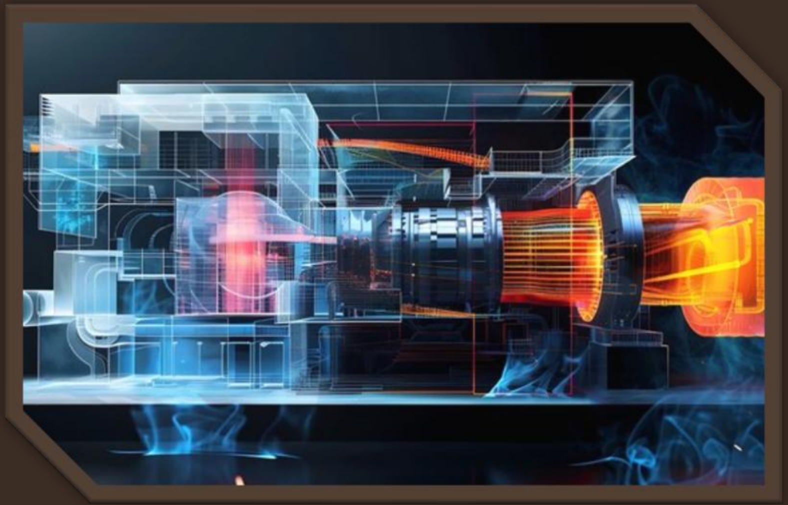

Thermodynamics

Prepared By

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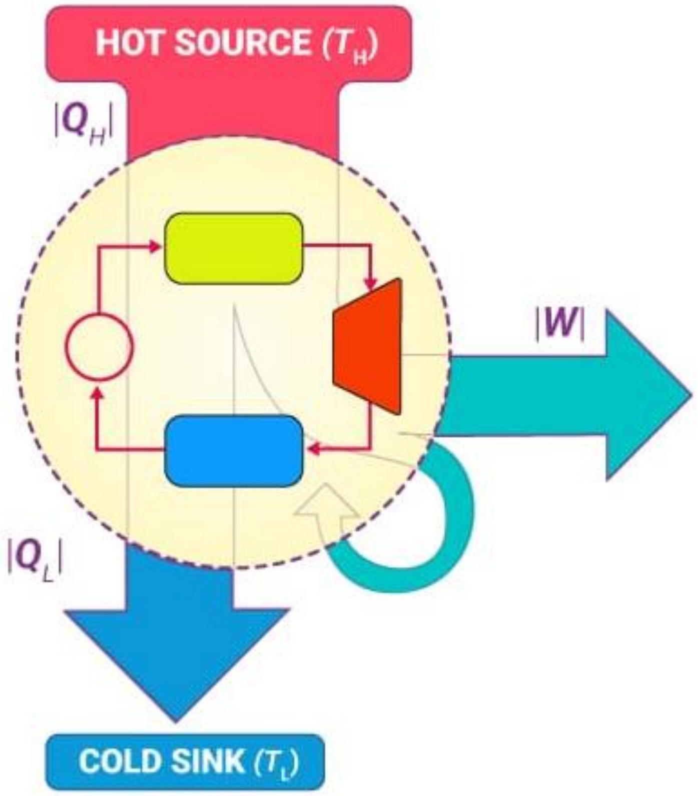
2024

Definition of Thermodynamics

- **Thermodynamics** is the branch of physics that deals with the relationships between heat, work, temperature, and energy. It describes how energy is transferred and transformed in physical systems and provides the principles governing the behavior of matter under various conditions.

- The term originates from the Greek words "therme," meaning heat, and "dynamics," meaning power or force, indicating its focus on energy transformations and their effects on matter.

- There are two types of thermodynamics based on the study of particles: **classical thermodynamics**, which focuses on macroscopic properties, and **statistical thermodynamics**, which studies the behavior of individual particles and their impact on macroscopic properties.



Application Areas of Thermodynamics

- Thermodynamics has a wide range of applications across various fields. Here are some key areas:
  - **Engineering**
    - Mechanical Engineering: Design of engines, turbines, and refrigeration systems.
    - Chemical Engineering: Process design for chemical reactions, separation processes, and heat exchangers.
  - **Chemistry**
    - Reaction Thermodynamics: Understanding energy changes in chemical reactions and predicting reaction spontaneity.
    - Phase Equilibria: Studying phase transitions and the behavior of mixtures.
  - **Physics**
    - Statistical Mechanics: Linking macroscopic thermodynamic properties to microscopic behavior.
    - Condensed Matter Physics: Investigating the properties of solids and liquids.

Cont...

