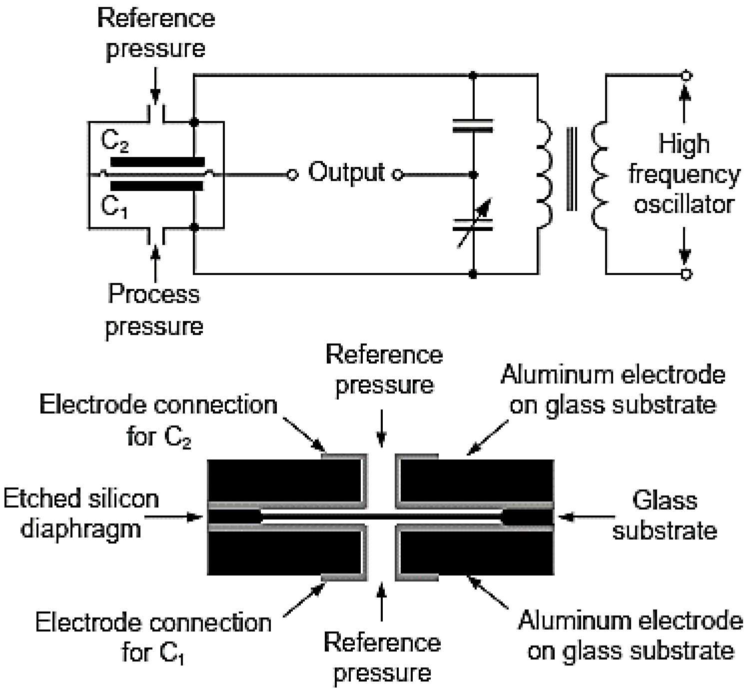


Figure 2.19: Capacitance-based pressure cell

In microsensors, the diaphragm is typically fabricated from micro-machined monocrystalline silicon. The capacitive transducer can function as either an absolute gauge or a differential pressure transducer.

Capacitance pressure transducers are capable of measuring pressure ranges from high vacuum up to 70 MPa. They exhibit lower drift characteristics in comparison to strain-gauge transducers.

Table 2.6: Advantages and disadvantages of standard capacitive pressure sensors

ADVANTAGES	DISADVANTAGES
– compactness – low drift – high bandwidth	– sensitive to stray capacitance – sensitive to vibrations

2.3.4.3 Capacitance thin – film sensors

These sensors operate by detecting variations in the relative permittivity of the dielectric material situated between the two electrodes. ONERA (France) has developed ultra-thin capacitance pressure microsensors, utilizing either solid or gas dielectrics, with a thickness of approximately 80 µm. These sensors are designed for the measurement of dynamic pressure, specifically to capture rapid fluctuations in pressure (see Figure 2.20).

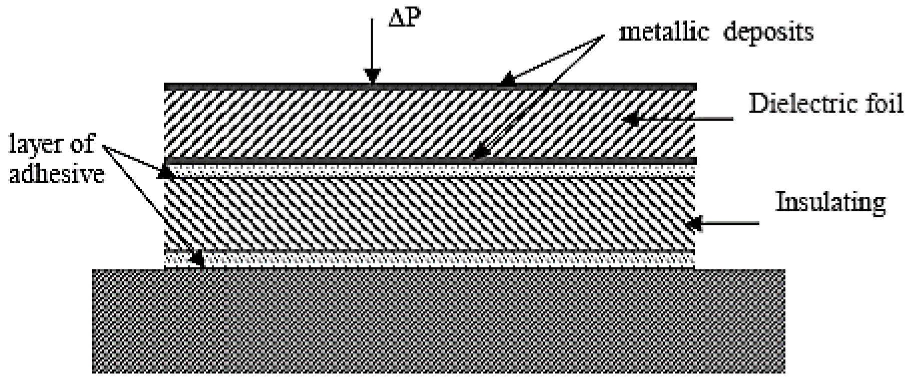


Figure 2.20: Principle of a capacitance thin – film (pellicular) sensor

Table 2.7: Advantages and disadvantages of pellicular sensors

ADVANTAGES	DISADVANTAGES
– compactness – resistant to vibrations – high bandwidth: 50 to 200 kHz	– sensitive to temperature

To eliminate the need for an external power source, a diaphragm can be employed that maintains a stable electric polarization, known as the electret effect. This phenomenon is similarly utilized in microphones, which function as sensitive pressure sensors.

2.3.5 Conversion by inductance variation

These pressure sensors operate by altering the reluctance within a magnetic circuit through modifications to one or more of its air gaps. Additionally, variations in the reluctance can be achieved by leveraging the magnetic characteristics of the material used for the sensing element.

The linearity of these sensors can be enhanced through the application of differential transformers.
The output signal reflects both the amplitude and direction of the core's displacement. This core is connected to a diaphragm, capsule, or bellows that is subjected to pressure or a pressure differential.
The most common configuration, illustrated in Figure Figure 2.21, employs an LVDT position sensor. In this setup, the capsule, upon which pressure is applied, moves a core that alters the inductive coupling between the primary and secondary windings of the LVDT transformer. The advantages and disadvantages of these sensors are summarized in Table 2.8.

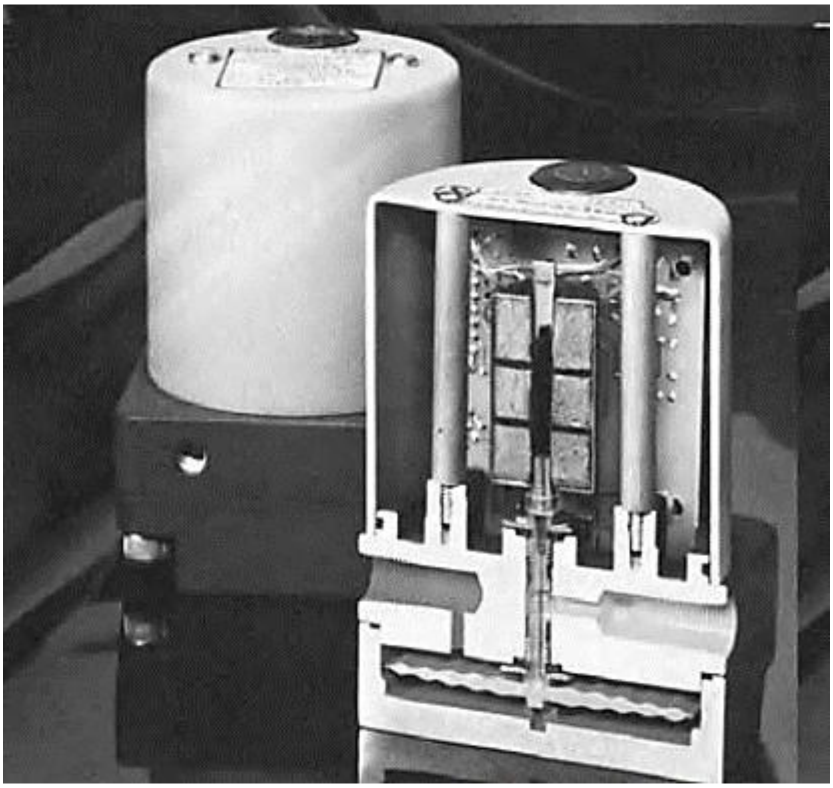


Figure 2.21: Photograph: Inside of the model P3000 series from Schaevitz

Table 2.8: Advantages and disadvantages of sensors with inductance variation

ADVANTAGES	DISADVANTAGES
– very good resolution – good stability – economic – large output signal	– sensitive to vibrations and shocks – sensitive to large magnetic field

2.3.6 Conversion by piezoelectric effect

The piezoelectric structures employed as sensing elements convert the strain induced by the applied force F into an electric charge q. These sensors are designed to measure temporal variations in pressure rather than static pressure, as the electric signal is generated solely during changes in stress.

A small plate, cut from a quartz crystal and oriented perpendicular to one of its three electrical axes, is equipped with metal electrodes (Figure 2.22). When subjected to compression or extension, this configuration generates dielectric polarization, resulting in the development of a charge q on the electrodes.

The dimensions of the disks or plates are determined based on the permissible maximum strain, which varies according to the characteristics of the sensor material, such as quartz, PVDF, barium titanate, or seignette salt.

The maximum applicable strain is largely influenced by the quality of the contact between the crystal and the electrodes. To achieve this, the parallelism of the faces must be maintained within 10 µm, and the flatness must be within 1 µm. Optical polishing and precise grinding of the surfaces are essential to eliminate irregularities that could lead to strain concentration, potentially surpassing the material's breaking load.

The tubular design facilitates an increase in load while simplifying the assembly of the elements. This tube, resembling a bi-strip, is created by joining two components of opposite polarity relative to its symmetry plane. Tubular structures are particularly suitable for manufacturing pressure sensors that are cooled through water circulation, which comes into contact with the metallization of the crystal and the diaphragm.

Pressure transmission is accomplished through a rigid metallic component that also serves to secure the diaphragm. This component is extended by a stem, which, in conjunction with a robust return spring, applies an initial tension or pre-strain that enhances linearity. This initial tension allows for the measurement of pressures below atmospheric levels.

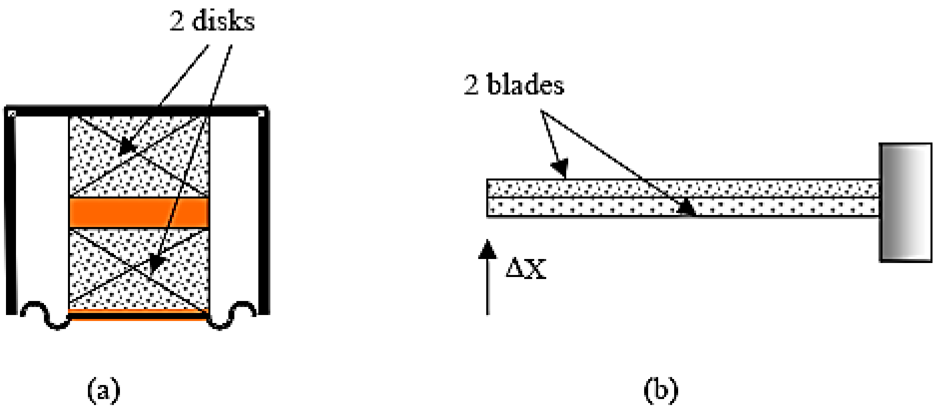


Figure 2.22: Piezoelectric principle a) disks b) bi-strip

Piezoelectric sensors can be quite easily miniaturized to a few millimeters.

Table 2.9: Advantages and disadvantages of piezoelectric sensors

ADVANTAGES	DISADVANTAGES
– large bandwidth – possible miniaturization – not very sensitive to accelerations	– high sensitivity to temperature – processing of low-level signals is necessary – need for special connecting cable for dynamic measurement – cannot measure static pressure

Chapter 3:
Flow measurements

3.1. Introduction

Accurate measurement of the flow of liquids, gases, steam, or solids is crucial for both the processing industry and for sporadic assessments. In certain processes, imprecise flow rate measurements can significantly impact profitability. Additionally, in other scenarios, incorrect or faulty flow measurements may lead to severe or potentially catastrophic outcomes.

3.2 Volume flow and mass flow

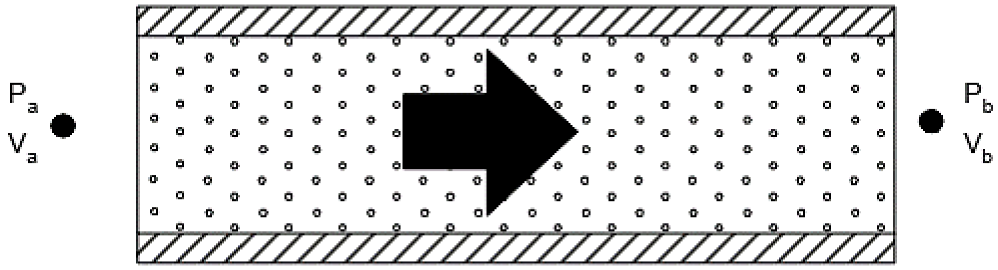


Figure 3.1: Flow in a pipe

The flow (Q) is characterized as the quantity of a substance that traverses a specific point or section within a defined time interval. It is important to differentiate between volume-flow measurements and mass-flow measurements (QV and Qm). Numerous principles governing volume-flow measurements are based on the following formula.

$$Q_V = v.A$$

Where

Q_V: volume flow [m^3/s]

v: mean velocity [m/s]

A: cross-sectional area [m^2]

The flow is ascertained by evaluating the velocity or the variation in kinetic energy of the medium. The velocity is influenced by the pressure differential across a pipe or covering (refer to Figure 3.1). This pressure differential propels the medium through the pipe or covering.

