Chapter 10: Thermal Properties of Matter

Comprehensive Study Notes

Class 11 Physics - NCERT Based

EXAM SPRINT - Complete Coverage for JEE and NEET Examinations

10.1 INTRODUCTION

What is Heat and Temperature?

Definition:

- **Temperature**: Measure of 'hotness' of a body - relative indication of thermal state
- **Heat**: Form of energy transferred between systems due to temperature difference

Key Characteristics:

- Temperature is relative (like tall/short)
- Heat flows from higher to lower temperature
- Both bodies reach thermal equilibrium eventually
- Heat transfer continues until temperature difference vanishes

Units:

- Heat: Joule (J) - SI unit
- Temperature: Kelvin (K) - SI unit, Celsius (°C) - commonly used

Physical Understanding:

- Touch sensation unreliable for scientific measurement

- Hot utensil = high temperature
- Ice cube = low temperature
- Temperature difference drives heat transfer

10.2 TEMPERATURE AND HEAT

Temperature Fundamentals

Relative Nature:

- No absolute hot or cold
- Always comparison between objects
- Higher temperature object = hotter
- Scientific measurement requires instruments

Heat Transfer Process:

- Glass of ice water warms up on hot day
- Cup of hot tea cools down at room temperature
- Energy flows until thermal equilibrium
- Direction: hot → cold always

Energy Transfer Definition: Heat = Energy transferred between systems due to temperature difference

10.3 MEASUREMENT OF TEMPERATURE

Thermometer Principles

Physical Properties Used:

- Volume expansion of liquids (mercury, alcohol)

- Electrical resistance changes
- Thermocouple voltage
- Gas pressure changes

Calibration Requirements:

- Two fixed reference points needed
- Standard scale establishment
- Numerical value assignment
- Reproducible measurements

Fixed Points:

- **Ice Point**: Pure water freezing temperature
- **Steam Point**: Pure water boiling temperature
- Both at standard atmospheric pressure

Temperature Scales

Celsius Scale:

- Ice point: 0°C
- Steam point: 100°C
- 100 equal divisions

Fahrenheit Scale:

- Ice point: 32°F
- Steam point: 212°F
- 180 equal divisions

Conversion Formula:

$$(t_F - 32)/180 = t_C/100$$

or

$$t_F = (9/5)t_C + 32$$

10.4 IDEAL-GAS EQUATION AND ABSOLUTE TEMPERATURE

Gas Laws Foundation

Boyle's Law: PV = constant (at constant T) **Charles' Law**: V/T = constant (at constant P)

Combined Gas Law: PV/T = constant

Ideal Gas Equation

Standard Form:

$$PV = \mu RT$$

where:

- μ = number of moles
- R = universal gas constant = 8.31 J mol^{-1} K^{-1}
- T = absolute temperature in Kelvin

Gas Thermometer:

- Uses gas pressure changes

- More reliable than liquid thermometers
- Same reading regardless of gas type
- Foundation for absolute temperature scale

Absolute Temperature Scale

Absolute Zero:

- Temperature: -273.15°C
- Theoretical minimum temperature
- Gas pressure would reach zero
- Foundation of Kelvin scale

Kelvin Scale:

- Absolute temperature scale
- 0 K = -273.15°C
- Same unit size as Celsius
- **Conversion**: $T = t_C + 273.15$

10.5 THERMAL EXPANSION

Expansion Fundamentals

Universal Behavior: Most substances expand when heated, contract when cooled

Types of Expansion:

1. **Linear Expansion**: Change in length
2. **Area Expansion**: Change in surface area
3. **Volume Expansion**: Change in volume

Linear Expansion

Mathematical Relation:

$$\Delta l/l = \alpha l \, \Delta T$$

where:

- αl = coefficient of linear expansion (K^{-1})
- Δl = change in length
- l = original length
- ΔT = temperature change

