Chapter 2: Thermal measurement methods and techniques

(4 weeks)

- Temperature measurement
- Pressure measurement
- Flow measurement

2.1 Introduction

Accurate thermal measurement methods and techniques form the foundation of modern engineering analysis, energy management, and process control. Understanding how heat is transferred and distributed within systems requires not only the determination of thermal conductivity but also the precise measurement of related physical parameters such as temperature, pressure, and flow. These three quantities are closely interconnected in heat transfer and thermodynamic processes, and their accurate monitoring is essential for performance evaluation, optimization, and safety in a wide range of applications.

- **Temperature measurement** is one of the most fundamental tasks in thermal analysis, as temperature directly governs heat transfer rates and material properties. Techniques for temperature measurement range from simple contact thermometers to advanced non-contact infrared and digital sensing systems, each offering specific advantages depending on the application.
- **Pressure measurement** is equally important since pressure variations affect phase changes, heat transfer coefficients, and system stability. Accurate pressure measurement techniques are essential in industries such as power generation, chemical processing, and fluid dynamics research.
- **Flow measurement** provides insight into the movement of fluids and gases, which plays a critical role in convective heat transfer. Techniques for measuring flow—whether volumetric, mass, or velocity-based—help determine energy transport rates and ensure the efficiency of thermal systems.

This chapter focuses on the principles, techniques, and practical applications of **temperature, pressure, and flow measurement methods**. Emphasis is placed on their theoretical basis, instrumentation, accuracy, and limitations, providing a comprehensive overview of how these parameters contribute to effective thermal measurement and analysis in both research and industrial contexts.

2.2 Temperature measurement

Temperature is one of the most frequently measured physical quantities in science, engineering, medicine, and daily life. Accurate temperature measurement is essential for industrial process control, environmental monitoring, medical diagnosis, and research. Because temperature cannot be measured directly, it is usually determined through the effect it has on physical properties of materials, such as electrical resistance, electromotive force, expansion, or radiation.

2.2.1 Fundamental Concepts and Scales

Before discussing how temperature is measured, it is essential to understand the scales on which it is expressed.

- **International System of Units (SI):** The SI base unit of temperature is the **kelvin (K)**. The Kelvin scale is an absolute thermodynamic scale where 0 K is absolute zero, the point at which all classical molecular motion ceases. Its increments are the same size as degrees Celsius.
- **Common Scales:**
  1) **Celsius (°C):** Also known as centigrade, this scale is based on the properties of water, with 0 °C defined as the freezing point and 100 °C as the boiling point of water at standard atmospheric pressure. It is widely used in most of the world and in scientific contexts. The conversion is: T(K) = T(°C) + 273.15.
  2) **Fahrenheit (°F):** Primarily used in the United States for non-scientific applications. On this scale, water freezes at 32 °F and boils at 212 °F. The conversion is: T(°F) = (T(°C) × 9/5) + 32.

2.2.2 Classification of Temperature Measurement Devices

Temperature measuring devices, often called thermometers or sensors, can be classified into two primary categories: contact and non-contact.

- **Contact Sensors:** Require physical contact with the object or medium whose temperature is being measured. They achieve thermal equilibrium with the object.
- **Non-Contact Sensors:** Measure temperature by sensing the thermal radiation emitted by an object. They do not require physical contact.

2.2.2.1 Contact Temperature Sensors

2.2.2.1.1 Mechanical Sensors

These devices operate based on the thermal expansion of materials.

1) **Liquid-in-Glass Thermometers:** The most traditional type. A liquid (typically mercury or alcohol) expands and contracts inside a glass capillary tube. The temperature is read from a scale on the tube. They are simple and inexpensive but fragile, slow to respond, and unsuitable for recording or control.
2) **Bimetallic Strip Thermometers:** consist of two strips of different metals (e.g., brass and steel) bonded together. As temperature changes, the metals expand at different rates, causing the strip to bend. This deflection is translated into a pointer on a dial. Common in oven thermometers and industrial dial thermometers.

2.2.2.1.2 Electrical Sensors

These are the most common sensors in modern industrial and electronic applications. They provide an electrical output (resistance or voltage) that can be easily measured, recorded, and used for control.

1) **Resistance Temperature Detectors (RTDs):** A Resistance Temperature Detector (RTD) is a precision temperature sensor that works on the principle of the variation of electrical resistance of a metal with

temperature. RTDs are widely used in scientific and industrial applications due to their **high accuracy, repeatability, and stability** over a broad temperature range. Platinum is the most common material used, leading to the designation **Platinum RTDs (Pt100, Pt1000, etc.)**, where the number indicates the resistance in ohms at 0 °C. The resistance of a pure metal increases with temperature in a predictable way. The relationship between resistance and temperature can be expressed as:

$$R(T) = R_0 \left[1 + \alpha(T - T_0)\right]$$

Where:

- R(T) = resistance at temperature T
- R_0 = resistance at reference temperature T_0 (usually 0 °C)
- α = temperature coefficient of resistance (for platinum ≈ 0.00385/°C)

This near-linear response makes RTDs easy to calibrate and reliable over time.

Table 2 summarizes the key characteristics of Resistance Temperature Detectors (RTDs), including their temperature range, accuracy, response time, linearity, stability, repeatability, and durability, which make them reliable sensors for precise temperature measurement in industrial and scientific applications.

Table 1: Characteristics of RTDs

Parameter	Typical Values / Description
Temperature Range	−200 °C to +850 °C (Platinum RTDs)
Accuracy	±0.1 °C to ±0.3 °C (depending on Class A or B, IEC 60751 standard)
Response Time	0.5 – 5 seconds (slower than thermocouples due to larger thermal mass)
Linearity	Nearly linear resistance–temperature relationship
Stability	Excellent long-term stability, minimal drift
Repeatability	High; measurements are consistent over repeated cycles
Durability	Good, but sensing element can be fragile without protective sheath

2) Thermocouples: A thermocouple works on the Seebeck effect, which states that when two dissimilar metals are joined to form two junctions at different temperatures, an electromotive force (emf) is produced. One junction, called the hot junction, is exposed to the temperature to be measured, while the other, the cold junction, is maintained at a known reference temperature. The voltage generated is proportional to the temperature difference between these two junctions. This relationship can be expressed as :

$$E = \alpha\left(T_{\text{hot}} - T_{\text{cold}}\right)$$

Where:

- E= Thermoelectric voltage (mV)
- α = Seebeck coefficient (µV/°C, depends on thermocouple type)
- T_{hot} = Temperature at the measuring junction (°C)
- T_{cold} = Temperature at the reference junction (°C)

Table 2 summarizes the main characteristics of thermocouples, including their temperature range, accuracy, response time, linearity, stability, repeatability, durability, and cost, which highlight their suitability for a wide range of industrial and scientific applications.