Given that the diameter of the pipe is known, the average velocity serves as an indicator of the flow rate.

In the International System of Units, the standard unit for volume flow is cubic meters per second (m^3/s), although cubic meters per hour (m^3/h) or liters per hour (l/h) are frequently utilized. It is important to note that, in practice, flow is typically represented as volume flow rather than mass flow. When considering incompressible materials such as liquids and solids, a straightforward relationship exists between volume flow and mass flow.

$$m = \rho.V$$

where

m: mass [kg]

ρ: density [kg/m^3]

V: volume [m^3]

For a specific quantity of a compressible substance, such as gas or steam, each combination of temperature and pressure is associated with a unique volume. Consequently, when discussing the volume flow of gas or steam, it is essential to specify the operating conditions (p, T), or alternatively, to standardize the flow to reference conditions. This standardization typically involves expressing the flow at a pressure of 1 bar and a temperature of 273 K, rather than at the actual operating conditions. The conversion to these standard conditions is achieved through the application of the general gas law.

$$\frac{p_0 \cdot V_0}{T_0} = \frac{p \cdot V}{T}$$

3.3 Factors affecting flow

Various elements influence the flow, including the viscosity and friction of the medium as it traverses the pipe. The performance of flow meters is significantly reliant on the dimensionless quantity known as the Reynolds number. This number is defined as the ratio of inertial forces to frictional forces and can be expressed mathematically as follows:

$$Re = v \cdot D \cdot \rho / \eta = v \cdot D / \nu$$

where

Re: Reynolds number [-]

v: velocity [m/s]

D: diameter of the pipe [m]

η: dynamic viscosity (friction coefficient) [Pa·s]

ν: kinematic viscosity [m^2/s]

The velocity, the density of the liquid, and the diameter of the pipe influences the force of inertia, with a frictional force occurring at the interface between the solid and the liquid. In most applications, the diameter of the pipe and the density are typically maintained at constant values.

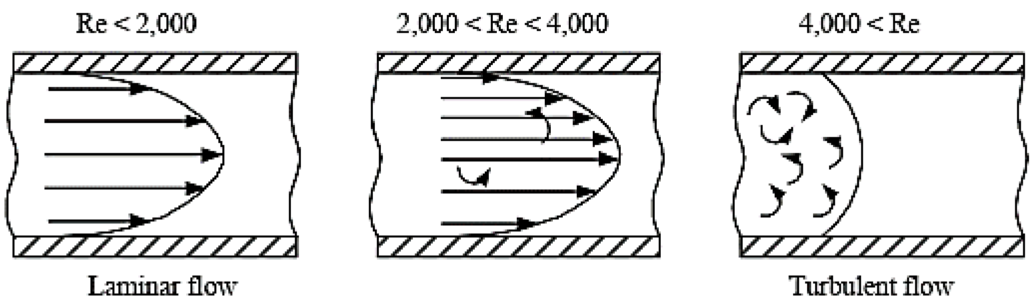


Figure 3.2: Laminar versus turbulent flow

At low velocities or in the presence of high viscosity, the Reynolds number is low, resulting in a smooth, layered flow of liquid. In this scenario, the highest velocity occurs at the center of the pipe, while lower velocities are observed at the edges due to frictional forces impeding the liquid's movement. This type of flow is referred to as laminar flow, characterized by a Reynolds number remaining below 2000. The velocity profile in laminar flow typically exhibits a parabolic shape (see Figure 3.2).

Conversely, most practical applications involve turbulent flow, where the Reynolds number exceeds 4000. Turbulent flow arises under conditions of high velocity and low viscosity, leading to a state of turbulence where the average velocity is uniform across the entire diameter of the pipe. As the Reynolds number increases, the velocity distribution becomes more consistent.

There exists a transitional region between laminar and turbulent flow, defined by the range of 2000 to 4000 for the Reynolds number. This transition is influenced by factors such as the pipe characteristics and flow velocity, allowing for the possibility of laminar, turbulent, or mixed laminar-turbulent flow. Understanding the flow type relevant to a specific application is essential for selecting the appropriate flow meter.

The wide range of media and varying measurement conditions, including pressure, temperature, and viscosity, have led to a diverse market for flow meters and the evolution of various flow measurement principles. Consequently, it is crucial to determine which type of flow meter is best suited for a given application.

Depending on the measured parameter and the medium, we can categorize flow measurements into the following types:

- ✓ velocity measurements for liquids, gases, and steam;
- ✓ volume-flow measurements for liquids, gases, and steam;
- ✓ mass-flow measurements for liquids, gases, and steam;
- ✓ flow measurements for solids;
- ✓ flow measurements for liquids in open channels;
- ✓ quantitative measurements.

3.4 Bernoulli equation

Numerous flow measurement techniques are founded on the principles of the Bernoulli equation. In Figure 3.3 a pipe is illustrated, through which an incompressible fluid is flowing. The velocity and diameter of the pipe indicate that the flow is turbulent (Re > 4000).

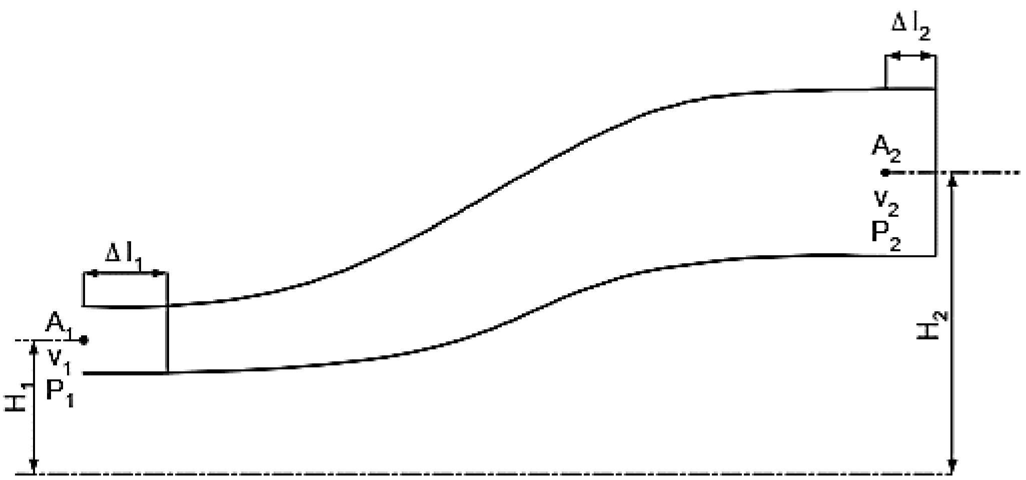


Figure 3.3: Bernoulli equation

Because the fluid is incompressible, the mass that enters the pipe through A_1 during one time unit must be the same as the mass that leaves the pipe through A_2 per time unit:

$$\rho \cdot A_1 \cdot v_1 = \rho \cdot A_2 \cdot v_2 \text{ or } A_1 \cdot v_1 = A_2 \cdot v_2 \quad \text{or} \quad A \cdot v = \text{constant}$$

Furthermore, the overall energy (both potential and kinetic) remains constant. These represent continuity equations, which hold true for an incompressible fluid; otherwise, the fluid would either accumulate or disperse within the pipe. These equations culminate in a more comprehensive formula:

$$p + \rho.g.H + \frac{1}{2}.\rho.v^2 = \text{const.}$$

This is called the Bernoulli equation.

The term $p + \rho.g.H$ represents static pressure, in which $\rho.g.H$ is the contribution of the hydrostatic pressure.

The term $½.\rho.v^2$ represents dynamic pressure.

From the continuity equation and the Bernoulli equation we can conclude the following: at the position where the velocity is highest, the static pressure must be at its smallest, and vice versa. The Bernoulli equation thus gives us the relation between the velocity of a fluid in a pipe and the corresponding static pressure.

When we are dealing with a laminar flow profile, the flow law of Poiseuille can be applied. For a cylindrical pipe with radius R, a difference in pressure p comes into existence over a length l:

$$Q_v = \pi.R^4.\Delta P/8.\eta.l$$

with

ρ: dynamic viscosity

It is essential to verify whether the flow profile is laminar or turbulent, particularly for flow measurements that rely on the principle of pressure differential.

3.5 Flow measurements based on the principle of difference in pressure

This principle is the most fundamental, grounded in the observation that matter flows in a specific direction only when there exists a moving force, or potential, that varies at each point along the flow. Often, this potential manifests as pressure, which decreases from a maximum to a minimum value, with the reduction in pressure uniformly distributed across the entire length of the flow.

Nevertheless, localized reductions in pressure can be introduced along the flow path through the use of constrictions, which arise from the pressure differential before and after the constriction. These localized pressure variations are referred to as primary elements. The most prevalent examples include:

- ✓ The Prandtl tube;
- ✓ The diaphragm or orifice plate;
- ✓ The Venturi tube;
- ✓ The Dall tube.

Flow measurement, using the principle of difference in pressure is standardized by ISO 5167 and DIN 1952. This contains geometry, configuration and calculating methods.

3.5.1 The Pitot and Prandtl tube

Principle

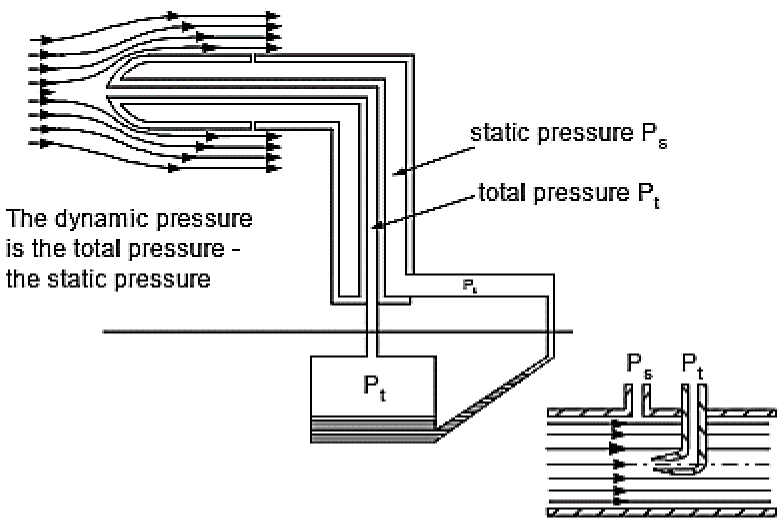


Figure 3.4: Pitot tube (double-walled construction as Prandtl tube on the left, construction with two separate tubes on the right)

The Pitot tube serves the purpose of measuring the flow rate of liquids, steam, or gas streams. Its operation is founded on the assessment of the pressure difference between two surfaces: one oriented perpendicular to the flow direction and the other aligned parallel to it. The parallel surface experiences minimal disturbance from the flow, allowing for the accurate measurement of the medium's actual pressure, referred to as static pressure (P_s).

When the surface is positioned perpendicular to the flow, the liquid impacting it is decelerated to a complete stop. At this point of stagnation, a higher pressure is recorded, known as total pressure (P_t). The variation in pressure, or dynamic pressure ($P_d = P_t - P_s$), arises from the kinetic energy of the liquid.

This relationship can be expressed through the Bernoulli equation.

$$P_d = \rho . \frac{v^2}{2}$$

Or, it can be converted to velocity and measured pressure:

$$v = \sqrt{\frac{2.(P_t - P_s)}{\rho}}$$

It is important to recognize that the velocity is influenced by the fluid's density, which in turn is affected by both pressure and temperature. Furthermore, it is observed that the velocity exhibits a quadratic relationship with the measured pressure differential. To achieve a linear output signal, an additional conversion process is required.

The flow rate can be calculated by multiplying this velocity by the cross-sectional area of the flow.

$$Q_v = v.A$$

This condition holds true only when the velocity is uniformly high across the entire flow surface or when the flow exhibits turbulence (with a sufficiently high Reynolds number). To mitigate the effects of the flow profile, a Pitot tube equipped with multiple measurement points can be employed. This approach allows for the measurement of an average pressure difference, which corresponds to the average velocity.

Characteristics

Advantages:

- ✓ minimal installation expenses, applicable even to pre-existing setups;
- ✓ exceptionally low pressure loss.