- **Materials Science**
  - Material Properties: Understanding how thermal properties affect material performance and stability.
  - Nanotechnology: Investigating thermodynamic principles at the nanoscale.
- **Astrophysics**
  - Stellar Processes: Analyzing thermodynamic processes in stars and other celestial bodies.
  - Cosmology: Understanding the thermodynamic history of the universe.
- **Renewable Energy**
  - Solar Energy: Evaluating thermodynamic efficiency in solar collectors and photovoltaic systems.
  - Bioenergy: Analyzing energy production from biomass and waste through thermochemical processes.
  - Wind Energy: Wind turbines convert the kinetic energy of wind into mechanical energy and then into electrical energy.

Cont…

- **Environmental Science**
  - Energy Systems: Analyzing energy conversion processes and sustainability.
  - Climate Studies: Understanding heat transfer and energy balance in the atmosphere.
- **Biology**
  - Biothermodynamics: Studying energy transformations in biological systems, such as metabolism.
  - Pharmacology: Designing drugs based on thermodynamic principles.

Cont…

(a) Refrigerator

(b) Boats

(c) Aircraft and spacecraft

(d) Power plants

(e) Human body

(f) Cars

(g) Wind turbines

(h) Food processing

(i) A piping network in an industrial facility.

Some application areas of thermodynamics.

Importance of Dimensions and Units

- Dimensions and units are fundamental concepts in science and engineering. Their importance can be summarized as follows:
  - **Standardization**
    - Consistency: Dimensions and units provide a standard way to measure and communicate physical quantities, ensuring that everyone interprets measurements the same way.
    - Global Communication: Standard units (like SI units) facilitate international collaboration and understanding in scientific and engineering fields.
  - **Clarity**
    - Precision: Using specific units helps eliminate ambiguity in measurements, making it clear what is being measured (e.g., length in meters vs. kilometers).
    - Interpretation: Clear definitions of dimensions ensure that calculations and results can be easily understood and replicated.

Cont…

- **Dimensional Analysis**
  - Validation of Equations: Dimensional analysis allows for checking the correctness of equations and relationships between different physical quantities.
  - Conversion: It aids in converting between different units, which is crucial in calculations involving multiple systems of measurement.
- **Performance Evaluation**
  - Quantitative Assessment: Dimensions and units enable the quantitative evaluation of performance in engineering systems (e.g., efficiency, power, and energy).
  - Design Specifications: They are essential for specifying parameters in design, manufacturing, and testing of materials and products.
- **Scientific Research**
  - Measurement and Experimentation: Accurate dimensions and units are critical in experimental design, data collection, and analysis, influencing the validity of research findings.
  - Comparative Studies: They enable comparison of results across different studies, facilitating the advancement of knowledge.

Cont…

- **Safety and Compliance**

  - Regulations: Many industries have safety standards and regulations that are defined in terms of specific units and dimensions, ensuring safety in design and operation.

  - Quality Control: Maintaining consistent units in measurements is crucial for quality assurance in manufacturing and production processes.

Cont…

❖ Dimensions

- **Dimensions** are fundamental properties used to describe physical quantities and their relationships in the natural world. They represent the nature of a measurement and indicate what physical phenomenon is being observed. Common dimensions include:
  - **Length (L):** The measure of distance (e.g., meters, centimeters).
  - **Mass (M):** The measure of the amount of matter in an object (e.g., kilograms, grams).
  - **Time (T):** The measure of the duration of events (e.g., seconds, minutes).
  - **Temperature (Θ):** The measure of thermal energy (e.g., Kelvin, Celsius).
  - **Electric Current (I):** The flow of electric charge (e.g., Amperes).
  - **Amount of Substance (N):** The measure of the quantity of entities (e.g., moles).
  - **Luminous Intensity (J):** The measure of the perceived power of light (e.g., candelas).
- Dimensions can be categorized into **fundamental dimensions**, which are independent and cannot be derived from others, and **derived dimensions**, which are formed by combining fundamental dimensions (e.g., velocity, force).

Cont…

❖ Units

- **Units** are standardized quantities used to measure and express physical properties. They provide a consistent framework for quantifying various attributes, allowing for clear communication, comparison, and calculation in science, engineering, and everyday life.

- Fundamental units that describe basic physical quantities. For example, in the International System of Units (SI):
  - Length: Meter (m)
  - Mass: Kilogram (kg)
  - Time: Second (s)

- Units that are derived from base units through mathematical relationships. For example:
  - Velocity: Meters per second (m/s)
  - Force: Newton (N), which is $kg.m/s^2$

- Units are organized into systems, such as the SI system, CGS (Centimeter-Gram-Second), British (Imperial), and US customary units. Each system has its own base and derived units.