Table 2: characteristics of thermocouples.

Characteristic	**Details**
Temperature Range	Very wide; −200 °C to +2000 °C (depending on type: J, K, T, R, S, etc.).
Accuracy	Moderate; typically ±1 °C to ±2 °C.
Response Time	Fast; milliseconds to a few seconds depending on junction and sheath size.
Linearity	Non-linear relationship; requires calibration tables or software correction.
Stability	Good but can drift over time due to oxidation or contamination.
Repeatability	Moderate; depends on operating environment.
Durability	Very rugged and suitable for harsh environments (e.g., furnaces, engines).
Cost	Low compared to RTDs; simple and inexpensive sensors.

Table 3 presents the most common thermocouple types along with their typical temperature ranges, sensitivities, and common applications.

Table 3: Common Thermocouple Types and Applications.

Type	**Material Composition**	**Temperature Range (°C)**	**Sensitivity (µV/°C)**	**Typical Applications**
J	Iron – Constantan	−40 to +750	~55	Plastics, food industry, general-purpose heating
K	Chromel – Alumel	−200 to +1260	~41	Furnaces, gas turbines, engines
T	Copper – Constantan	−200 to +350	~43	Cryogenics, food storage, low-temperature use
R	Platinum – Rhodium (13%)	0 to +1600	~10	High-temperature furnaces, glass industry
S	Platinum – Rhodium (10%)	0 to +1600	~10	Laboratories, calibration, metallurgical processes

3) Thermistors: A thermistor is a temperature-sensitive resistor made from semiconductor materials. Its resistance changes significantly with temperature due to the variation in the number of charge carriers in the material. There are two main types: **Negative Temperature Coefficient (NTC)** thermistors, where resistance decreases with increasing temperature, and **Positive Temperature Coefficient (PTC)**

thermistors, where resistance increases with temperature. The resistance–temperature relationship of an NTC thermistor can be expressed by the **Steinhart–Hart equation**:

$$\frac{1}{T} = A + B\ln(R) + C\left[\ln(R)\right]^3$$

Where:

- T= Absolute temperature (Kelvin)
- R = Resistance of the thermistor at temperature T (Ω)
- A,B,C = Material-specific constants determined by calibration

For simpler cases, an exponential approximation is often used:

$$R(T) = R_0\, e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

Where: R_0 is the resistance at reference temperature T_0, and β is a material constant.

Table 4 highlights the main characteristics of thermistors, including their temperature range, accuracy, response time, linearity, stability, repeatability, durability, cost, and sensitivity, which demonstrate their usefulness in precise and rapid temperature measurements over limited ranges.

Table 4: Characteristics of Thermistors.

Characteristic	Details
Temperature Range	Typically −100 °C to +300 °C
Accuracy	High over limited ranges (±0.1 °C possible with calibration)
Response Time	Very fast; milliseconds to a few seconds
Linearity	Highly non-linear; requires compensation or calibration
Stability	Good for short-term use; can drift over long periods
Repeatability	High within a limited temperature range
Durability	Fragile (small bead type) but can be ruggedized with coatings
Cost	Low-cost and widely available
Sensitivity	Very high (large change in resistance per degree of temperature change)

4) **Integrated Circuit (IC) Sensors:** Integrated Circuit (IC) temperature sensors are solid-state devices that measure temperature using the predictable behavior of semiconductor junctions. They commonly rely on the **base–emitter voltage (V_{BE}) of a diode-connected transistor**, which changes linearly with temperature when biased with a constant current. The relationship can be expressed as:

$$V_{BE} = V_{g0} - \frac{kT}{q}\ln\left(\frac{I_C}{I_S}\right)$$

Where:

- V_{BE} = Base–emitter voltage (V)
- Vg_0 = Band-gap voltage of the semiconductor at 0 K (≈ 1.205 V for silicon)
- k = Boltzmann constant
- q= Electron charge
- T = Absolute temperature (K)
- I_C= Collector current
- I_S = Saturation current

To simplify practical use, many IC sensors provide a direct **voltage or digital output proportional to temperature**, e.g.:

- **Analog IC sensors (LM35, TMP36):**

  $$V_{OUT} = 10\,\mathrm{mV}/^{\circ}\mathrm{C} \times T(^{\circ}C)$$

- **Digital IC sensors (DS18B20, TMP102):** Provide calibrated digital temperature readings via serial interfaces (I²C, 1-Wire, SPI).

Table 5 summarizes the key characteristics of integrated circuit (IC) temperature sensors, including their range, accuracy, response time, linearity, stability, and output type, which demonstrate their advantages for compact and embedded temperature measurement applications.

Table 5: Characteristics of IC Temperature Sensors.

Characteristic	Details
Temperature Range	Typically −55 °C to +150 °C
Accuracy	±0.25 °C to ±2 °C (depending on device)
Response Time	Moderate; milliseconds to seconds depending on packaging
Linearity	Excellent linear output, easy to interface
Stability	Very stable over time with minimal drift
Repeatability	High; consistent readings with built-in calibration
Durability	Robust solid-state device, suitable for embedded systems
Cost	Low-cost and easily available
Output Type	Analog voltage (e.g., LM35) or digital signal (e.g., DS18B20, TMP102)

2.2.2.2 Non-Contact Temperature Sensors (Radiation Thermometry)

Non-contact temperature sensors are devices that determine temperature without making physical contact with the object being measured. Instead, they rely on detecting the **infrared (IR) radiation** naturally emitted by all objects whose temperature is above absolute zero. The amount and wavelength distribution of this radiation are directly related to the object’s surface temperature. Their operation is governed by two key physical laws:

- **Planck’s Law**: Describes the spectral distribution of radiation emitted by a blackbody as a function of temperature and wavelength. It explains why hotter objects emit more radiation at shorter wavelengths.
- **Stefan–Boltzmann Law**: States that the total radiant energy emitted per unit area is proportional to the fourth power of the absolute temperature ($E=\sigma T^4$). This means small increases in temperature cause large increases in emitted energy.