Uses:

- ✓ assessing air velocity in ducts lacking fixed measurement devices (utilizing a portable reading instrument);
- ✓ conducting on-site measurements to identify discrepancies;
- ✓ analyzing the velocity and flow profiles within a pipe;
- ✓ appropriate for larger pipe diameters: DN200 – DN12,000 (though it is also effective for smaller diameters).

3.5.2 The orifice plate

Principle

The orifice plate is undoubtedly the most commonly employed flow meter, primarily due to its straightforward design, affordability, and the extensive experience accumulated over many years of its application. Figure 3.5 illustrates a standard configuration of the orifice plate.

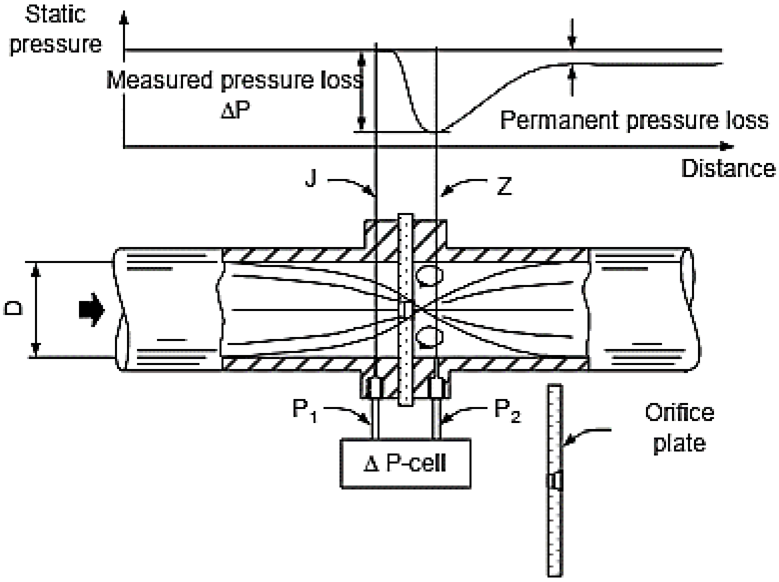


Figure 3.5: The orifice plate

Calculating the flow

In examining the turbulent flow of a one-dimensional, incompressible liquid, while disregarding any alterations due to heat or work, the flow rate Q_v can be characterized in the following manner:

$$Q = A_1 \cdot v_1 = A_2 \cdot v_2$$

$$A_1^2 \cdot v_1^2 = A_2^2 \cdot v_2^2$$

$$v_1^2 = \left(\frac{A_2}{A_1}\right)^2 \cdot v_2^2$$

For a horizontal pipe, the Bernoulli equation is reduced to:

$$Q = A_2 \cdot v_2 = \frac{A_2}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}} \cdot \sqrt{\frac{2\cdot(p_1 - p_2)}{\rho}}$$

with:

A_1, A_2: the cross-section of the “flow” where P_1 and P_2 are [m^2]

ρ : the density [kg/m^3]

P_1, P_2: the static pressure [Pa]

The equation indicates that in order to determine Qv, it is essential to have the values of A_1, A_2, and ɖ, while P_1 and P_2 must be accurately measured. Furthermore, it is evident that, akin to the Pitot tube, the measurement is influenced by the fluid's density.

3.5.4 The Venturi tube

The Venturi tube, as illustrated in Figure 3.19, represents a variation of the orifice plate and is utilized primarily when minimizing permanent pressure loss is essential. It is particularly advantageous for applications involving fluids that contain a significant amount of solid particles or for highly viscous liquids. Measurements taken with a Venturi tube are less susceptible to variations in viscosity. However, it is important to note that the Venturi tube is a relatively costly device. The design of the Venturi tube is optimized for the flow characteristics of the fluid, resulting in minimal turbulence, which is advantageous for maintaining consistent pressure loss. The structure of the Venturi tube includes a gradually converging section, AB, a cylindrical constriction, BC, and a diffuser, CE. The length of section BC is equal to the diameter of the pressure connection, extended by a length ranging from 0.2 to 0.4 times the diameter of the pipe. Additionally, the half-angle of the diffuser, CE, must be less than 150° (Figure 3.6).

As the angles of sections AB and CE decrease, the permanent pressure loss is further reduced.

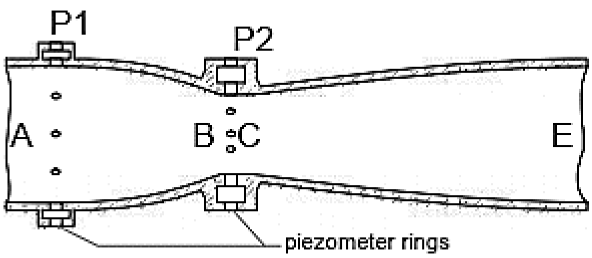


Figure 3.6: Venturi tube

3.6 Flow measurements based on variable passage

3.6.1 The float flow meter (rotameter)

Principle

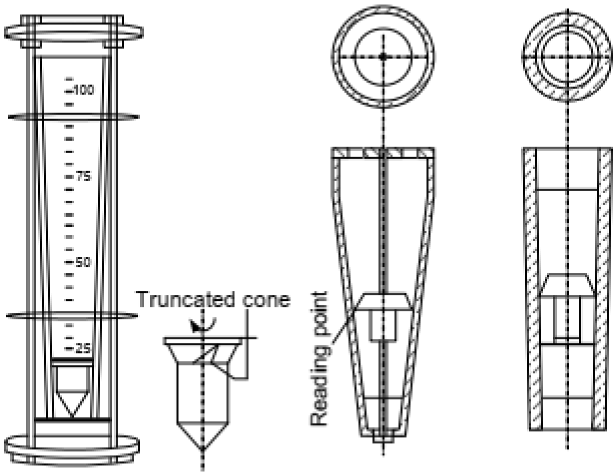


Figure 3.7: The float flow meter or rotameter

The float flow meter features a variable passage area and maintains a nearly constant pressure drop (refer to Figure 3.7). The variable rotaflow meter is designed with a tube that has a truncated conical shape on the interior. Within this tube, a float is positioned, which is elevated by the liquid or gas being measured and is maintained at a specific level. The design and material of the float vary among manufacturers and are influenced by the characteristics of the substance, the flow rate, the flow profile, and the pressure within the pipe. Either to prevent the float from tipping within the conical tube, it is guided along a central rod or an inclined notch is incorporated to allow for continuous rotation of the float. Typically, the conical tube is constructed from durable glass to facilitate direct reading. In situations where higher pressures are present, a metal tube may be utilized, with the float's position being determined through a magnetic field or a movement sensor.

The flow rate of a liquid through a rotaflow meter is expressed by:

$$Q_v = k_1(ah + bh^2)\sqrt{\frac{\rho_2 - \rho_1}{\rho_1}} = C_d \cdot (A_1 - A_2)\sqrt{\frac{2 \cdot g \cdot V}{A} \cdot (\frac{\rho_2}{\rho_1} - 1)}$$

Where

ρ_1: density of the liquid

ρ_2: density of the float

A_2: surface area of the float

V_2: volume of the float

k_2: coefficient caused by the type of the float

C_d: the frictional loss coefficient

A_1-A_2: the surface area of the ring between the float and tube

A_2 is variable; all the other factors remain constant for a particular instrument and the same liquid.

The equation illustrates that the measurement is contingent upon the liquid's density. Nevertheless, if the float is constructed from a material with a density that is double that of the liquid, the variations in the liquid's density can be disregarded. The viscosity of the fluid being assessed affects the coefficient of frictional loss, Cd. In a laminar flow scenario, the value of Cd can vary significantly. Conversely, a turbulent flow occurs when the value of Cd remains constant. Consequently, the nature of the flow plays a crucial role in determining the design of the float.

Characteristics

- ✓ The visible float also controls the operation.
- ✓ Quasi-linear scale.
- ✓ No need for equalization pipes.
- ✓ Small and constant pressure loss.
- ✓ Vertical installation.
- ✓ Not equipped for non-transparent substances.
- ✓ Dependent on the decline in pressure over the reading instrument and on the temperature of the fluid.

3.6.2 Target flow meter

The target flow meter was initially developed for applications where conventional flow meters fall short, particularly in the measurement of highly viscous liquids, under extreme temperature conditions, and for gas flows at elevated velocities.

Principle

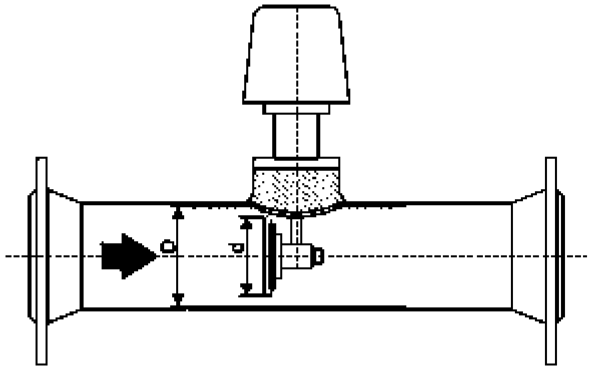


Figure 3.8: Target flow meter

The flow meter (Figure 3.8) is composed of a target that experiences a force from the liquid or gas. The flow can be determined based on the force applied.

$$Q = C_d \cdot \frac{\pi}{4} \cdot (D^2 - d^2) \cdot \sqrt{\frac{2.F}{K.A.\rho}} = C' \cdot \frac{D^2 - d^2}{d} \sqrt{\frac{2.F}{\rho}}$$

$$A = \frac{\pi}{4} d^2$$

where

K: proportionality constant

v: velocity of the fluid

ρ: density of the fluid

A: target surface area

The equation indicates that the flow is directly proportional to the force exerted by the liquid on the target. To achieve a linear transfer, it is necessary to utilize a square-root extractor. A dynamometer or a motion converter can facilitate the conversion to either an electrical or pneumatic signal. When assembling a target flow meter, it is essential to observe the same precautions as those applied to a metering orifice.

Characteristics

- ✓ Well-adapted for viscous substances.
- ✓ Relatively inexpensive for extreme measurements (high viscosity).
- ✓ Long equalization pipes are required.

- ✓ Low rate of accuracy (5% FS).
- ✓ Individual calibration is required for each application and each substance.

3.7 Turbine flow meter

Principle

This flow meter derives its name from the turbine located within the flow line (see Figure 3.9). The speed of the fluid being measured causes the turbine to rotate, and this rotation occurs with minimal friction, making it proportional to both the velocity and the flow rate of the fluid.

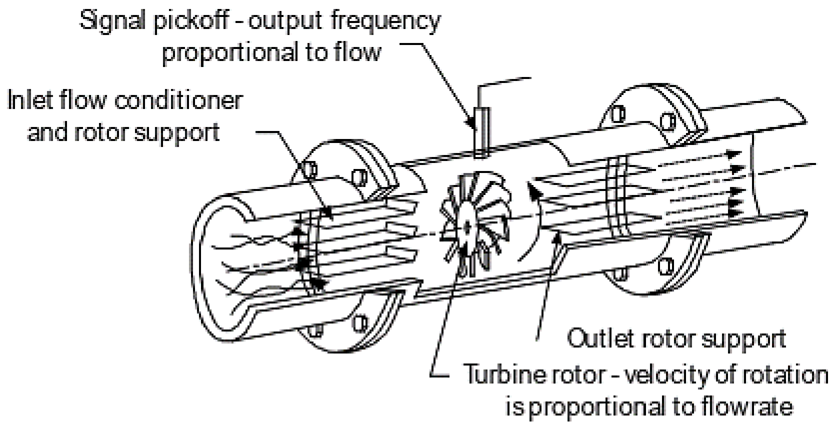


Figure 3.9: Turbine flow meter

A reader or "pick-off" device is positioned at a right angle to the rotor. There are two primary types of pick-off assemblies: the magnetic pick-off and the no drag pick-off.

The magnetic pick-off is composed of a permanent magnet encircled by a coil. As the blades of the turbine rotor traverse the magnetic field, an alternating current is generated in the coil, with a frequency that correlates to the flow rate. Conversely, the no drag pick-off utilizes an oscillator that sends a high-frequency carrier wave to the coil of the pick-off (Figure 3.10). The turbine's rotation modulates this carrier wave in accordance with the rotor's speed. In both scenarios, pulses that are proportional to the flow are generated.

