Temperature Measurements

Topics
- Temperature Standards and Definition
- Thermometry Based on Thermal Expansion
- Electrical Resistance Thermometry
- Thermoelectric Temperature Measurement
- Radiative Temperature Measurements

References

Temperature Measurements

Historical Background
- Temperature—One of the most commonly used and measured engineering variables
  - Galileo (1565–1642)
    - Attempted to use the volumetric expansion of liquids in tubes as a relative measure of temperature
  - Gabriel Fahrenheit (1686-1736)
    - Attempted to use body temperature as the median point on a scale
    - Scale: 180 divisions
    - Extremes: Freezing point and boiling point of water
    - Used mercury as the liquid in a bulb thermometer
  - Andres Celsius (1701-1744)
    - Boiling point of water at 1 atm pressure as 0
    - Freezing point of water at 1 atm pressure as 100
- Carolus Linnaeus (1707-1778)
  - Reversed the scale
- 1948
  - Change from centigrade to Celsius officially adopted

Temperature Standards and Definition

Introduction
- Temperature—Property of an object describing its hotness or coldness
- Heat transfer tends to equalize temperature
  - Systems in thermal communication eventually have equal temperatures
- Zeroth law of thermodynamics—Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other
- Temperature scale provides essential aspects of
  1. The definition of the size of the degree
  2. Fixed reference points for establishing known temperatures
  3. Means for interpolating between fixed temperature points

Sub-Topics
- Fixed Point and Interpolation
- Temperature Scales and Standards
Temperature Standards and Definition
Fixed Point and Interpolation

- Fixed points defined by
  - Phase transition temperatures
  - Triple point of a pure substance
- Phase transition temperatures
  - E.g., water boils at one standard atmosphere pressure
  - Reproducible
- Triple point of a pure substance
  - Substance can exist in equilibrium in the liquid, solid, and gaseous states
  - E.g., water 0.01°C
- Size of a degree
  - 1/100th of the temperature difference

Interpolating between the fixed points
- Liquid-in-glass thermometer
- Calibrate to mark fixed points
- Divide the distance into equal degree divisions

Need information
- Theory on behavior of liquid
- Or many fixed points for calibration

Calibration and interpolation for a liquid-in-glass thermometer

Temperature Scales and Standards

- Temperature scale with an absolute reference
  - Absolute zero for thermodynamics
  - Governs behavior of an ideal gas
  - Celsius related to the Kelvin
  \[ C = K - 273.15 \]
- International standard established
  - Kelvin as the unit
  - Fixed points for temperatures
  - E.g., triple point of hydrogen: 13.8033 K (-259.3467°C)
  - E.g., solid-liquid equilibrium for silver at 1 atm: 1234.93 K
  - Procedures for interpolating
    - Providing accurately calibrated thermometers
      - Use as secondary standards

Thermometry Based on Thermal Expansion

Sub-Topics

- Liquid-in-Glass Thermometers
- Bimetallic Thermometers

Thermometry Based on Thermal Expansion

Introduction

- Physical phenomenon
  - Most material change in size with changes in temperature
  - Well defined and repeatable
- Based on phenomenon
  - Liquid-in-glass
    - Bimetallic thermometers
### Thermometry Based on Thermal Expansion

**Liquid-in-Glass Thermometers**

- Measures temperature by thermal expansion of a liquid
- Liquid in glass structure
  - Bulb—A reservoir
  - Stem—Glass capillary tube
- Difference in thermal expansion of liquid and glass
- Calibration immersion
  1. Complete—Entire thermometer is immersed
  2. Total—Thermometer is immersed up to the liquid level
  3. Partial—Thermometer is immersed to a predetermined level
- Most accurate: Thermometer should be immersed in the same manner in use as during calibration

<table>
<thead>
<tr>
<th>Immersion Type</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Partial</td>
<td>Thermoenter is immersed to a predetermined level</td>
</tr>
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<tr>
<td>Complete</td>
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</tbody>
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### Uncertainties as Low as 0.01 °C under Controlled Conditions

### Pressure Changes Increase Indicated Temperature by 0.1 °C per Atmosphere

### Change in Bulb Volume Over Time

### Typical Total Uncertainty Range from 0.2 °C to 2 °C

### Thermometry Based on Thermal Expansion

**Bimetallic Thermometers**

- Bimetallic Temperature sensor—Physical phenomenon of differential thermal expansion of two metals
- Bonding two strips of different metals
- Variety of shapes
- Linear construction, straight at assembly temperature: $T_1$
- Curvature at other temperature: $T_2$
- Thickness: $d$
- Thermal expansion coefficient $\alpha_i$
- Radius of curvature $r_i \propto \frac{d}{(C_{i1} - C_{i2})(T_2 - T_1)}$