Using these principles, non-contact sensors convert the detected IR radiation into an electrical signal, which is then processed to display the corresponding temperature. There are two main types of non-contact temperature sensors:

1) **Infrared Pyrometers:** An infrared (IR) pyrometer, also commonly known as a **spot thermometer** or **non-contact thermometer**, is an optoelectronic sensor designed to measure the temperature of a surface from a distance without making physical contact. It does this by detecting the intensity of the infrared thermal radiation emitted by the object.

   Core Principle: Capturing Radiant Energy: The fundamental principle is based on the fact that all objects with a temperature above absolute zero emit electromagnetic radiation. For temperatures commonly encountered in industry and daily life (from below 0°C to thousands of °C), this radiation is predominantly in the infrared band of the spectrum, invisible to the human eye. The pyrometer's internal optics (a lens) collect this emitted IR radiation from a specific spot on the target object and focus it onto a detector. The detector, typically a **thermopile** (which generates a voltage proportional to heat) or a **photodetector** (sensitive to specific IR wavelengths), converts the radiant energy into an electrical signal.

2) **Thermal Imaging Cameras (Thermographic Cameras):** A thermal imaging camera, often called an IR camera or thermographic camera, is an advanced non-contact temperature measurement device that translates infrared radiation into a visual, two-dimensional image called a **thermogram**. Unlike a pyrometer, which provides a single average temperature for a spot, a thermal camera simultaneously measures the temperature of tens of thousands of points to create a comprehensive heat map of an entire scene.

   Core Principle: From Pixels to a Temperature Picture: The fundamental operation can be broken down into a series of steps:

   - **Infrared Detection:** The camera's lens, made of specialized IR-transparent material like Germanium, focuses the infrared radiation emitted by all objects in its field of view onto a **focal plane array (FPA)**. This is a microbolometer detector chip containing a grid of hundreds of thousands of tiny pixels (e.g., 320x240, 640x480).

- **Pixel-Level Measurement:** Each individual pixel on the FPA acts as a miniature, independent infrared thermometer. It absorbs the IR radiation focused upon it, heats up minutely, and changes its electrical resistance. This change is measured and converted into a digital value.
- **Temperature Calculation:** For each of these hundreds of thousands of digital values, the camera's processor performs a complex calculation based on the principles of Planck's Law and the Stefan-Boltzmann Law. Crucially, this calculation incorporates user-input parameters like **emissivity**, **reflected apparent temperature**, and atmospheric conditions to convert the raw IR data into an accurate temperature value for that specific pixel.
- **Image Construction:** The camera assigns a specific color or shade of gray to each temperature value. By assembling all these colored pixels together, it constructs a complete visual image where color represents temperature, not visible light. This final image is the **thermogram**.

Exercises :

- **Exercise01:**
- **Solution:**
- **Exercise02:**
- **Solution:**
- **Exercise03:**
- **Solution:**

2.3 Pressure measurement

Pressure is one of the most important physical quantities measured in science, engineering, and industry. It is defined as the force exerted per unit area and is expressed in **pascals (Pa)** in the SI system. Accurate measurement of pressure is essential in fields such as **fluid mechanics, hydraulics, aerodynamics, meteorology, chemical processing, biomedical applications, and industrial automation**. In instrumentation systems, pressure measurement enables monitoring, control, and safety in processes involving gases and liquids.

2.3.1 Fundamental Concepts of Pressure

The mathematical expression for pressure (P) is:

$$P = \frac{F}{A}$$

Where:

- P = Pressure (Pa)
- F = Force (N), it is perpendicular to the area
- A = Area (m^2)

The SI unit of pressure is the **Pascal (Pa)**, which is equal to one Newton per square meter (N/m^2), it means that 1 Pa = 1 N/m^2. This is a very small unit, so multiples like the kilopascal (kPa = 10^3 Pa) and megapascal (MPa = 10^6 Pa) are commonly used. In engineering and industry, many other units are prevalent, making conversion between them a essential skill:

- **Bar** (1 bar = 10^5 Pa, commonly used in meteorology and Europe)
- **millibar** (1 mbar = 100 Pa)
- **Pounds per square inch (psi):** 1 psi ≈ 6,895 Pa (widely used in the US for tire pressure, hydraulic systems)
- **Inches of Water Column (inH$_2$O)** is the pressure exerted by a **1-inch** high column of water at 4 °C. Its exact value in pascals is: 1inH$_2$O =249.0889Pa
- **Millimeters of Mercury (mmHg) or Torr:** 1 Torr=1mmHg ≈ 133.3 Pa (Both mmHg and Torr are pressure units traditionally used in medicine, physics, and vacuum technology)

- **Atmosphere (atm)** (1 atm = 101,325 Pa, approximately the Earth's atmospheric pressure at sea level)

  It is critical to understand the types of pressure:
- **Absolute Pressure (P_abs):** Pressure measured relative to a perfect vacuum (absolute zero pressure). It is always positive.
- **Gauge Pressure (P_gauge):** Pressure measured relative to the local atmospheric pressure. A gauge pressure reading is zero when it is equal to atmospheric pressure. **P_gauge = P_abs - P_atm**
- **Differential Pressure (ΔP):** The difference in pressure between two points. It is not referenced to atmospheric pressure or a vacuum.
- **Vacuum Pressure:** A negative gauge pressure, indicating a pressure below atmospheric pressure.

2.3.2 Methods of Pressure Measurement

2.3.2.1 Mechanical Pressure Gauges

A pressure gauge is an instrument for measuring fluid intensity in a pressure-powered machine. This fluid intensity is specified by the force that the fluid would exert on a specific unit area. Typical pressure gauge intensity measurement units are pounds per square inch (**psi**), or newtons per square meter called the **pascal**.