Typical Values ($\times 10^{-5}$ K^{-1}):

- Aluminum: 2.5
- Copper: 1.7
- Iron: 1.2
- Glass (pyrex): 0.32

Area and Volume Expansion

Area Expansion:

$$\Delta A/A = 2\alpha l \, \Delta T$$

Volume Expansion:

$$\Delta V/V = 3\alpha l \, \Delta T = \alpha V \, \Delta T$$

Relationship: $\alpha V = 3\alpha l$

Special Cases

Water Anomaly:

- Contracts between 0°C and 4°C
- Maximum density at 4°C
- Important for aquatic life survival
- Lakes freeze from top down

Gases:

- Much larger expansion than solids/liquids
- For ideal gas: $\alpha V = 1/T$
- At 0°C: $\alpha V = 3.7 \times 10^{-3}\ K^{-1}$

Thermal Stress

Definition: Stress developed when thermal expansion is prevented

Formula:

$$\text{Thermal Stress} = Y \times \alpha l \times \Delta T$$

where Y = Young's modulus

Applications: Railway track expansion joints, building design

10.6 SPECIFIC HEAT CAPACITY

Heat Capacity Concepts

Heat Capacity (S):

$$S = \Delta Q/\Delta T$$

- Amount of heat needed to change temperature by 1 unit
- Depends on mass of substance

Specific Heat Capacity (s):

$$s = \Delta Q/(m \times \Delta T)$$

- Heat per unit mass for unit temperature change
- Characteristic property of material
- SI unit: $J\ kg^{-1}\ K^{-1}$

Molar Specific Heat (C):

$$C = \Delta Q/(\mu \times \Delta T)$$

- Heat per mole for unit temperature change
- SI unit: $J\ mol^{-1}\ K^{-1}$

Key Values

High Specific Heat:

- Water: 4186 $J\ kg^{-1}\ K^{-1}$

- Alcohol: 2400 J kg^{-1} K^{-1}

Low Specific Heat:

- Mercury: 140 J kg^{-1} K^{-1}
- Lead: 127.7 J kg^{-1} K^{-1}

Applications of High Specific Heat:

- Water as coolant in radiators
- Water as heater in hot water bags
- Coastal climate moderation
- Desert temperature variations

Gas Specific Heats

Two Types:

- Cp: At constant pressure
- Cv: At constant volume
- Cp > Cv always

10.7 CALORIMETRY

Calorimetry Principle

Fundamental Law: Heat lost by hot body = Heat gained by cold body

Calorimeter Design:

- Metallic vessel with stirrer
- Heat insulating material

- Thermometer arrangement
- Minimizes heat loss to surroundings

Mathematical Expression:

```
mhot × shot × ΔThot = mcold × scold × ΔTcold
```

Problem-Solving Strategy

1. Identify hot and cold substances
2. Apply conservation of energy
3. Account for calorimeter heat capacity
4. Use appropriate specific heat values
5. Solve for unknown quantity

10.8 CHANGE OF STATE

Phase Changes

Types:

- **Melting/Fusion**: Solid → Liquid
- **Vaporization**: Liquid → Gas
- **Sublimation**: Solid → Gas (direct)
- **Freezing**: Liquid → Solid
- **Condensation**: Gas → Liquid

Characteristics:

- Temperature remains constant during phase change

- Heat energy continues to be supplied/removed
- Both phases coexist in equilibrium

Latent Heat

Definition: Heat per unit mass required for phase change at constant temperature

Mathematical Form:

```
Q = m × L
```

where L = latent heat

Types:

- **Lf**: Latent heat of fusion (solid → liquid)
- **Lv**: Latent heat of vaporization (liquid → gas)

Important Values:

- Water: Lf = 3.33×10^5 J kg^{-1}
- Water: Lv = 22.6×10^5 J kg^{-1}

Why Steam Burns More: Steam at 100°C contains 22.6×10^5 J kg^{-1} more energy than water at 100°C