### Increased Sensitivity

- One metal with high thermal expansion coefficient
- Another with low coefficient
- Invar (nickel–iron alloy)
  - Often used
  - Uniquely low coefficient of $1.7 \times 10^{-8}$ m/m°C
- Typical steels
  - Coefficient range of $2 \times 10^{-5}$ to $20 \times 10^{-5}$ m/m°C
- Used in many temperature control systems
- Primary element in most dial thermometers
- Uncertainty of ±1 °C

### Expansion Thermometry Using Bimetallic Materials: Strip, Spiral, and Helix Forms
Electrical Resistance Thermometry

Sub-Topics

- Resistance Temperature Detectors
- Thermistors

Introduction

- Electrical resistance of a conductor or semiconductor varies with temperature
- Two basic classes of resistance thermometers
  - Resistance temperature detectors (RTD) (conductors)
  - Thermistors (semiconductors)
- As temperature increases: Resistance may increase or decrease
  - Positive temperature coefficient (PTC): Metals or alloys
  - Negative temperature coefficient (NTC): Semiconductors
  \( R - R_0 = k(T - T_0) \)
- Germanium excellent choice: Large sensitivity

Resistance Temperature Detectors

General construction
- Mounting a metal wire on insulating support structure to eliminate mechanical strains
- Encasing the wire to prevent influence from the environment (e.g., corrosion)
- Length: \( L \)
- Cross sectional area: \( A_c \)
- Temperature dependence of resistivity
- Resistance of conductor
  \( R = \frac{\rho_c L}{A_c} \)

Resistance Temperature Detectors

Construction of a platinum RTD

Metal conductor
- Reference temperature at \( T_s \): \( R_s \)
- Material constants: \( \alpha, \beta, \ldots \)
  - E.g., \( \alpha \) for Platinum is 0.003927 °C⁻¹ at 20°C
- Relationship between resistance of a metal conductor and its temperature
  \( R = R_s[1 + \alpha(T - T_s) + \beta(T - T_s)^2 + \ldots] \)
- Approximation
  \( R = R_s[1 + \alpha(T - T_s)] \)
Electrical Resistance Thermometry
Resistance Temperature Detectors

- Linear relationship over small temperature ranges
- E.g., Platinum linear approximation accurate within
  - ±0.3% for the 0-200°C
  - ±2.2% for the 200-800°C

- Platinum (Pt) is most common material for RTD
- Predictable and reproducible change in resistance
- Platinum wire provides a precise measure of temperature
- RTD usage
  - Temperature range from cryogenics to 650°C
  - Uncertainty as low as ±0.005°C possible
- RTD resistance measured by Bridge circuits
- Wheatstone bridge circuits modified to consider the resistance of lead wires

\[
\frac{R_1}{R_2} = \frac{R_i + r_s}{R_{RTD} + r_s}
\]

- Example: An RTD with resistance of 25 Ω at 0°C with α of 0.003925°C⁻¹ is used. Value of 37.36 Ω is required to balance the bridge circuit. What is the temperature of the RTD?

\[
R_i = 25 \Omega \\
R_{RTD} = 37.36 \Omega \\
\alpha = 0.003925 \text{ °C}^{-1} \\
R = R_i[1 + \alpha(T - T_0)] \\
37.36 = 25[1 + (0.003925 \times (T - 0))] \\
T = 125.96°C
\]

- Transient thermal response of RTD is slow
- Not chosen for transient measurements
- RTD used for measuring in noncorrosive flowing gases
- Wires with diameters in the order of 10 μm
- High frequency response due to very low thermal capacitance
- Smallest impact destroys this sensor
- RTD Film sensors
  - Thin metallic films coated with ceramic glass
  - Thickness from 0.1 to 2 μm
  - Continuous exposure at 600°C possible
  - Used for heating systems and cooking devices
  - Uncertainty level of ±0.1 to ±2°C

- Thermistors—Thermally sensitive resistors
- Ceramic-like semiconductor devices
- Parameter: β
  - Ranges from 3500 to 4600 K
  - Depends on material, temperature, construction
- Resistance decreases rapidly with temperature

\[
R = R_{e} e^{\frac{\beta}{T - T_0}}
\]

- Used for high sensitivity, ruggedness, or fast response time
- Encapsulated in glass for corrosive or abrasive environments
- High resistance eliminates the problem of lead wire resistance compensation
**Thermoelectric Temperature Measurement**

**Sub-Topics**
- Seebeck Effect
- Peltier Effect
- Thomson Effect
- Fundamental Thermocouple Laws
- Basic Temperature Measurement with Thermocouples
- Multiple-Junction Thermocouple Circuits

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**Thermoelectric Temperature Measurement**