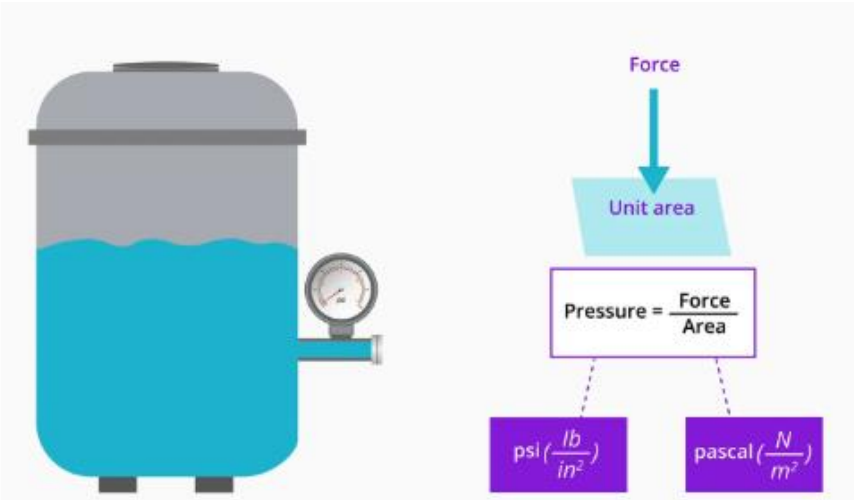


Figure 2.4: Mechanical Pressure Gauge**.**

Categorizing Pressure gauges has become more challenging with the introduction of electronic transducers and devices. Historically, pressure gauges were mechanical devices with **analog** scales. Today we have pressure gauges with pressure-sensing transducers operating electronic **digital** readouts

Figure 2.5: Analog and digital pressure gauges.

There are many types of **mechanical** pressure gauges. Three of the most common types are:

- **Diaphragm Gauge:** Uses elastic deflection of a diaphragm to measure low pressures.
- **Bellows Gauge:** Uses collapsible bellows sensitive to pressure changes.
- **Bourdon Tube:** A curved tube straightens under pressure, transmitting motion to a pointer.

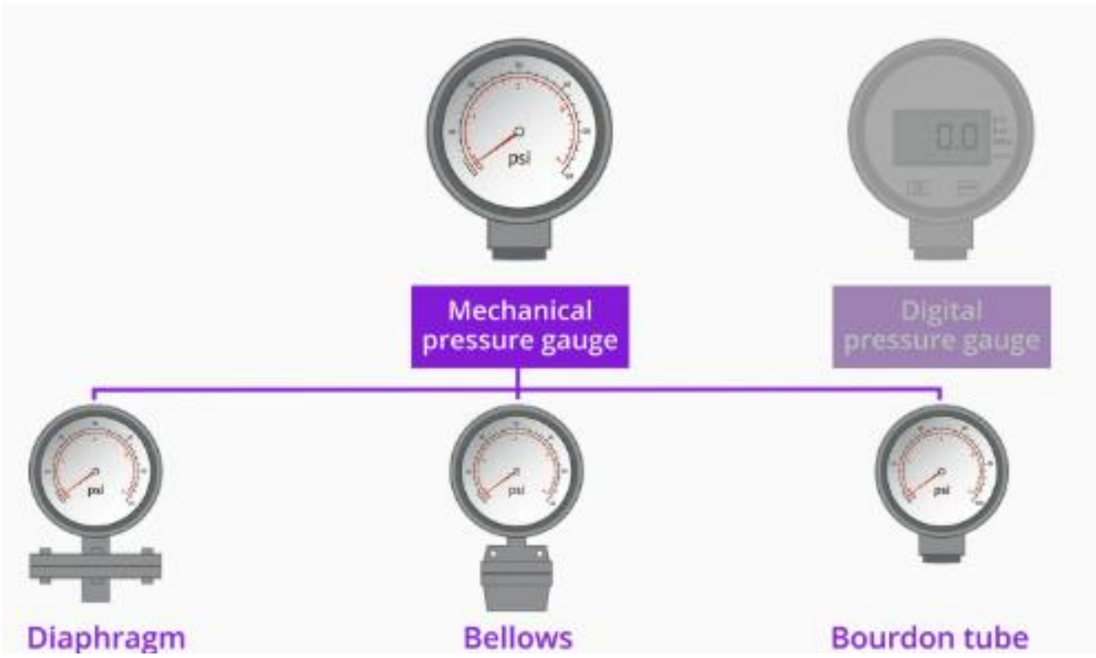


Figure 2.6:

2.3.2.2 Liquid Column Manometers

Manometers are simple devices that measure pressure by balancing a column of liquid against the pressure. They are commonly used for lowpressure applications and are essential for ensuring system safety and efficiency.

1) U-Tube Manometer:

The fluid manometer is a widely used device for measurement of fluid pressures under steady-state and laboratory conditions. Consider the u-tube manometer shown in figure 1, the difference in pressure between the unknown pressure *p* and the atmosphere is determined as a function of the differential height *h*.

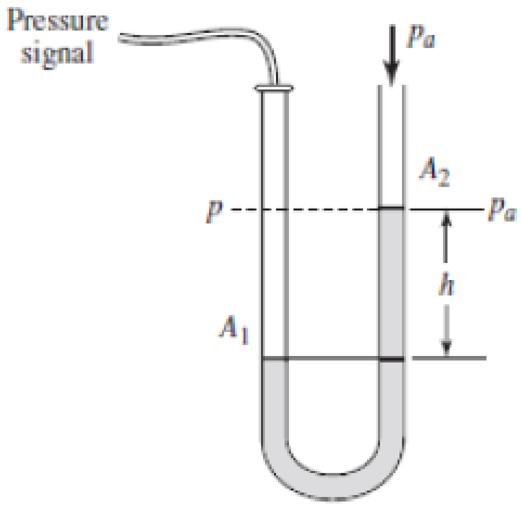


Figure 2.7: U-tube manometer.

The density of the fluid transmitting the pressure *p* is ρ_f , and the density of the manometer fluid is designated as ρ_m. A pressure balance of the two columns dictates that:

$$p_a + \frac{g}{g_c} h \rho_m = p + \frac{g}{g_c} h \rho_f$$

$$p - p_a = \frac{g}{g_c} h(\rho_m - \rho_f) \qquad (1)$$

The sensitivity of the U-tube manometer may be defined as:

Sensitivity = $h/(p - p_a) = h/\Delta p = 1/(g/g_c)(\rho_m - \rho_f)$

or for a manometer with $\rho_m >> \rho_f$, Sensitivity = $1/\rho_m(g/g_c)$.

- **<u>Exemple:</u>** A U-tube manometer employs special oil having a specific gravity of 0.82 for the manometer fluid. One side of the manometer is open to local atmospheric pressure of 29.3 inHg and the difference in column heights is measured as 20 cm±1.0 mm when exposed to an air source at 25◦C. Standard acceleration of gravity is present. Calculate the pressure of the air source in Pascals and its uncertainty.