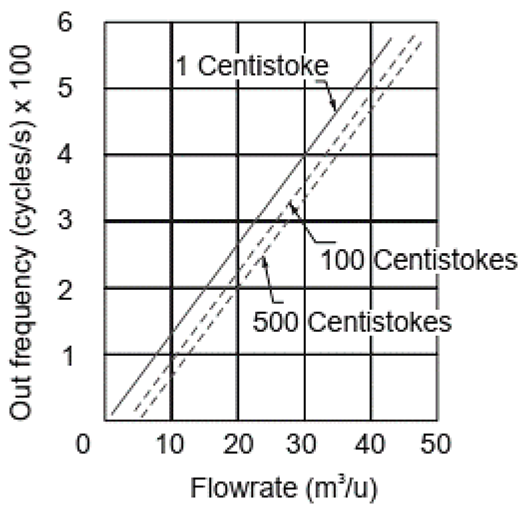


Figure 3.10: Output frequency and viscosity

Each turbine flow meter is defined by its K-factor, which is a coefficient indicating the number of pulses produced per liter for a specific flow of a given fluid. The K-factor can be determined through the following calculation:

$$K = \frac{60.f}{Q_v}$$

where

Q_V: the flow [liter/minute]

f: frequency [pulse/s]

K: K-factor [pulse/liter]

Depending on the fluid viscosity. The typical characteristics of the turbine flow meter are shown in Figure 3.10.

Practical installation

The turbine flow meter necessitates the installation of equalization pipes both upstream and downstream of the device. The required lengths of the horizontal pipes, as illustrated in Figure 3.11, are contingent upon the specific flow conditions. Generally, it is recommended to have an equalization pipe measuring 15D upstream and another measuring 5D downstream.

The precision of the instrument is significantly affected by the quality of the blade construction and the friction between the rotor and its axis. The rotor's inertia can substantially affect the response time, particularly in applications involving gases.

For the purpose of digital-to-analog conversion, a frequency-to-voltage transformer may be employed to convert the pulses into a standardized electrical signal. To prevent any contaminants that could obstruct the turbine, a filter may be installed in front of the turbine flow meter if necessary. Implementing a bypass is advantageous for continuous operations, as it facilitates the maintenance and cleaning of the flow meter (and the filter) without halting the process.

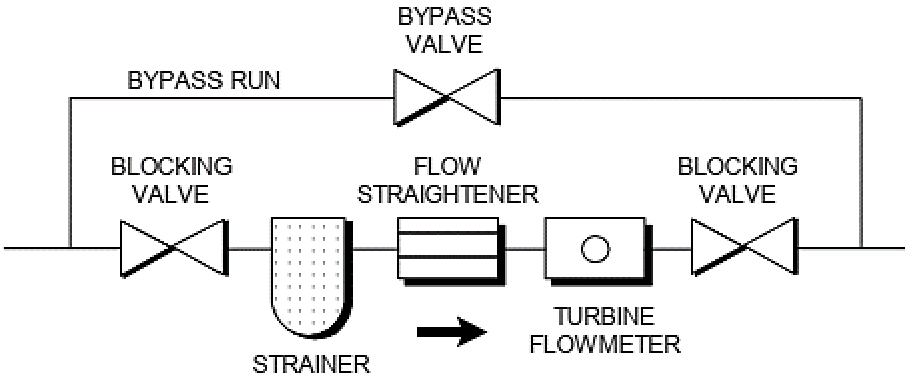


Figure 3.11: Installation of the turbine flow meter

Characteristics

- ✓ A wide variety of ranges is offered for both gases and liquids.
- ✓ Under certain conditions, a high degree of accuracy (0.2-0.3%) can be achieved due to the digital output.
- ✓ The device is particularly susceptible to wear, especially when dealing with heavily contaminated materials and at elevated speeds.
- ✓ While it demonstrates high reproducibility, its linearity is restricted to a limited range, which constrains the overall measuring capacity.
- ✓ The paddlewheel flow meter represents one of the variations (refer to Figures 3.12 and 3.13).

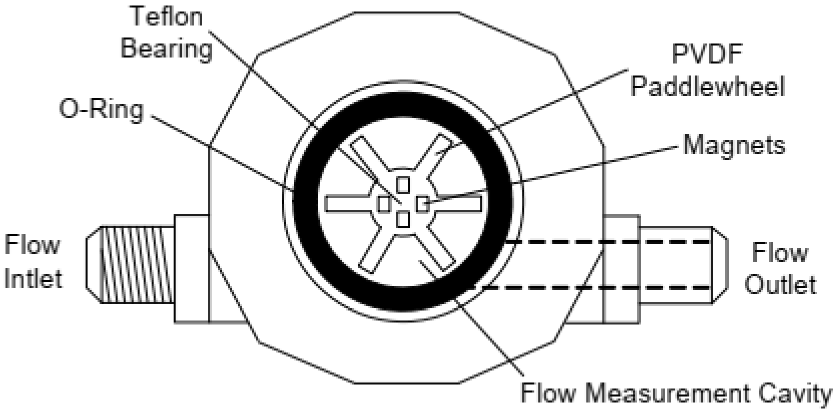


Figure 3.12: Paddlewheel flow meter

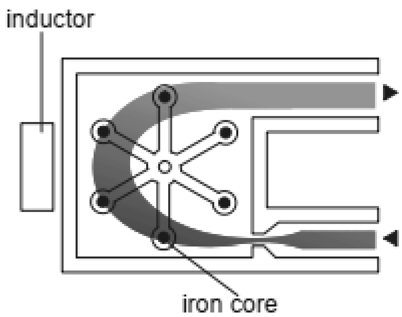


Figure 3.13: Paddlewheel flow meter

3.8 Magnetic flow meter

Principle

The operation of the magnetic flow meter is founded on Faraday's law.

$$U_e = B.L.v$$

where

B: magnetic field (flux density) [Tesla]

L: distance between the electrodes [m]

v: velocity of the flow [m/s]

When a medium that conducts electricity, containing free electrons or ions, is subjected to motion within a magnetic field, an electric field is induced, resulting in a potential difference across the conductor. This electric field is oriented at right angles to both the magnetic field and the direction of motion, as described by the left-hand rule. The magnitude of the potential difference is directly related to the strength of the magnetic field and the velocity of the movement.

It is crucial to understand that the voltage generated is independent of various factors such as pressure, temperature, viscosity, and conductivity. A minimal level of conductivity is necessary to produce this signal, which possesses a very small amount of power. Furthermore, this signal is directly proportional to the volume flow.

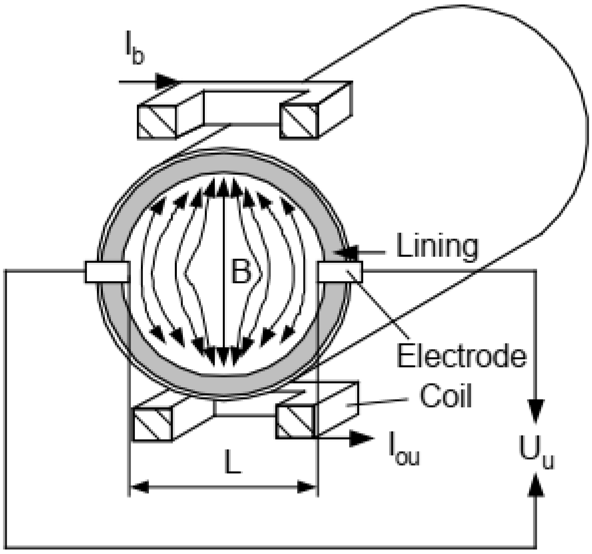


Figure 3.14: Magnetic flow meter

The conventional magnetic flow meter is composed of two primary components: the measuring probe (refer to Figure 3.14) and an electronic converter-amplifier that converts the millivolt signal into one or more standard analog or digital outputs. An increasing number of models that integrate these two components into a single unit, such as the E+H Pulsmag and Picomag, are becoming available in the market.

3.9 The vortex flow meter

Principle

The vortex flow meter operates based on the principle of vortex shedding, which takes place when a fluid—be it steam, gas, or liquid—flows past a non-streamlined object known as a bluff body (refer to Figure 3.15). The cylindrical flow of the fluid cannot conform to the contours of the bluff body, resulting in the formation of vortices downstream, collectively referred to as the Karman vortex street. These vortices detach alternately from either side of the bluff body, with a frequency that is directly proportional to the average velocity of the fluid moving through the pipe.

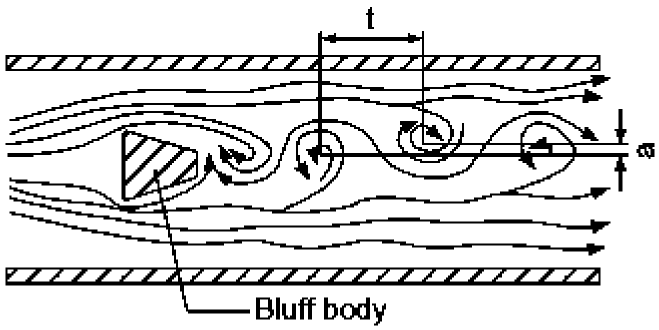


Figure 3.15: Vortex flow meter

Sensors such as thermistors, piezoelectric or capacitive cells, and ultrasonic measuring devices are employed to detect the velocity or pressure pulses generated by vortex shedding. The output signal is produced by local electronic components. Vortex flow meters from various manufacturers are differentiated by the design of the bluff body, the type of sensor utilized, the detection location, and the electronic systems implemented.

Since their introduction in 1970, vortex flow meters have been utilized for industrial flow measurement. Advances have been made in the design of bluff bodies to enhance the signal-to-noise ratio, and significant improvements have been achieved in sensor technology. Many professionals regard the vortex flow meter as a promising solution for measuring non-conductive fluids, positioning it as a potential replacement for metering orifices and other pressure measurement devices.

Practical installation

Vortex flow meters can be installed in both horizontal and vertical orientations. When positioned vertically, the flow should ideally move from the bottom to the top. Additionally, certain guidelines must be adhered to, similar to those applicable to electromagnetic flow meters.

It is essential that the pipes are completely filled, as is the case with electromagnetic flow meters. The effective operation of the vortex flow meter relies on a fully developed and undisturbed flow profile. Consequently, long straight sections of pipe are required: a minimum of 5 diameters upstream of the meter and 3 diameters downstream. Some manufacturers even recommend 20 diameters upstream and 10 diameters downstream of the meter.

Proper alignment of the measuring instrument with the pipe is crucial. The installation should occur in an area with minimal vibration, and if necessary, the pipes should be supported both upstream and downstream of the meter.

When temperature and pressure measurements are also required alongside flow measurement, the pressure gauge should be positioned one diameter upstream of the meter, while the thermometer should be located at least 5 diameters downstream.

Several factors can significantly affect the accuracy of the measurement instrument, including:

- ✓ Deformation of the bluff body due to corrosion.
- ✓ Corrosion within the pipe housing the meter.
- ✓ Contamination of the bluff body.
- ✓ Hydraulic vibrations affecting both the pipe and the instrument.
- ✓ Misalignment of the flange gaskets.
- ✓ Incomplete filling of the measuring instrument.

Characteristics

- ✓ Low installation costs.
- ✓ Wide dynamic span.
- ✓ The minimum measurable velocity depends on the type of sensor.
- ✓ The maximum velocity of the fluid is allowed approximately 7.5 m/s for liquids and approximately 75 m/s for gases and steam.
- ✓ High level of accuracy at Re-number > 10,000 (1% for liquid, 1.5% for gases).
- ✓ Limited linearity at Re-number < 10,000.
- ✓ Good stability and drifting.
- ✓ Linearity does not depend on density, viscosity and pressure.
- ✓ Valid for gases, liquids and steam.
- ✓ Small permanent pressure loss.
- ✓ Almost no moving parts, little or no maintenance.
- ✓ Limited use at high viscosity and large pressure pulses.
- ✓ Good flow profile is required for a correct functioning of the vortex flow meter.
- ✓ Resistant to temperature shocks of 100°C/s.
- ✓ Depending on the type of sensor, it is insensitive to vibrations up to 1 g (1-500 Hz).

Specific applications

Steam:

- ✓ Steam boilers: in the main pipes (overheated steam).
- ✓ Chemistry: measuring saturated steam to heat reaction vessels.
- ✓ Industrial processes: heating and cooling systems.

Gases:

- ✓ Purification plant: flow measurement of methane.
- ✓ Industry: measuring compressed air.
- ✓ Cryogen gases: liquid nitrogen at temperatures down to –200°C.