Phase Diagrams

Triple Point: Temperature and pressure where all three phases coexist

- Water triple point: 273.16 K, 6.11×10^{-3} Pa
- Used as fundamental temperature reference

Curves:

- **Fusion curve**: Solid-liquid boundary
- **Vaporization curve**: Liquid-gas boundary
- **Sublimation curve**: Solid-gas boundary

Pressure Effects

Boiling Point:

- Increases with pressure increase
- Decreases with pressure decrease
- Explains cooking difficulties at high altitudes
- Pressure cooker principle

Regelation: Ice melts under pressure, refreezes when pressure removed

10.9 HEAT TRANSFER

Three Modes of Heat Transfer

10.9.1 Conduction

Mechanism: Heat transfer through molecular collisions without bulk motion

Fourier's Law:

```
H = KA(TC - TD)/L
```

where:

- H = rate of heat flow

- K = thermal conductivity
- A = cross-sectional area
- L = length
- (TC - TD) = temperature difference

Thermal Conductivity Values (W m^{-1} K^{-1}): **Good Conductors**:

- Silver: 406
- Copper: 385
- Aluminum: 205

Poor Conductors (Insulators):

- Wood: 0.12
- Glass wool: 0.04
- Air: 0.024

Applications:

- Cooking utensil design
- Building insulation
- Heat sink design

10.9.2 Convection

Mechanism: Heat transfer by bulk motion of fluids

Types:

1. **Natural Convection**: Density differences drive motion
2. **Forced Convection**: External force drives motion

Examples:

- Sea breeze formation
- Trade winds
- Home heating systems
- Blood circulation

Sea Breeze Mechanism:

- Day: Land heats faster than water
- Hot air rises over land
- Cool air from sea moves inland
- Night: Process reverses

10.9.3 Radiation

Mechanism: Heat transfer via electromagnetic waves

Characteristics:

- No medium required
- Travels at speed of light
- All bodies emit thermal radiation
- Amount depends on temperature and surface properties

Stefan-Boltzmann Law:

$$H = \sigma A T^4 \text{ (perfect radiator)}$$
$$H = e\sigma A T^4 \text{ (real body)}$$

where:

- $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}
- e = emissivity ($0 \le e \le 1$)
- T = absolute temperature

Wien's Displacement Law:

$$\lambda_m T = \text{constant} = 2.9 \times 10^{-3} \text{ m K}$$

- Peak wavelength shifts with temperature
- Used to determine star temperatures

Net Radiation:

$$H = e\sigma A(T^4 - T_s^4)$$

Applications:

- Solar energy
- Thermal imaging
- Infrared heaters
- Spacecraft thermal control

10.10 NEWTON'S LAW OF COOLING

Cooling Law Statement

Mathematical Form:

$$-dQ/dt = k(T_2 - T_1)$$

where:

- T_2 = body temperature
- T_1 = surrounding temperature
- k = positive constant

Conditions:

- Small temperature differences
- Combined effect of conduction, convection, radiation
- Constant surroundings temperature

Derivation and Solution

Starting from heat capacity:

$$dQ = ms\, dT_2$$

Rate equation:

$$-ms(dT_2/dt) = k(T_2 - T_1)$$

Solution:

$$T_2 = T_1 + C'e^{(-Kt)}$$

where $K = k/(ms)$

Verification: Plot $\ln(T_2 - T_1)$ vs t gives straight line with slope -K

Applications

- Forensic science (time of death)
- Food cooling calculations
- Industrial process control
- HVAC system design

SUMMARY - KEY CONCEPTS

1. Temperature and Heat Fundamentals

- Temperature = measure of hotness (relative quantity)
- Heat = energy transfer due to temperature difference
- SI units: Temperature (K), Heat (J)

2. Temperature Measurement

- Thermometric properties vary with temperature
- Fixed points needed for scale calibration
- Celsius and Fahrenheit scales
- Conversion: $t_F = (9/5)t_C + 32$