✓ **<u>Solution :</u>** The manometer fluid has a density of 82 percent of that of water at 25◦C; so,

$\rho_m = 0.82\rho_w = (0.82)(996 \text{ kg/m}^3) = 816.7 \text{ kg/m}^3$

The local atmospheric pressure is $p_a = 29.3$ inHg $= 9.922 \times 10^4$ Pa

The “fluid” in this problem is the air which has a density at the above pressure and 25◦C (298 K) of

$\rho_f = \rho_a = p/RT = 9.922 \times 10^4/(287)(298) = 1.16\ kg/m^3$

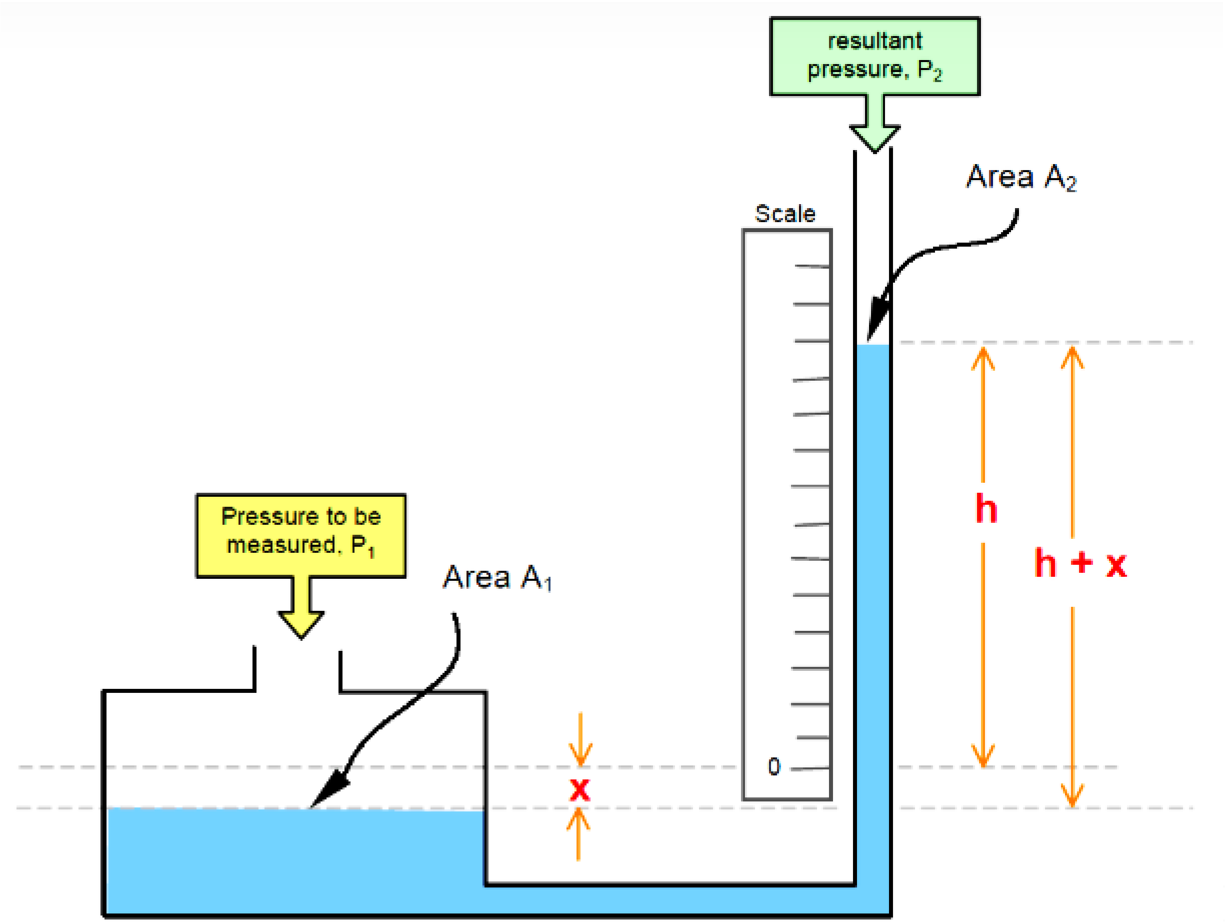
For this problem, the density is negligible compared to that of the manometer fluid, but we shall include it anyway. From Equation (1).

$p - p_a = (g)h(\rho_m - \rho_f) = 9.807/1(0.2)(816.7 - 1.16) = 1600\ Pa$

or $p = 1600 + 9.922 \times 104 = 1.0082 \times 105\ Pa$

The uncertainty of the column height measurement is 1mm/(20cm×10mm/cm) = 1/200= 0.5 %

2) Well Type Manometer: Well Manometer – same as the U-tube except for the reservoir on the high-pressure side. It is sometimes called a single column gauge. The manometer consists of a metal well of large cross sectional area connected to a glass tube, or limb. This system normally contains mercury as the filling liquid. As shown in figure above, both the well and the limb are open to atmosphere, in which case the level of mercury in the well is equal to that in the limb.



In the well type manometer, the pressure to be measured is normally applied to the well. When pressure applied to the well the level of liquid in the well falls by the distance ” x ” and the level in the limb rises by the distance ” h “. When the column of liquid (h + x) exerts a pressure equal to the pressure applied to the well, the liquid stops moving.

The value of (h + x) will increase as the pressure to be measured increases and will decrease as the pressure to be measured decreases. The value of (h + x) can be read from a scale positioned as shown in the diagram above. This scale is normally calibrated in units of pressure, e.g. mm of mercury gauge or Pascal (Pa), so that the pressure can be read directly from the device.

$$\Rightarrow \quad A_1 \cdot x = A_2 \cdot h$$

$$\therefore \quad x = \frac{A_2 \cdot h}{A_1} \quad \text{-------------} \ (1)$$

Differential Pressure on manometer ;

$$P_1 - P_2 = \rho \cdot g \cdot (h + x)$$

Applying (1) $$= \rho \cdot g \cdot \left(h + \frac{A_2 \cdot h}{A_1}\right)$$

$$= \rho \cdot g \cdot h\left(1 + \frac{A_2}{A_1}\right)$$

If $\frac{A_2}{A_1}$ value is too small (negligible), then we can have;

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

3) **Inclined tube Manometer:** it is the type of manometer that has an inclined tube of about ten degrees measurement. This type of manometer is sensitive to even small changes in pressure and is used to detect those small changes only. The image below depicts an inclined tube manometer.