Liquids:

- ✓ Non-conductive liquids: distilled or demineralized water, glycol, etc.
- ✓ Low-viscous hydrocarbon: gasoline, diesel, hydraulic oil, etc.

3.10 Ultrasonic flow meter

Principle

The operational mechanism of the ultrasonic flow meter relies on the propagation of sound waves through an acoustically transparent medium (Figure 3.16). One or multiple pairs of ultrasonic transmitters and receivers are positioned within or on the pipe, directly opposite each other. The initial pair is situated slightly downstream of the second pair, creating a specific angle relative to the longitudinal axis of the pipe.

There are two types of measuring instruments categorized by their measurement principles:

- ✓ Ultrasonic flow meters that utilize the time-of-flight (transit time) principle.
- ✓ Ultrasonic flow meters that operate based on the Doppler effect.

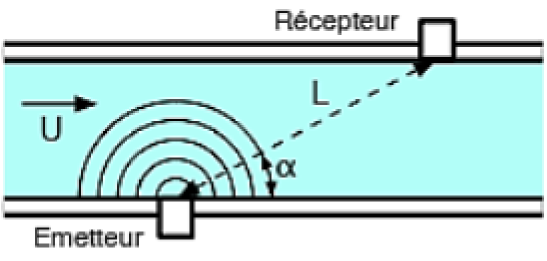


Figure 3.17: Ultrasonic flow meter

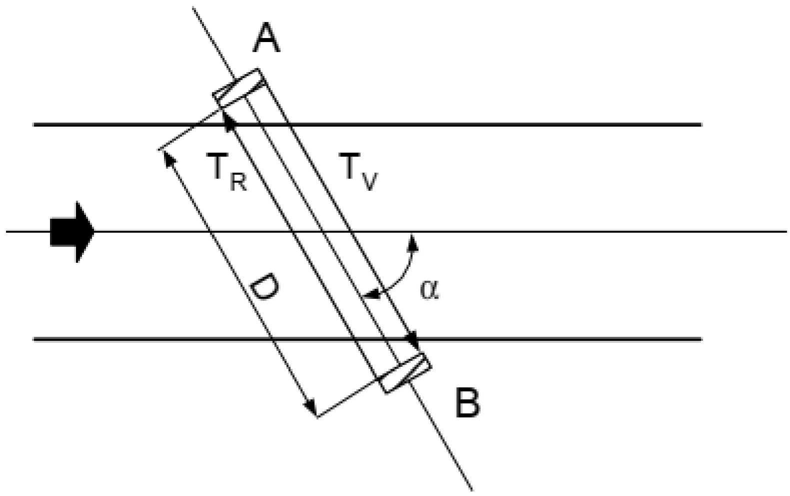


Figure 3.17: Time-of-flight principle

Measuring the flow in accordance with the execution time principle

Due to the vectorial addition of sound velocity and flow velocity, and considering that transmitter-receiver B is positioned downstream of A, the sound wave train traveling from A to B will reach its destination more quickly than the wave train moving from B to A (refer to Figure 3.17). This indicates that the execution time from A to B is less than that from B to A, expressed as Tr > Tv (assuming velocity is greater than zero). The disparity in execution times yields the average flow rate v_{gem}:

$$v_{gem} = \frac{\Delta t.(\frac{D}{t_v})^2}{2.D.\cos\theta} = \frac{\Delta t.D}{2.(t_v)^2.\cos\theta}$$

Measurements based on the Doppler effect

This historical technique, first identified by Christiaan Doppler in 1842, has gained significant recognition primarily due to its use in "clamp-on" meters. The Doppler Effect is applicable to both sound and electromagnetic waves. When either the source or the receiver is in motion relative to the wave medium, the frequency detected by the receiver will differ from that emitted by the transmitter. Specifically, the frequency increases when moving toward the source and decreases when moving away from it. This phenomenon arises from the constant speed of the wave within the medium. By considering all velocities in the same direction as positive, we can articulate the Doppler Effect in the following manner:

$$f_w = \frac{c - v_w}{c - v_b} . f_b$$

where

f_w: observed frequency for movement

f_b: frequency of the source in rest

c: transmission velocity in the medium

v_w: velocity of the observer with respect to the medium

v_b: velocity of the source with respect to the medium

In the course of measurement, both the source (transmitting crystal) and the observer (receiving crystal) remain stationary, while the intervening medium, the fluid, is in motion. The transmitted signal is detectable solely when it is scattered by the particles of the moving fluid. These particles may consist of solid materials or small gas bubbles (refer to Figure 3.18). The Doppler method is effective only in liquids that possess a sufficient concentration of solids or gas bubbles. Such liquids are typically classified as "challenging" substances that can adversely affect the performance of standard flow meters.

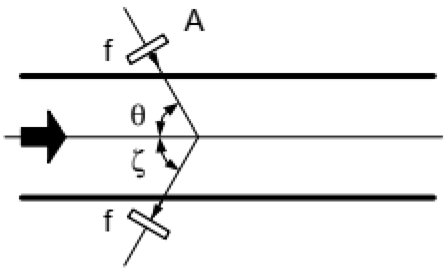


Figure 3.18: Transmitting crystals A and B

The Doppler frequency shift is:

$$\Delta f \approx \pm f_s . \frac{v}{c} . (\cos\theta + \cos\zeta)$$

The ± sign indicates the direction of the velocities, thus also the position of the sensors.

Note t: Δf is proportional to v. So for a very sensitive measurement:

- ✓ f_s needs to be as large as possible (limited by attenuating);
- ✓ cos θ + cos ξ needs to be as large as possible, which means that s and u need to be as small as possible.

Practical installation

Acoustic flow meters generally do not have specific installation requirements when positioned on or within the process pipe. However, the following considerations are advisable:

- ✓ It is recommended to install the meter in a vibration-free environment, particularly for Doppler type flowmeters, as vibrations can generate erroneous signals that may mislead the electronic components.
- ✓ As with most flow meters, it is essential that the measuring pipe is entirely filled with the fluid; this is particularly important when measuring gases.
- ✓ A well-established flow profile is crucial for ensuring reliable and precise measurements. Therefore, it is advisable to use equalization pipes measuring between 10 to 20 diameters (D) upstream and 5 diameters (D) downstream of the meter to achieve the specified accuracy level of 2%.
- ✓ The presence of pilot valves immediately downstream of the flow meter can adversely affect measurement accuracy, particularly in situations involving cavitation or supersonic flow conditions.

Characteristics

- ✓ There is no loss of pressure within the pipe.
- ✓ Measurement can be conducted without direct contact with the fluid through "clamp-on" methods.
- ✓ This technique is applicable solely to liquids that possess acoustic transparency.
- ✓ A minimal, yet not excessive, level of contamination in the liquid is required for the Doppler Effect, while the time-of-flight principle necessitates minimal impurities.
- ✓ Challenges arise when measuring small diameters, particularly with the time-of-flight method.
- ✓ The time-of-flight differential meter can achieve a turndown ratio of 1:1000, with potential accuracy ranging from 1% to 2.5%.
- ✓ The Doppler type meter can reach a turndown ratio of 1:3000, with accuracy levels between 2% and 5%.
- ✓ Each medium requires individual calibration.
- ✓ The Doppler Effect influences readings based on the flow profile.
- ✓ Accuracy levels of up to 1% are achievable, although this is not the case with clamp-on methods.
- ✓ Currently, ultrasonic measurement of gas, steam, and even high-temperature steam flow is feasible.

Chapter 4:
Velocity measurements

4.1 Introduction

Velocity is a vector quantity in physics that requires both magnitude and direction for its definition. The scalar representation of velocity's magnitude is referred to as speed, which is a coherent derived unit measured in the International System of Units (SI) as meters per second (m/s or $m \cdot s^{-1}$).

4.2 Difference between speed and velocity

Although the terms speed and velocity are frequently used interchangeably in everyday language to describe the rate at which an object is moving, they have distinct meanings in scientific contexts. Speed, which is the scalar quantity derived from a velocity vector, refers solely to the rate of motion of an object. In contrast, velocity encompasses both the speed of the object and the direction in which it is moving.

4.3 Equation of motion

Velocity is characterized as the rate at which an object's position changes over time. This concept is often referred to as instantaneous velocity to differentiate it from average velocity. In certain contexts, it may be necessary to determine the average velocity of an object, which is defined as the constant velocity that would yield the same overall displacement as a variable velocity during a specified time interval, v(t), over a duration of Δt. The calculation of average velocity can be expressed as:

$$\bar{V} = \frac{\Delta x}{\Delta t}$$

4.4 Velocimetry

Velocity measuring devices are classified into two types according to the measurement method

Intrusive methods

- ✓ Pitot tube
- ✓ Directional probes
- ✓ Hot wire anemometer,
- ✓ Hot film anemometry.

Optical methods

- ✓ Particle image velocimetry,
- ✓ Laser Doppler anemometry,
- ✓ Pulsed ultrasound velocimetry.

4.4.1 Velocimetry based on intrusive methods

4.4.1.1 Hot wire anemometer

The fundamental concept of a hot-wire anemometer involves a slender metal wire positioned within a fluid (Figure 4.1). By passing an electric current through this wire, it is heated to a temperature that exceeds that of the surrounding fluid. As the fluid flows vertically past the wire, it removes some of the heat from the wire, leading to a decrease in its temperature.

The rate at which heat is dissipated is directly linked to the fluid's velocity. The change in temperature of the hot wire, which affects its resistance, translates the heat dissipation into an electrical signal that corresponds to the velocity of the fluid (Figure 4.2). This principle is typically illustrated in the operation of a hot-wire anemometer:

Figure 4.1: Hot-wire anemometer

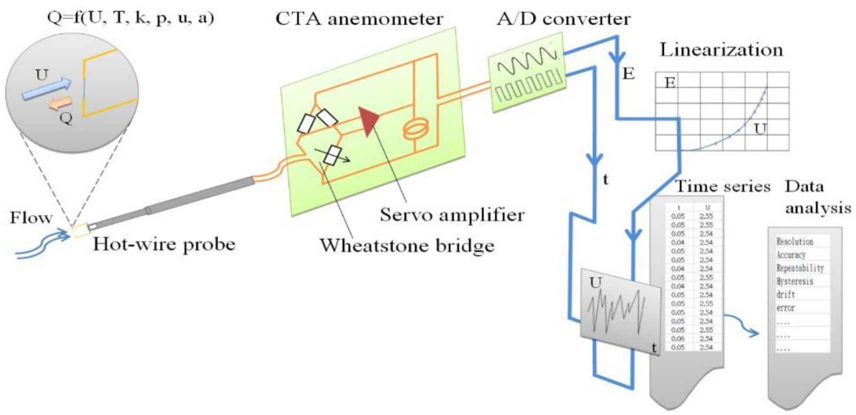


Figure 4.2: Hot wire anemometer measuring principle

Flow or wind speed measurement is a crucial sensing application in numerous production systems and equipment, including agriculture, industry, and everyday life. The hot-wire anemometer has found extensive application across different sectors.

4.4.2 Velocimetry based on optical methods

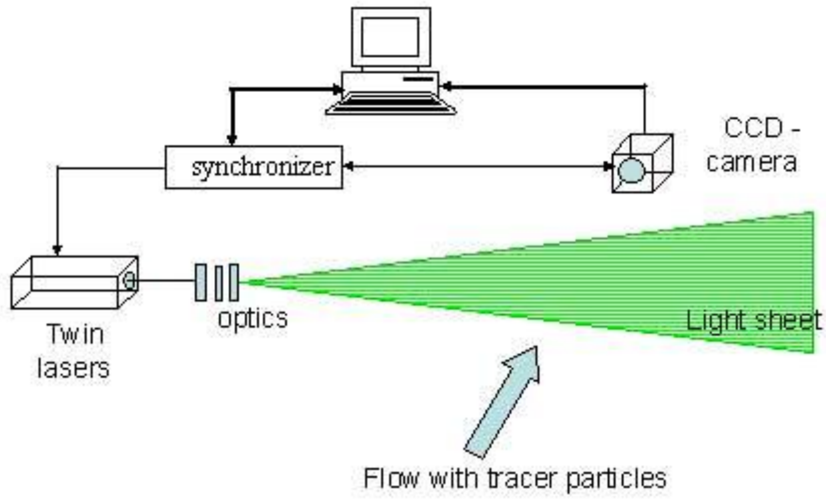
4.4.2.1 Particle image velocimetry

Particle Image Velocimetry (PIV) is a comprehensive flow measurement technique that enables the acquisition of instantaneous velocity vector data across a flow cross-section. As a non-intrusive method, PIV is particularly suitable for high-speed flows and boundary layer investigations in fluid dynamics.