3. Absolute Temperature

- Ideal gas equation: $PV = \mu RT$
- Absolute zero: -273.15°C = 0 K
- Kelvin scale: $T = t_C + 273.15$

4. Thermal Expansion

- Linear: $\Delta l = \alpha l\ l\ \Delta T$
- Volume: $\Delta V = \alpha V\ V\ \Delta T = 3\alpha l\ V\ \Delta T$
- Water anomaly: maximum density at 4°C
- Thermal stress when expansion prevented

5. Heat Capacity

- Specific heat capacity: $s = \Delta Q/(m\Delta T)$
- Water has highest specific heat among common substances
- Explains coastal climate moderation

6. Calorimetry

- Heat lost = Heat gained (isolated system)
- Accounts for calorimeter heat capacity
- Conservation of energy principle

7. Phase Changes

- Temperature constant during phase change
- Latent heat: $Q = mL$
- Fusion, vaporization, sublimation
- Phase diagrams and triple point

8. Heat Transfer Modes

- **Conduction**: $H = KA(\Delta T)/L$
- **Convection**: Bulk fluid motion
- **Radiation**: $H = e\sigma AT^4$

9. Newton's Law of Cooling

- Rate ∝ temperature difference
- Valid for small temperature differences
- Exponential cooling: $T = T_1 + C'e^{(-Kt)}$

POINTS TO PONDER - CRITICAL INSIGHTS

1. Temperature Scale Choice

- Absolute zero is fundamental physical limit
- Kelvin scale eliminates negative temperatures
- Triple point provides precise reference

2. Heat vs Temperature

- Adding heat doesn't always increase temperature
- Phase changes involve latent heat
- Temperature measures average kinetic energy

3. Thermal Expansion Applications

- Railway tracks need expansion joints
- Bimetallic strips in thermostats
- Fit tight lids by heating
- Glass cracking due to uneven expansion

4. Specific Heat Significance

- High specific heat = thermal stability
- Water's role in climate regulation

- Material selection for thermal applications

5. Heat Transfer Efficiency

- Conduction needs material contact
- Convection needs fluid medium
- Radiation works in vacuum
- Combined effects in real situations

JEE/NEET SPECIFIC IMPORTANT POINTS

High-Yield Topics

1. Thermal Expansion

Master these relationships:

- Linear, area, volume expansion coefficients
- Thermal stress calculations
- Bi-metallic strip behavior
- Applications in daily life

2. Calorimetry Problems

Key skills:

- Heat balance equations
- Multi-component systems
- Phase change calculations
- Mixture temperature determination

3. Heat Transfer

Applications:

- Conduction in composite rods
- Radiation from hot bodies
- Convection current formation
- Newton's law of cooling

4. Phase Changes

Standard scenarios:

- Ice melting calculations
- Steam condensation problems
- Latent heat determinations
- P-T diagram interpretation

Common Question Types

1. Direct Application Problems

- Thermal expansion calculations
- Specific heat determinations
- Heat transfer rate problems
- Temperature conversions

2. Calorimetry Problems

- Mixture problems
- Metal cooling in water

- Ice melting calculations
- Heat capacity measurements

3. Heat Transfer Analysis

- Conduction through composite materials
- Radiation from bodies
- Cooling rate calculations
- Thermal resistance problems

4. Conceptual Understanding

- Phase diagram interpretation
- Heat capacity comparisons
- Thermal property explanations
- Real-world applications

Problem-Solving Strategy

1. Setup Phase

- Identify type of thermal process
- List given and required quantities
- Choose appropriate equations
- Set up proper sign conventions

2. Calculation Phase

- Apply conservation of energy
- Account for all heat transfers

- Include phase changes if present
- Substitute values carefully

3. Verification Phase

- Check dimensional consistency
- Verify physical reasonableness
- Consider limiting cases
- Review calculation steps