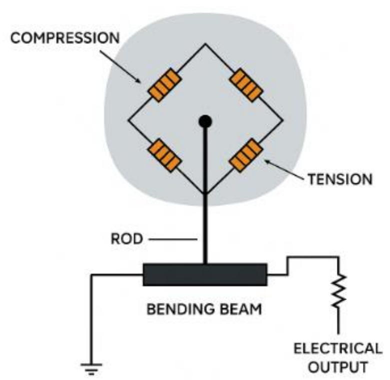
For a manometer inclined at an angle θ with the horizontal the sensitivity becomes :

Sensitivity = $L/\Delta p = L/(g/gc)\ (\rho_m - \rho_f) \times L\sin\theta$

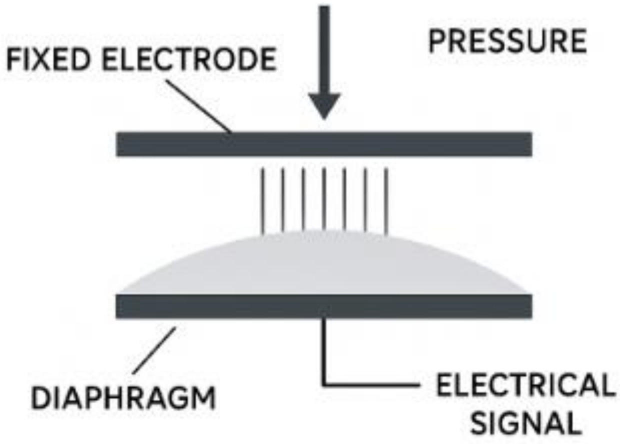
where L is the measured fluid displacement along the incline and $h = L\sin\theta$

2.3.2.3 Electrical / Electronic Pressure Sensors

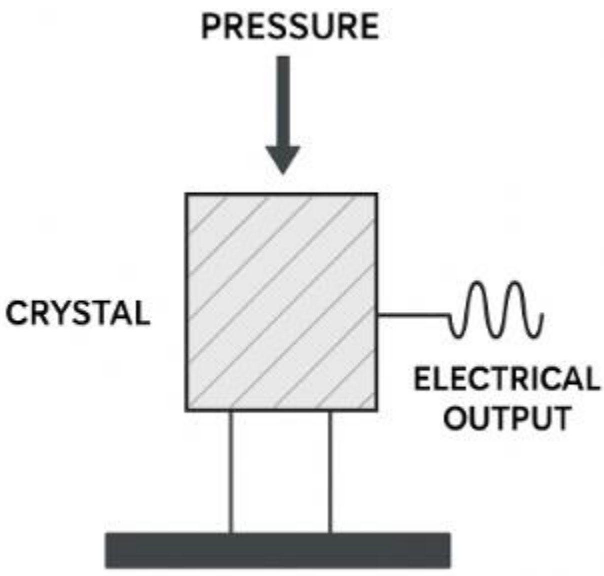
1) **Strain Gauge Pressure Transducers:** A strain gauge pressure transducer measures pressure using a thin diaphragm. When pressure is applied, the diaphragm bends, making some strain gauges stretch and others compress. These changes are converted into an electrical signal through a Wheatstone bridge, giving a value proportional to the pressure. Temperature effects are also balanced out, making the measurement accurate.



2) **Capacitive Pressure Sensors:** A capacitive pressure sensor works by measuring the change in capacitance between two plates. One plate is a fixed electrode, and the other is a flexible diaphragm that moves when pressure is applied. As the diaphragm deflects, the distance between the plates changes, altering the capacitance. This change is then converted into an electrical signal proportional to the pressure.

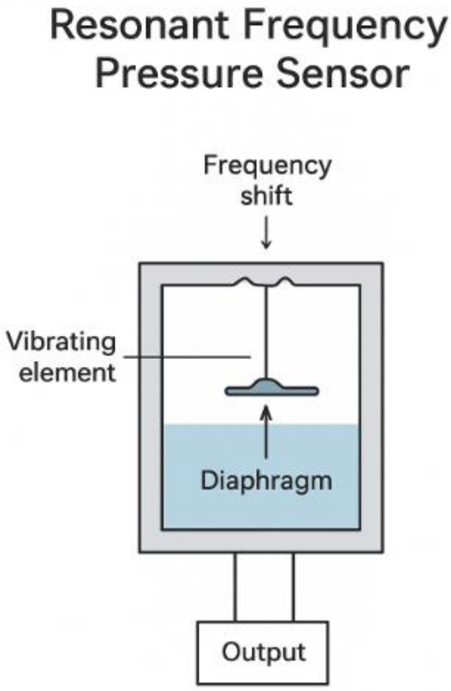


3) **Piezoelectric Sensors:** A piezoelectric sensor works on the principle that certain crystals (such as quartz) generate an **electric charge** when subjected to mechanical stress or pressure. When pressure is applied, the deformation of the crystal produces a voltage proportional to the applied force. These sensors are mainly used for **dynamic pressure measurements** (e.g., vibration, explosions, or engine monitoring), since the generated charge quickly dissipates and they are less suitable for static or steady pressures.



4) **Resonant Frequency Sensors:** A resonant frequency sensor measures pressure by detecting changes in the natural vibration frequency of an element (such as a wire, beam, or diaphragm). When pressure is applied, the tension or stress on the vibrating element changes, causing its resonant frequency to

shift. The frequency shift is directly proportional to the applied pressure, and it can be accurately measured as an electrical signal. These sensors are known for their **high precision and stability**.



2.3.2.4 Modern Digital Pressure Measurement

1) **MEMS (Micro-Electro-Mechanical Systems):** MEMS pressure sensors are **tiny devices** made on silicon chips that combine a mechanical diaphragm with electronic circuits. When pressure bends the diaphragm, the change is detected and converted into a **digital signal**. These sensors are compact, accurate, low-cost, and easily integrated into modern electronics like smartphones, cars, and medical devices.
2) **Wireless Pressure Sensors:** Wireless pressure sensors measure pressure using a diaphragm-based sensing element (such as strain gauge, capacitive, or MEMS) and then transmit the data wirelessly using technologies like **Bluetooth, Wi-Fi, or LoRa**. They are widely used in **Industrial IoT (IIoT) systems** for remote monitoring, reducing the need for wiring, and enabling real-time data collection from hard-to-reach or hazardous locations.