This technique can be applied to various liquid and gaseous flows. The fluid is infused with seeding particles, which are typically regarded as accurately reflecting the flow dynamics. The velocity information is derived from the movement of these seeding particles, which is captured by taking two images in quick succession. The distance traveled by individual particles during this interval is analyzed to determine the displacement field, which is then divided by the known time separation to yield the velocity field.

A standard PIV configuration includes a CCD camera, a high-power laser, and an optical system to transform the laser output into a light sheet, tracer particles, and a synchronizer. A specialized camera is employed to ensure that the first image is captured quickly enough to prepare for the subsequent exposure. Various types of CCD sensors are available, including full frame, frame transfer, interline transfer, and full frame interline transfer CCDs. A full frame interline transfer progressive scan CCD camera is typically utilized to capture two single-exposed images with a time separation on the order of microseconds (Figure 4.3).

To prevent image blurring during the analysis of rapid flows, laser pulses are employed. These pulses effectively freeze motion and serve as a flash for the digital camera. A pulsed laser, such as a double-pulsed Nd-YAG laser or a copper vapor laser, is preferred to achieve high light energy in a brief time frame. Laser light is uniquely capable of being focused into a sufficiently thin light sheet, ensuring that only particles within that specific plane are imaged. The light sheet is generated using the laser as the illumination source.



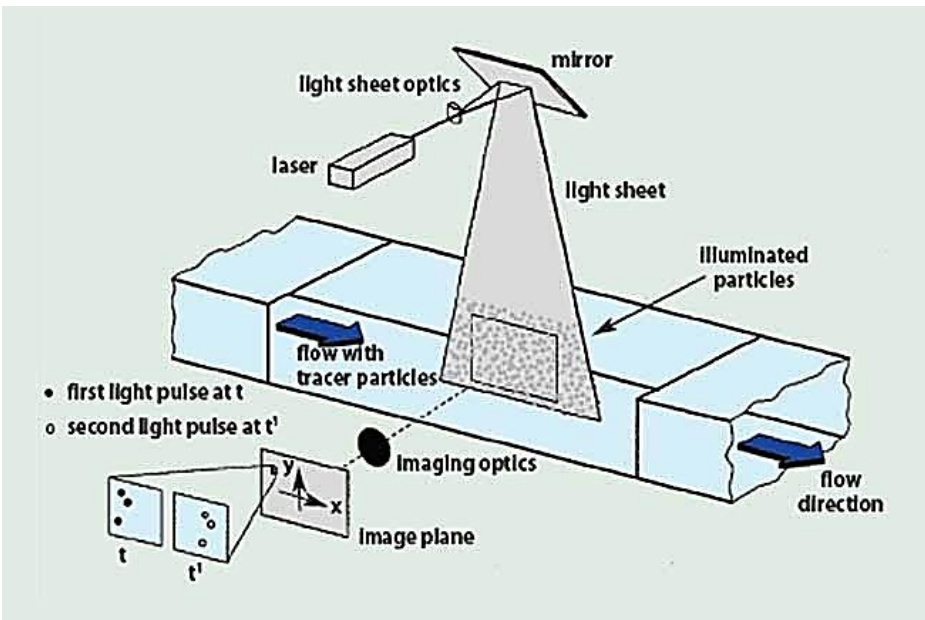


Figure 4.3: Particle image velocimetry measuring principle

Limitations of PIV

1. The interval between laser pulses must be sufficiently extended to allow for the measurement of tracer particle displacement, while also being brief enough to prevent particles with an out-of-plane velocity component from exiting the light sheet.
2. Utilizing high-power lasers enables a reduction in the size of tracer particles, which significantly enhances the precision of Particle Image Velocimetry (PIV) measurements, as the particles will more accurately adhere to the flow dynamics.
3. The dimensions of the interrogation area should be minimized to ensure that there are no considerable velocity gradients present within that region.

4.4.2.2 Laser Doppler Anemometry (Velocimetery)

The Laser Doppler Anemometer (LDA) is a highly regarded instrument utilized for fluid dynamic studies in both gases and liquids, having been in use for over thirty years. This technique is well-established and provides valuable data regarding flow velocity.

Its non-intrusive nature and sensitivity to direction render it particularly effective for scenarios involving reversing flows, chemically reactive substances, high-temperature environments, and rotating machinery, where the use of physical sensors may be challenging or unfeasible. The presence of tracer particles in the flow is necessary for its operation.

The method offers several distinct advantages, including non-intrusive measurements, high spatial and temporal resolution, elimination of calibration requirements, and the capability to measure in reversing flow conditions.

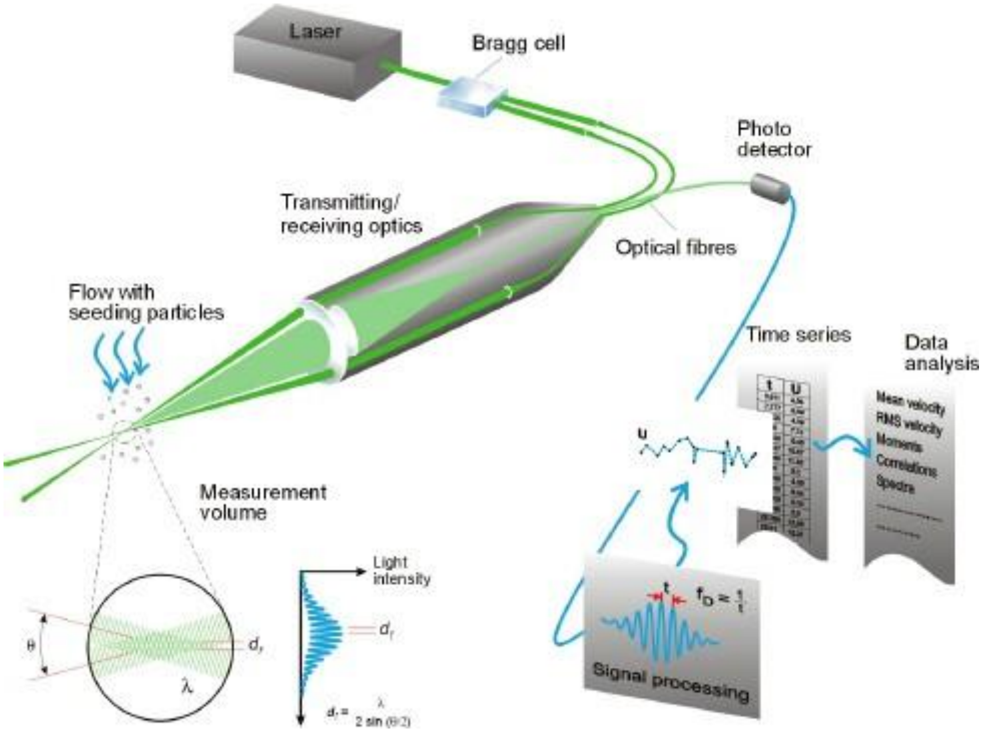


Figure 4.4: LDA principle

Principles

The fundamental setup of a Laser Doppler Anemometer (LDA) includes the following components (Figure 4.4):

- ✓ A continuous wave laser
- ✓ Transmitting optics, which consist of a beam splitter and a focusing lens
- ✓ Receiving optics, which are made up of a focusing lens, an interference filter, and a photodetector
- ✓ A signal conditioner along with a signal processor

Advanced systems may incorporate traverse mechanisms and angular encoders. A Bragg cell frequently serves as the beam splitter. This device consists of a glass crystal affixed with a vibrating piezoelectric crystal (Figure 4.5). The vibrations produce acoustic waves that function similarly to an optical grid.

Figure 4.5: The Bragg cell used as a beam splitter.

The Bragg cell produces two beams of identical intensity, characterized by frequencies f_0 and fshift. These beams are directed into optical fibers, which transport them to a probe.

Within the probe, a lens, allowing them to converge in the probe volume, concentrates the parallel beams exiting the fibers (Figure 4.6).

The probe volume

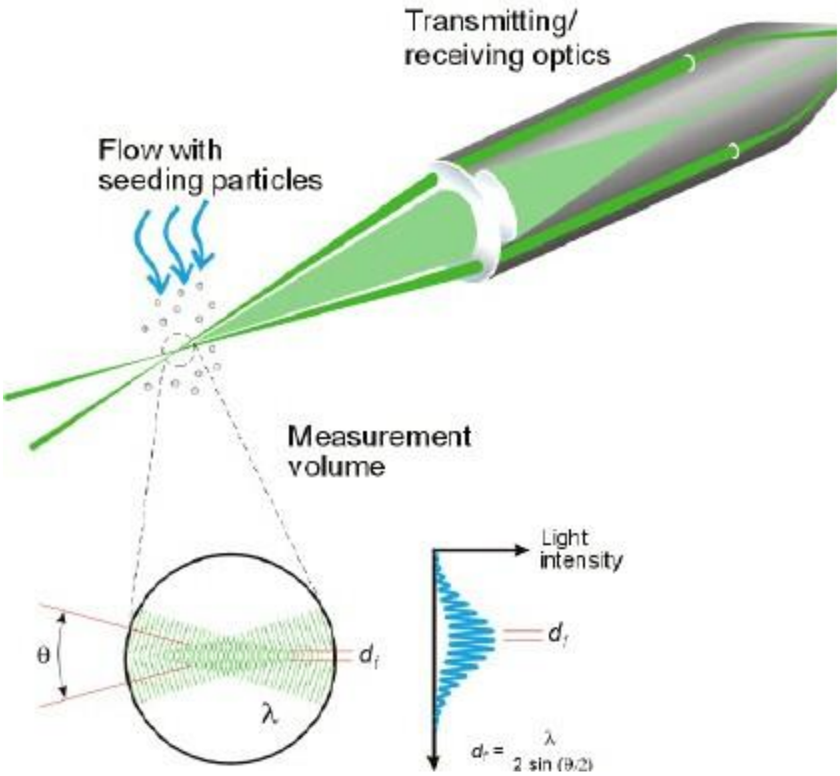


Figure 4.6: The probe and the probe volume.

The probe volume generally measures a few millimeters in length. The intensity of the light is altered as a result of interference occurring between the laser beams. This phenomenon generates parallel planes of elevated light intensity, referred to as fringes. The distance between these fringes, denoted as d_f, is determined by the wavelength of the laser light and the angle formed between the beams.

$$U = d_f \cdot f_D = \frac{\lambda}{2 \sin(\theta/2)} \; f_D$$

Each passage of particles scatters light in proportion to the local light intensity.

Information regarding flow velocity is derived from the light scattered by small "seeding" particles that are transported within the fluid as they traverse the probe volume. This scattered light exhibits a Doppler shift, denoted as the Doppler frequency f_D, which correlates with the velocity component that is perpendicular to the bisector of the two laser beams, aligning with the x-axis depicted in the probe volume.

The scattered light is captured by a receiving lens, which directed onto a photo detector. An interference filter positioned before the photo-detector allows only the necessary wavelength to reach the photo-detector, effectively eliminating noise from ambient light and other wavelengths.

Signal processing

The photo-detector transforms the varying light intensity into an electrical signal known as the Doppler burst, which manifests as a sinusoidal wave with a Gaussian envelope, reflecting the intensity profile of the laser beams.

The Doppler bursts undergo filtering and amplification within the signal processor, which calculates f_D for each particle, frequently employing frequency analysis through the efficient Fast Fourier Transform algorithm.

The fringe spacing d_f yields insights into the distance traveled by the particle.

The Doppler frequency f_D provides temporal information, expressed as t = 1/fD.

Given that velocity is defined as distance divided by time, the formula for velocity can be articulated as: Velocity $v = d_f * f_D$.

Determination of the sign of the flow direction.

The frequency shift produced by the Bragg cell results in the movement of the fringe pattern at a constant velocity. Particles that remain stationary will produce a signal corresponding to the shift frequency, denoted as f_{shift}. In contrast, particles moving with velocities V_{pos} and V_{neg} will generate signal frequencies f_{pos} and f_{neg}, respectively.

LDA systems that do not incorporate frequency shifting are unable to differentiate between positive and negative flow directions or to measure a velocity of zero.

Conversely, LDA systems equipped with frequency shifting can effectively identify the flow direction and accurately measure a zero velocity.