MEMORY AIDS AND MNEMONICS

Thermal Expansion

"LAV 123":

- L: Linear (αl)
- A: Area (2αl)
- V: Volume (3αl)

Heat Transfer Modes

"CCR - Call Convection Radiation":

- Conduction (contact required)
- Convection (currents in fluids)
- Radiation (no medium needed)

Calorimetry

"Heat Lost = Heat Gained": Always apply energy conservation Account for all components

Phase Changes

"TLC - Temperature Level Constant": Temperature remains constant during phase changes Latent heat involved

PRACTICE PROBLEMS FOR JEE/NEET

Level 1: Basic Application

Problem 1: A steel rod of length 1m at 20°C is heated to 100°C. Find the increase in length. (αsteel = 1.2×10^{-5} K^{-1})

Solution: $\Delta l = \alpha l \, l \, \Delta T = 1.2 \times 10^{-5} \times 1 \times 80 = 9.6 \times 10^{-4}$ m

Problem 2: 100g of water at 80°C is mixed with 200g of water at 20°C. Find final temperature.

Solution: Heat lost by hot water = Heat gained by cold water 100 × 4.18 × (80 - T) = 200 × 4.18 × (T - 20) T = 40°C

Level 2: Intermediate

Problem 3: An iron ball at 100°C is dropped into 1kg of water at 20°C. Final temperature is 25°C. Find mass of iron ball. (siron = 450 J kg^{-1} K^{-1})

Solution: Heat lost by iron = Heat gained by water m × 450 × (100-25) = 1 × 4180 × (25-20) m = 0.62 kg

Level 3: Advanced

Problem 4: A composite rod with steel and copper sections is heated. Find temperature distribution and heat flow rate.

Solution: Requires thermal conductivity analysis and steady-state heat flow principles.

ADVANCED TOPICS FOR JEE

1. Composite Heat Transfer

- Series and parallel thermal resistance
- Interface temperature calculations
- Multi-layer insulation systems

2. Radiation Heat Transfer

- Stefan-Boltzmann law applications
- Emissivity effects
- Net radiation exchange
- Wien's displacement law

3. Phase Diagram Analysis

- Critical point understanding
- Phase boundary equations
- Clausius-Clapeyron equation

4. Non-Steady State Problems

- Transient heat conduction
- Lumped capacity method
- Time-dependent solutions

ERROR ANALYSIS IN THERMAL PHYSICS

Common Mistakes

1. Sign Convention Errors

- Heat gained vs lost confusion
- Temperature difference signs
- Direction of heat flow

2. Unit Conversion Problems

- °C vs K confusion
- Energy unit mixing
- Area/volume calculations

3. Phase Change Oversight

- Ignoring latent heat
- Temperature change during phase transition
- Multi-step process analysis

Prevention Strategies

1. Always define positive directions clearly
2. Check units at each calculation step
3. Draw energy flow diagrams
4. Verify answers using limiting cases

EXPERIMENTAL CONNECTIONS

1. Historical Experiments

- Joule's mechanical equivalent of heat
- Black's calorimetry studies
- Stefan-Boltzmann radiation law

2. Modern Applications

- Thermal imaging technology
- Solar panel efficiency
- Building energy management
- Spacecraft thermal control

3. Laboratory Techniques

- Calorimeter design principles
- Temperature measurement accuracy
- Heat transfer coefficient determination

EXAM SPRINT SUMMARY

Master Thermal Properties through focused study of:

- Temperature scales and conversion
- Thermal expansion applications
- Heat capacity and calorimetry
- Phase changes and latent heat
- Heat transfer mechanisms
- Newton's law of cooling

Regular practice of numerical problems and conceptual understanding essential for JEE/NEET success.

Source: NCERT Physics Class 11, Chapter 10 - Comprehensive coverage for competitive exam preparation