2.4 Flow measurement

Flow measurement is the process of quantifying the movement of fluids (liquids, gases, or steam) through a pipe or channel. It is essential in industries such as water supply, oil and gas, chemical plants, power generation, and HVAC systems. **Flow rate** is typically measured as the volume of fluid passing a point per unit time. The relationship is:

$$Q = \frac{V}{t}$$, Units: m³/s, L/s, or gallons/min.

Where:

- **Volumetric flow rate (Q):** volume per unit time (m³/s, L/min).
- **Mass flow rate (ṁ):** mass per unit time (kg/s).

$$\dot{m} = \rho Q$$

and where ρ = density of the fluid.

- **Velocity (V):** distance traveled per unit time (m/s), it is the speed of the fluid at a given point.

Q=A×V, Where: **A** is the cross-sectional area of the pipe.

2.4.1 Classification of Flow Measurement devices

Flow measurement devices can be classified into categories such as Differential Pressure (e.g., orifice, venturi), Positive Displacement (e.g., oval gear), Velocity (e.g., turbine, ultrasonic, electromagnetic, vortex), , open channel meters. and Mass Flow (e.g., Coriolis, thermal) meters, with each category measuring flow via different physical principles.

2.4.1.1 Differential Pressure (Head-Type) Flow Meters

These meters measure flow by creating a pressure drop across a restriction in the pipe.

1) Orifice Plate

- A flat plate with a hole in the center.
- Causes a pressure drop related to flow rate.
- Common, simple, but causes energy loss.

$$Q = C_d A \sqrt{\frac{2\Delta P}{\rho}}$$

where C_d= discharge coefficient.

2) Venturi Meter

- Has a smooth converging-diverging section.
- Measures pressure difference between inlet and throat.
- High accuracy, less energy loss than orifice plate.

3) Flow Nozzle

- Similar to Venturi but simpler.
- Used for steam and gas flows.

2.4.1.2 Velocity Meters

Directly measure fluid velocity.

1) Pitot Tube

- Measures stagnation and static pressure.
- Common in airspeed and water velocity measurement.

2) Turbine Flow Meter

- A rotor spins with the flow; rotation speed ∝ flow velocity.
- Good accuracy for clean liquids and gases.

3) Electromagnetic Flow Meter

- Based on Faraday's law of electromagnetic induction.
- Works only for conductive fluids.
- No moving parts, low maintenance.

$$E = B \times D \times v$$

Where: E = induced voltage, B = magnetic flux, D = pipe diameter, v = velocity.

4) Ultrasonic Flow Meter

- Uses sound waves to measure velocity.
- Types: Transit-time and Doppler.
- Suitable for clean or dirty liquids.

2.4.1.3 Positive Displacement Meters

1) Measure actual volume of liquid passing through.

Examples:

- Rotary piston meters
- Oval gear meters

2) High accuracy, used for custody transfer (billing).

2.4.1.4 Mass Flow Meters

1) Coriolis Flow Meter

- Measures mass flow directly using vibration.
- Very accurate; used for liquids and gases.

2) Thermal Mass Flow Meter

- Measures mass flow based on heat transfer.
- Used in gases.

2.4.1.5 Open Channel Flow Measurement

For flow in rivers, canals, or partially filled pipes.

1) **Weirs:** Sharp-edged barriers (rectangular, triangular, trapezoidal).
2) **Flumes:** Constricted channels (Parshall flume).

2.5.2 Flow Meter Selection Criteria

- Type of fluid (clean, dirty, conductive, etc.)
- Flow range and accuracy required
- Pressure and temperature
- Installation and maintenance needs
- Cost

2.4.3 Applications

Table 6: Flow measurement devices applications.

Industry	Flow Device	Application
Water Treatment	Electromagnetic	Water distribution
Oil & Gas	Turbine / Coriolis	Fuel measurement
HVAC	Orifice / Venturi	Flow balancing
Aerodynamics	Pitot Tube	Airspeed measurement
Food & Pharma	PD / Coriolis	Accurate dosing

❖ **Exercises :**

♣ **Exercise 01: Orifice Plate Flow Measurement**

Water flows through a horizontal pipe fitted with an orifice plate.

- Diameter of pipe, D_1=0.1 m
- Diameter of orifice, D_2=0.05 m
- Pressure difference across the orifice, ΔP=4000 Pa
- Discharge coefficient, C_d=0.62
- Density of water, ρ=1000 kg/m^3

Find **the flow rate** (Q).

$$Q = C_d A_2 \sqrt{\frac{2\Delta P}{\rho(1-(\frac{A_2}{A_1})^2)}}$$

✓ **Solution:**

Given:

- $D_1 = 0.100\ \text{m},\ D_2 = 0.050\ \text{m}$
- $\Delta P = 4000\ \text{Pa}$
- $C_d = 0.62,\ \rho = 1000\ \text{kg/m}^3$

Formulas / steps :

1) Areas:

$$A_1 = \frac{\pi D_1^2}{4}, \quad A_2 = \frac{\pi D_2^2}{4}$$

2) Area ratio:

$$\beta = \frac{A_2}{A_1}.$$

3) Flow rate:

$$Q = C_d A_2 \sqrt{\frac{2\Delta P}{\rho(1-\beta^2)}}$$

Calculations (digit-by-digit):

- $A_1 = \pi(0.100)^2/4 = 0.007853981634\ \text{m}^2.$
- $A_2 = \pi(0.050)^2/4 = 0.001963495408\ \text{m}^2.$
- $\beta = 0.001963495408/0.007853981634 = 0.25.$
- Denominator factor: $1 - \beta^2 = 1 - 0.25^2 = 1 - 0.0625 = 0.9375.$
- Inside sqrt: $2\Delta P/(\rho(1-\beta^2)) = 2 \cdot 4000/(1000 \cdot 0.9375) = 8000/937.5 = 8.533333333$ (units m^2/s^2).
- Sqrt = $\sqrt{8.533333333} = 2.921467\ldots$ m/s.
- $Q = 0.62 \times 0.001963495408 \times 2.921467 = 0.00355615707\ \text{m}^3/\text{s}.$

Answer:

$$\boxed{Q \approx 3.556 \times 10^{-3}\ \text{m}^3/\text{s} = 3.556\ \text{L/s}}.$$

♣ **Exercise 02: Venturi Meter**

A Venturi meter is installed in a pipeline carrying oil of density 850 kg/m^3. The inlet and throat diameters are 80 mm and 40 mm respectively. The differential pressure head is 0.25m of mercury (density=13600kg/m^3). Discharge coefficient C_d=0.98. Find **the discharge** (flow rate in m^3/s).