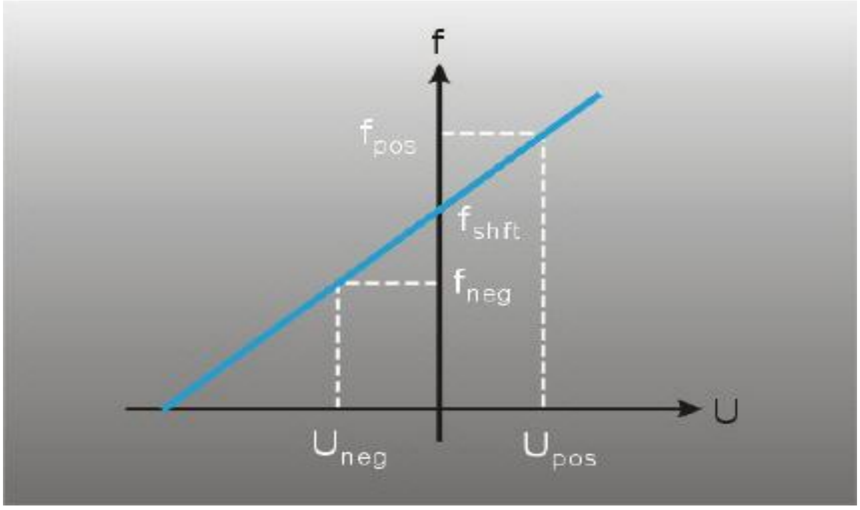


Figure 4.5: Doppler frequency to velocity transfer function for a frequency-shifted LDA system.

To facilitate the measurement of two velocity components, two additional beams can be introduced into the optical setup, positioned in a plane that is perpendicular to the initial beams. All three-velocity components can be captured using two distinct probes (Figure 4.6), which measure two and one components, respectively, with all beams converging in a shared volume as illustrated below. Different wavelengths are employed to distinguish the measured components, and three photodetectors equipped with suitable interference filters are utilized to detect the scattered light corresponding to the three wavelengths.

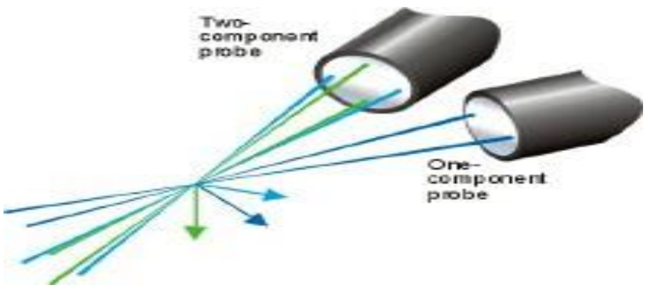


Figure 4.6: LDA optics for measuring three velocity components.

Contemporary LDA systems utilize a compact transmitter unit that includes a Bragg cell and color beam splitters, enabling the generation of up to six beams: both unshifted and frequency-shifted beams across three distinct colors. These beams are transmitted to the probes through optical fibers.

Seeding Particles

- ✓ Liquids generally possess adequate natural seeding, while gases typically require external seeding.
- ✓ The ideal particles should be sufficiently small to adhere to the flow dynamics, yet large enough to scatter an adequate amount of light, ensuring a favorable signal-to-noise ratio at the output of the photo-detector.
- ✓ The usual size range for these particles falls between 1 µm and 10 µm. The particle composition may be either solid (in the form of powder) or liquid (as droplets).

4.4.2.3 Pulsed ultrasound velocimetry

The Doppler ultrasound technique, which was first utilized in the medical sector, has a history spanning over three decades. The introduction of pulsed emissions has broadened the application of this technique to various other domains, paving the way for innovative measurement methods in fluid dynamics.

In pulsed Doppler ultrasound, rather than transmitting continuous ultrasonic waves, a transmitter periodically emits short bursts of ultrasound, while a receiver continuously gathers echoes reflected from potential targets within the ultrasonic beam's path (Figure 4.7). By synchronously sampling the incoming echoes in relation to the timing of the emitted bursts, it becomes possible to calculate the velocity of the particles.

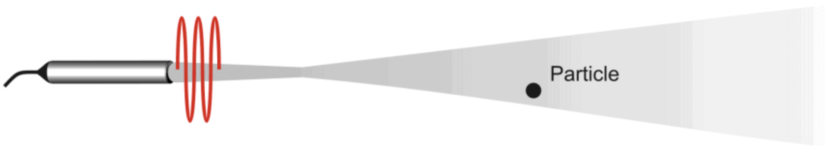


Figure 4.7: Pulsed ultrasound velocimetry principle

How the velocity is measured

Consider a scenario, as depicted in the accompanying figure, in which a single particle is located along the trajectory of the ultrasonic beam.

At time T_1, a burst is released. This burst travels through the liquid medium. At time T_2, the burst encounters the particle. If the dimensions of the particle are significantly smaller than the wavelength, only a minimal echo is produced (a scattering effect). This echo returns towards the transducer, while the primary energy continues to propagate forward.

At time T_3, the echo arrives at the transducer. The depth of the particle can be calculated based on the travel time (T_3-T_1).

$$\text{Depth} = \frac{C}{2 * (T3 - T1)}$$

C represents the sound velocity of the acoustic wave within the liquid medium.

In pulsed ultrasonic velocimetry, bursts are emitted at regular intervals. After each emission, the echo signal is captured at a predetermined delay (Figure 4.8). This delay, as indicated by the preceding equation, determines the depth.

If a particle shifts position between consecutive emissions, the sampled values recorded at time Ts will vary over time. Depending on the characteristics of the emitted signal, these values may exhibit a sinusoidal pattern.

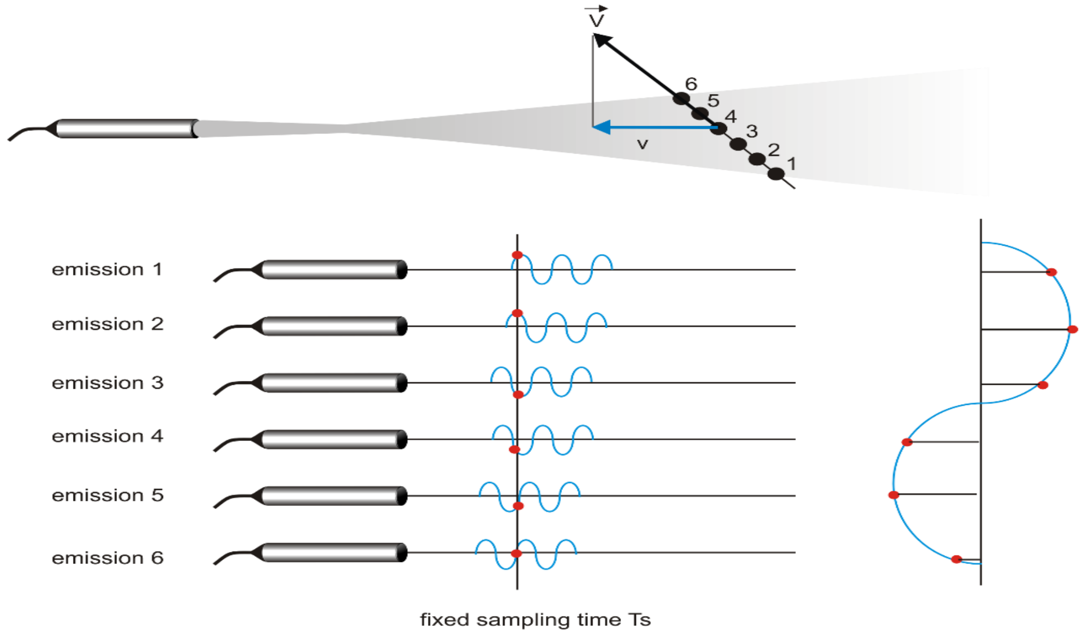


Figure 4.8: Spread the echo signal

Advantages and limitations

Pulsed Doppler ultrasound provides an immediate and comprehensive velocity profile. However, due to the periodic availability of the information, this method is constrained by the Nyquist theorem. Consequently, there is a maximum velocity associated with each pulse repetition frequency (Fprf).

Chapter 5:
Temperature measurements

5.1 Introduction

Temperature is a very important flow parameter, particularly for compressible flows and flows with heat transfer. It is a physical quantity, which is expressed quantitatively by the property of hotness or coldness. Temperature is quantified using a thermometer, which indicates the kinetic energy associated with the motion and interactions of atoms within a substance. In the International System of Units (SI), the fundamental unit of temperature is the kelvin, denoted by the symbol K. For practical purposes in daily life, the Celsius scale (°C) is frequently employed.

5.2 Thermometers

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

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

5.2.1 Mechanical temperature measurement

5.2.1.1 Glass Tube Thermometers

A diverse range of thermometers is currently available in the market. Glass thermometers continue to provide highly accurate measurements, primarily due to the well-understood properties of fluids, particularly mercury. The main constraints on accuracy and resolution are related to the precision with which the glass tube is manufactured. Certain manufacturers produce thermometers with adjustable scales tailored for specific applications, such as the process known as wet viscosity, where knowing the exact temperature of the water bath is crucial. The glass thermometer remains a preferred choice in this context due to its exceptional repeatability. These specialized instruments feature a bore that narrows at a designated point, enabling a two-degree temperature range in the middle of the scale to extend approximately two inches, thus allowing readings to be taken to a fraction of a tenth of a degree Celsius.

In response to the risks associated with mercury spills, many modern thermometers utilize alternative fluids that have been specifically designed to exhibit particular rates of expansion.

However, these fluids generally do not match the high-temperature capabilities of mercury. Additionally, a significant limitation of glass thermometers is their restricted pressure tolerance (Figure 5.1). Inserting the glass bulb into a pressurized environment can compromise the thermometer's accuracy. To address this issue, a thermowell—a closed-end metal tube—can be employed. This device extends into the chamber or fluid, allowing the thermometer to reside within the well while maintaining contact with its sides.

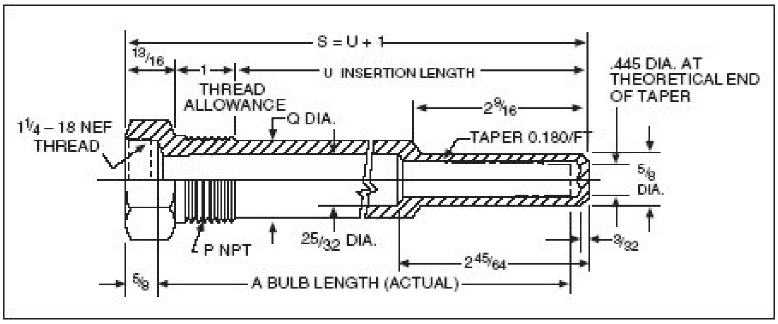


Figure 5.1: Glass Tube Thermometer

Ranges and accuracy

The accuracy and range of a thermometer are influenced by several factors, including the diameter of the opening, the length of the tube, and the type of fluid used within the thermometer. Generally, a thermometer with smaller increments in measurement will exhibit a reduced range. For instance, a mercury thermometer with an accuracy of 0.1° C and a range of 100°C typically measures around 600 mm in length. The limitations are primarily determined by the manufacturer's ability to produce a clear and legible scale. To enhance readability, some manufacturers have adopted non-circular designs for thermometer bodies. The rounded edge on the reading side functions similarly to a magnifying lens, making the liquid column appear wider and easier to interpret. Despite these innovations, the traditional round thermometer remains prevalent, accompanied by various holders and seals designed for compatibility. Additionally, armored sleeves are available to protect thermometers from breakage while allowing for their use. The accompanying chart presents a selection of commercially available thermometers, providing a glimpse into standard sizes and ranges, though it does not encompass the entirety of options available in the market.

The precision of a thermometer is significantly influenced by its manufacturing quality, as well as its operational conditions. As previously mentioned, the pressure applied to the thermometer bulb can impact the readings to some extent. More critically, the depth of immersion in the measuring fluid plays a vital role in determining accuracy. Most commercial thermometers feature etched lines indicating the proper calibrated immersion depth. Insufficient immersion can lead to lower readings, while excessive immersion may result in artificially elevated readings. It is important to note that thermometers are not intended for complete immersion in the fluid being measured.

5.2.1.2 Bimetal Thermometers

The bimetal thermometer was engineered to provide a more durable, albeit less precise, alternative to the glass thermometer. Its bimetallic sensing component is constructed from two distinct metallic materials that are bonded together in a flat spring configuration. When the sensing element detects a change in temperature, the two metals expand at varying rates, resulting in stress within the coil (Figure 5.2). This stress induces a twisting motion in the element. The indicator needle, which is either directly connected to the end of the sensing element or linked through a mechanism reflects this movement, thereby indicating the temperature.