**Introduction**
- Most common method is the thermocouple electrical circuit
- Two electrical conductors of dissimilar metals
- At least one electrical connection (junction)
- Output is voltage related to the temperatures of junctions
- Common form of circuit
  - Junctions with temperatures $T_1$ and $T_2$
  - Circuit measures the difference
  - If $T_1 \neq T_2$: Finite open circuit electric potential $\text{emf}_1$ (electromotive force) is measured
- Simultaneous flows of heat and electricity

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**Thermoelectric Temperature Measurement**

**Introduction**
- Electrical conductor subject to temperature gradient
  - Flow of thermal energy and flow of electricity
  - Good electrical conductor is good thermal conductor
- Phenomena in a thermocouple circuit
  - Seebeck effect
  - Peltier effect
  - Thompson effect
- Practical temperature measurement
  - One reference junction maintained at known constant temperature
  - One measuring junction

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**Thermoelectric Temperature Measurement**

**Introduction**
- Basic thermocouple circuit

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**Thermoelectric Temperature Measurement**

**Basic Temperature Measurement with Thermocouples**
- Ice bath as the reference junction
  - Temperature of $0^\circ \text{C}$
  - Uncertainty within $\pm 0.01^\circ \text{C}$
  - Crushed ice with enough water for slush
  - Not a few ice cubes with water
- Electronic reference junctions
  - Convenient (no need for ice bath)
  - Built-in reference junction compensation
  - Thermistor to determine local environment temperature
  - Uncertainty within $\pm 0.1^\circ \text{C}$
- Standards for material and construction
  - National Institute of Standards and Technology (NIST)
Thermoelectric Temperature Measurement
Multiple-Junction Thermocouple Circuits

- Multiple junction circuits
  - Measure temperature differences
  - Average temperatures
  - Amplify the output voltage
- Thermopile—Multiple-junction thermocouple circuit designed to amplify output
  - Thermocouple output millivolt range
  - \( N \) junctions for \( N \) times the output
  - Increase voltage to reduce uncertainty or transmit to recording device

Radiative Temperature Measurements
Sub-Topics

- Radiation Fundamentals
- Radiation Detectors
- Radiative Temperature Measurements
- Optical Fiber Thermometers

Radiative Temperature Measurements
Introduction

- Measuring temperature by detecting thermal radiation
  - Sensor need not to be in contact with surface to measure
  - Variety of applications
- Knowledge of the radiation characteristics of the surface

Radiative Temperature Measurements
Radiation Fundamentals

- Radiation—Emission of electromagnetic waves from the surface of an object
  - Characteristics of both waves and particles
  - Composed of photons
  - Travel in straight lines
  - Absorbed, reflected, or transmitted
- Range of wavelengths includes
  - X-rays
  - Ultraviolet radiation
  - Visible light
  - Infrared or thermal radiation

- Thermal radiation of an object
  - Related to its temperature
  - Wavelengths from \( 10^{-1} \) to \( 10^{-3} \) m
  - Proportional to the fourth power of temperature
- E.g., electric heating element in an oven
  - No current flow: Its room temperature color
  - Current flow: Temperature rises, change to reddish orange
  - Increase flow: Appear white
  - Color change a shift in intensity of radiation to shorter wavelength
  - Out of infrared into the visible
Radiative Temperature Measurements
Radiation Fundamentals

The electromagnetic spectrum

Radiative Temperature Measurements
Radiation Detectors

- Radiative energy detected in a sensor
- Two techniques
  1. Absorbed radiative energy elevates the detector temperature
  2. Interaction of photon with an electron results in an electric current
- Significantly faster than thermopile or thermistor detectors
  - If time response is important
  - Much wider frequency response

Schematic of a basic radiometer: (1) lens; (2) focusing mirror; (3) detector (thermopile or thermistor)

Radiative Temperature Measurements
Radiation Fundamentals

Commercially applicable radiation thermometers
- Radiometer
- Pyrometry
- Radiometer
  - Measures source temperature
  - By measuring the voltage output of a thermopile detector
  - E.g., measurement of total solar radiation upon a surface
  - Infrared (IR) thermopile sensors

Radiative Temperature Measurements
Radiation Detectors

Pyrometry—Identifies the temperature of a surface by the color of radiation it emits
- Technique
  - Standard lamp calibrated for current flow through its filament
  - Comparison made optically between the color of this filament and the surface of the object
  - Can measure high temperatures remotely
### Radiative Temperature Measurements

**Optical fiber Thermometers**

- **Optical fiber Thermometer**—Radiator optically coupled to a fiber-optic transmission system
- **Temperature sensor**: Thin, single-crystal aluminum oxide (sapphire) fiber
- **Absence of electrical signal**: Immunity from electromagnetic and radio-frequency interference
- **Superior frequency response and sensitivity**
- **Operating range**: 300-1900°C
- **Resolution**: 0.1 mK

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**Optical Fiber Thermometer**

- (1) blackbody cavity
- (2) sapphire fiber
- (3) protective coating

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**Disappearing filament optical pyrometer**