✓ **Solution:**

Given

- Inlet diameter $D_1 = 0.080$ m, throat $D_2 = 0.040$ m
- Oil density $\rho = 850$ kg/m^3
- Differential head $h = 0.25$ m of mercury (Hg), $\rho_{Hg} = 13600$ kg/m^3
- $C_d = 0.98$

Steps:

1. Convert head of mercury to pressure: $\Delta P = \rho_{Hg}\, g\, h$ with $g = 9.81$ m/s^2.
2. Use the same differential-pressure flow relation as for orifice/venturi:

$$Q = C_d A_2 \sqrt{\frac{2\Delta P}{\rho(1-(A_2/A_1)^2)}}$$

Calculations:

- $A_1 = \pi(0.08)^2/4 = 0.005026548246\ \mathrm{m}^2$.
- $A_2 = \pi(0.04)^2/4 = 0.001256637061\ \mathrm{m}^2$.
- $\Delta P = 13600 \cdot 9.81 \cdot 0.25 = 33\,354\ \mathrm{Pa}$.
- $\beta = A_2/A_1 = 0.25$.
- $1 - \beta^2 = 0.9375$.
- Inside sqrt: $2\Delta P/(\rho(1-\beta^2)) = 2 \cdot 33354/(850 \cdot 0.9375) \approx 88.9711$ (m²/s²).
- Sqrt = $\sqrt{88.9711} \approx 9.4310\ \mathrm{m/s}$.
- $Q = 0.98 \times 0.001256637061 \times 9.4310 \approx 0.0112675579\ \mathrm{m}^3/\mathrm{s}$.

Answer:

$$\boxed{Q \approx 1.1268 \times 10^{-2}\ \mathrm{m}^3/\mathrm{s} = 11.27\ \mathrm{L/s}}.$$

♣ **Exercise 03: Pitot Tube (Velocity from stagnation pressure)**

A Pitot tube measures a stagnation pressure of 1500 Pa in an air stream. If the air density is 1.2 kg/m^3, find the **velocity** of air.

$$v = \sqrt{\frac{2\Delta P}{\rho}}$$

✓ **Solution:**

Given:

- $\Delta P = 1500\ \mathrm{Pa},\ \rho_{air} = 1.2\ \mathrm{kg/m}^3$

Formula :

$$v = \sqrt{\frac{2\Delta P}{\rho}}$$

Calculations:

$$v = \sqrt{\frac{2 \times 1500}{1.2}} = \sqrt{\frac{3000}{1.2}} = \sqrt{2500} = 50.0\ \mathrm{m/s}.$$

Answer:

$$\boxed{v = 50.0\ \mathrm{m/s}}.$$

♣ **<u>Exercise 04:</u> Electromagnetic Flow Meter**

An electromagnetic flow meter is used in a pipe of diameter 0.1 m. The magnetic field strength is 0.2T and the induced voltage is 20 mV. Find **the flow velocity (v)** and **volumetric flow rate (Q)**.

$$E = BDv$$

✓ **<u>Solution:</u>**

Given:

- Pipe diameter $D = 0.100\ \mathrm{m}$
- Magnetic field $B = 0.2\ \mathrm{T}$
- Induced voltage $E = 20\ \mathrm{mV} = 0.020\ \mathrm{V}$

Relation :

$$E = BDv \quad \Rightarrow \quad v = \frac{E}{BD}$$

Volumetric flow $Q = Av$ with $A = \pi D^2/4$.

Calculations:

- $v = 0.020/(0.2 \times 0.1) = 0.020/0.02 = 1.0\ \mathrm{m/s}$.
- $A = \pi(0.1)^2/4 = 0.007853981634\ \mathrm{m}^2$.
- $Q = 0.007853981634 \times 1.0 = 0.007853981634\ \mathrm{m}^3/\mathrm{s}$.

Answer:

$$\boxed{v = 1.00\ \mathrm{m/s}, \quad Q \approx 7.854 \times 10^{-3}\ \mathrm{m}^3/\mathrm{s} = 7.854\ \mathrm{L/s}}.$$

♣ **<u>Exercise 05:</u> Open Channel Flow (Rectangular Weir)**

A rectangular weir has a width of 0.3 m and the head of water over the crest is 0.15 m. Assume discharge coefficient C_d=0.6. Find **the discharge (Q)** using:

$$Q = \frac{2}{3} C_d b \sqrt{2g} h^{3/2}$$

✓ **Solution:**

Given:

- Width $b = 0.30 \text{ m}$
- Head over crest $h = 0.15 \text{ m}$
- $C_d = 0.60$
- Formula for a rectangular (sharp-crested) weir:

$$Q = \frac{2}{3} C_d \, b \, \sqrt{2g} \, h^{3/2}$$

Calculations:

- $\sqrt{2g} = \sqrt{2 \times 9.81} = \sqrt{19.62} \approx 4.4294 \text{ (m/s)}$.
- $h^{3/2} = (0.15)^{1.5} = 0.15^{1.5} \approx 0.0589256 \text{ m}^{3/2}$.
- $Q = \frac{2}{3} \times 0.60 \times 0.30 \times 4.4294 \times 0.0589256 \approx 0.0308793 \text{ m}^3/\text{s}$.

Answer:

$$\boxed{Q \approx 3.088 \times 10^{-2} \text{ m}^3/\text{s} = 30.88 \text{ L/s}}.$$

2.5 Summary

In summary, the study of thermal measurement methods and techniques provides a vital foundation for understanding and managing heat-related processes in engineering systems. Accurate measurement of temperature, pressure, and flow is indispensable for effective thermal analysis, process optimization, and safety assurance. Each parameter offers unique yet interdependent insights: temperature defines thermal energy distribution, pressure governs system stability and phase behavior, and flow determines the rate and direction of energy transport. By mastering these measurement techniques and their underlying principles, engineers and researchers can ensure reliable data acquisition, enhance system efficiency, and develop innovative solutions to complex thermal challenges. Ultimately, the integration of precise temperature, pressure, and flow measurement methods forms the cornerstone of modern thermal engineering, bridging theoretical understanding with practical application in industrial and research environments.