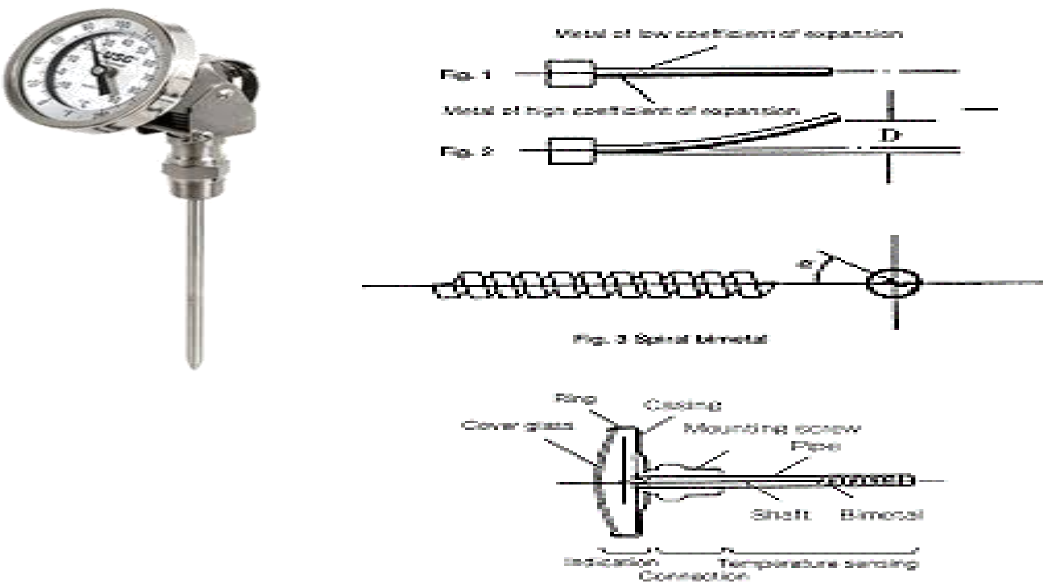


Figure 5.2: Bimetal Thermometer

5.2.2 Electrical temperature measurement

5.2.2.1 Thermistors

Thermistors are a category of semiconductors that function similarly to resistors with a sensitivity to temperature. This implies that their resistance is higher than that of conductive materials but lower than that of insulating materials. To facilitate temperature measurement, the electrical resistance of a thermistor can be related to the ambient temperature where the thermistor is located.

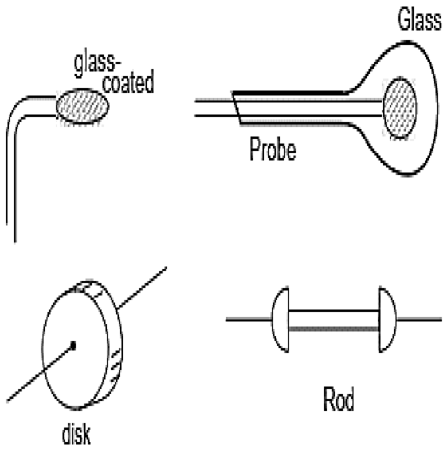


Figure 5.3: Thermistor probes

Types of Thermistors

Thermistors are available in two types: those with Negative Temperature Coefficients (NTC Thermistors) and those with Positive Temperature Coefficients (PTC Thermistors). An NTC Thermistor's resistance decreases as its temperature increases. A PTC Thermistor's resistance increases as its temperature increases.

5.2.2.2 Thermocouples

A thermocouple, often referred to as a "thermoelectrical thermometer," is an electrical instrument composed of two distinct electrical conductors that create an electrical junction. This device generates a voltage that varies with temperature, a phenomenon known as the Seebeck effect (Figure 5.4), allowing for the measurement of temperature through the interpretation of this voltage. Thermocouples are extensively utilized as temperature sensors in various applications.

The typical setup for utilizing a thermocouple is illustrated in the accompanying figure. In summary, the target temperature T_{sense} is determined through three inputs: the thermocouple's characteristic function E(T), the measured voltage V, and the temperature of the reference junction Tref. By solving the equation $E(T_{sense}) = V + E(T_{ref})$, one can derive T_{sense}. These components are frequently obscured from the user, as the reference junction block (which includes the T_{ref} thermometer), voltmeter, and equation solver are integrated into a single device.

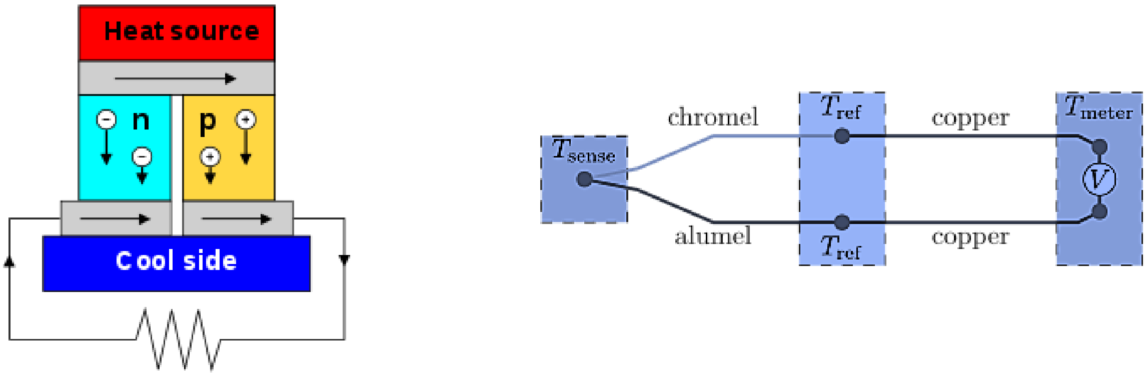
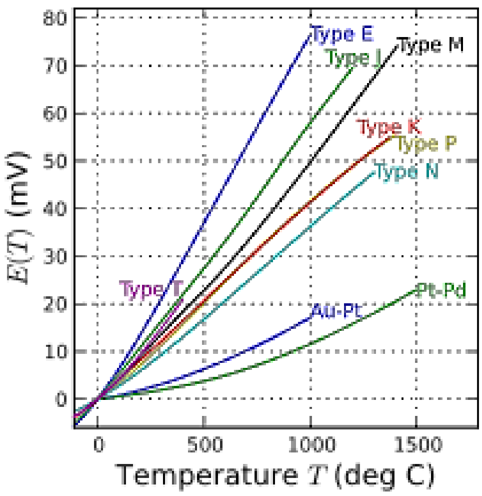


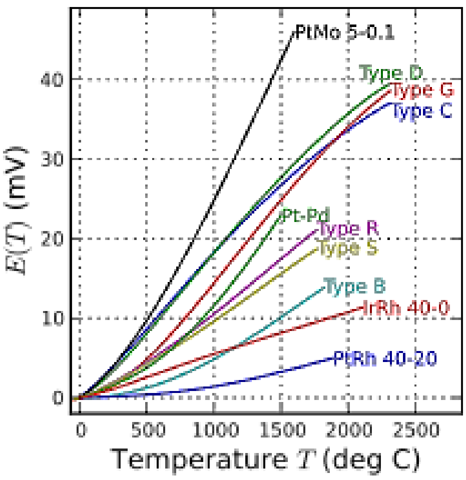
Figure 5.4: Thermocouple principle

Types

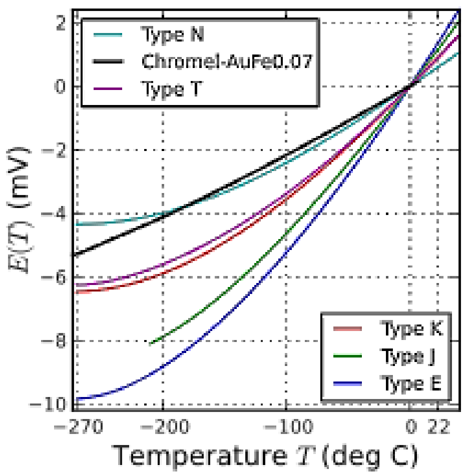
Nickel-alloy thermocouples



Platinum/rhodium-alloy thermocouples

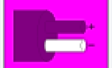
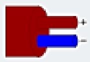
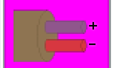
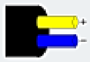
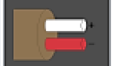
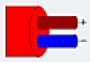
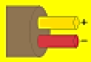
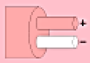
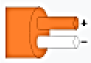
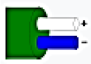
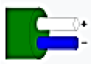
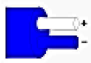
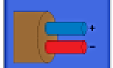


Chromel–gold/iron-alloy thermocouples



Figures 5.5: Different types of thermocouples with their temperature measurement range

Table 5.1: Comparing different types of thermocouples

Type	Temperature range (°C)				Tolerance class (°C)		Color code		
	Continuous		Short-term		One	Two	IEC[29]	BS	ANSI
	Low	High	Low	High					
B	+200	+1700	0	+1820	Not available	600 – 1700: ±0.0025×T	No standard	No standard	Not defined
Chromel/AuFe	−272	+300	—	—	Reproducibility 0.2% of the voltage. Each sensor needs individual calibration.				
E	0	+800	−40	+900	−40 – 375: ±1.5 375 – 800: ±0.004×T	−40 – 333: ±2.5 333 – 900: ±0.0075×T			
J	0	+750	−180	+800	−40 – 375: ±1.5 375 – 750: ±0.004×T	−40 – 333: ±2.5 333 – 750: ±0.0075×T			
K	0	+1100	−180	+1370	−40 – 375: ±1.5 375 – 1000: ±0.004×T	−40 – 333: ±2.5 333 – 1200: ±0.0075×T			
N	0	+1100	−270	+1300	−40 – 375: ±1.5 375 – 1000: ±0.004×T	−40 – 333: ±2.5 333 – 1200: ±0.0075×T			
R	0	+1600	−50	+1700	0 – 1100: ±1.0 1100 – 1600: ±0.003×(T − 767)	0 – 600: ±1.5 600 – 1600: ±0.0025×T			Not defined
S	0	+1600	−50	+1750	0 – 1100: ±1.0 1100 – 1600: ±0.003×(T − 767)	0 – 600: ±1.5 600 – 1600: ±0.0025×T			Not defined
T	−185	+300	−250	+400	−40 – 125: ±0.5 125 – 350: ±0.004×T	−40 – 133: ±1.0 133 – 350: ±0.0075×T			

5.2.3 Radiation temperature measurement

Pyrometer

A pyrometer, also referred to as a radiation thermometer, is a remote sensing instrument designed to measure the temperature of objects located at a distance. Throughout history, different variations of pyrometers have been developed. In contemporary applications, this device assesses the temperature of a surface from afar by analyzing the quantity of thermal radiation it emits, a method known as pyrometry, which falls under the broader category of radiometry.

Principle

The principle underlying this concept is that the amount of light perceived by an observer is influenced by both the observer's distance from the light source and the temperature of that source. A contemporary pyrometer is equipped with an optical system and a detector (Figure 5.6). The optical system directs the thermal radiation onto the detector. The detector's output signal, which indicates temperature T, is connected to the thermal radiation or irradiance j* of the target object via the Stefan–Boltzmann law, incorporating the proportionality constant σ, known as the Stefan–Boltzmann constant, as well as the object's emissivity ε.

$$j^* = \varepsilon\sigma T^4$$

This output allows for the determination of an object's temperature from a distance, eliminating the requirement for the pyrometer to maintain thermal contact with the object.

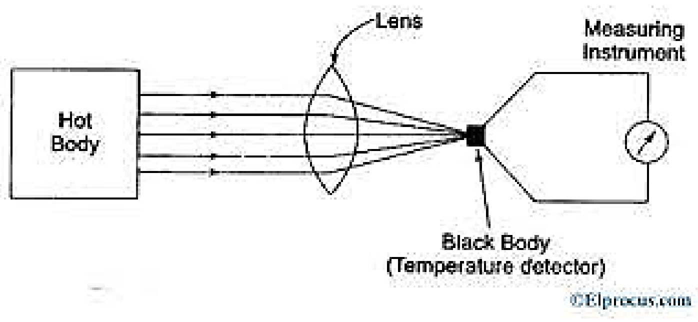


Figure 5.6: Pyrometer principle

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