Cont…

❖ Dimensional Homogeneity

- **Dimensionally homogeneous** refers to a property of equations or expressions in which all terms have the same dimensional units. This concept is crucial in physics and engineering because it ensures that mathematical relationships are physically meaningful.

- An equation is dimensionally homogeneous if every term in the equation can be expressed in terms of the same fundamental dimensions. For example, in an equation involving force, energy, and distance, all terms should be expressible in terms of mass, length, and time.

- Example:

  Consider the equation for kinetic energy:

$$E_k = \frac{1}{2} m v^2$$

  Here, E_k (energy) has dimensions of $[ML^2T^{-2}]$, m (mass) has dimensions of $[M]$, and v (velocity) has dimensions of $[LT^{-1}]$.

  The equation can be expressed as:

$$\frac{1}{2}[M][LT^{-1}]^2 = \frac{1}{2}[M][L^2T^{-2}]$$

  Hence both sides have the same dimensions, confirming that the equation is dimensionally homogeneous.

Cont…

Prefixes

- **Prefixes** are affixes added to the beginning of a unit of measurement to indicate a specific multiple or fraction of that unit. They provide a convenient way to express large or small quantities without the need to write out extensive values.

- An equation is dimensionally homogeneous if every term in the equation can be expressed in terms of the same fundamental dimensions. For example, in an equation involving force, energy, and distance, all terms should be expressible in terms of mass, length, and time.

Standard prefixes in SI units

Multiple	Prefix
10^{24}	yotta, Y
10^{21}	zetta, Z
10^{18}	exa, E
10^{15}	peta, P
10^{12}	tera, T
10^{9}	giga, G
10^{6}	mega, M
10^{3}	kilo, k
10^{2}	hecto, h
10^{1}	deka, da
10^{-1}	deci, d
10^{-2}	centi, c
10^{-3}	milli, m
10^{-6}	micro, μ
10^{-9}	nano, n
10^{-12}	pico, p
10^{-15}	femto, f
10^{-18}	atto, a
10^{-21}	zepto, z
10^{-24}	yocto, y

Cont…

- Prefixes are standardized in various unit systems, including the International System of Units (SI) and the CGS (Centimeter-Gram-Second) system, ensuring consistency in measurement.

- Each prefix corresponds to a specific power of ten, allowing for easy conversion between different scales. For example, the prefix "kilo-" means 10^3 (or 1,000), while "milli-" means 10^{-3} (or 0.001).

Cont…

- **Comprehensive Overview of Physical Quantities and Their Units Across Measurement Systems**

Quantity	Dimension	SI Unit	CGS Units	British Units	US Customary
Length	$[L]$	Meter (m)	Centimeter (cm)	Foot (ft), Inch (in), Mile (mi)	Foot (ft), Inch (in), Mile (mi), Yard (yd)
Mass	$[M]$	Kilogram (kg)	Gram (g)	Pound (lb), Ounce (oz)	Pound (lb), Ounce (oz)
Time	$[T]$	Second (s)	Second (s)	Minute (min), Hour (h)	Minute (min), Hour (h)
Temperature	[θ]	Kelvin (K)	Celsius (℃)	None	Fahrenheit (°F)
Electric Current	$[I]$	Ampere (A)	Abampere (abA)	None	None
Amount of Substance	$[N]$	Mole (mol)	None	None	None
Luminous Intensity	$[J]$	Candela (cd)	None	None	None
Force	$[ML^2T^{-2}]$	Newton (N)	Dyne (dyn)	Pound-force (lbf)	Pound-force (lbf)
Energy	$[ML^2T^{-2}]$	Joule (J)	Erg (erg)	British Thermal Unit (BTU), Calorie (cal)	British Thermal Unit (BTU), Calorie (cal)
Power	$[ML^2T^{-3}]$	Watt (W)	Watt (W)	Horsepower (hp)	Horsepower (hp)

Cont…

Pressure	$[ML^{-1}T^{-2}]$	Pascal (Pa)	Bar (bar)	Pounds per square inch (psi)	Pounds per square inch (psi)
Volume	$[L^3]$	Cubic meter (m^3)	Cubic centimeter (cm^3)	Gallon (gal), Quart (qt)	Gallon (gal), Quart (qt), Pint (pt), Fluid ounce (floz)
Density	$[ML^{-3}]$	kg/m^3	g/cm^3	lb/ft^3	lb/ft^3
Velocity	$[LT^{-1}]$	m/s	cm/s	(mph), ft/s	(mph), ft/s
Frequency	$[T^{-1}]$	Hertz (Hz)	Hertz (Hz)	None	None
Electric Charge	$[IT]$	Coulomb (C)	Franklin (Fr)	None	None
Electric Potential	$[ML^2T^{-3}I^{-1}]$	Volt (V)	Volt (V)	None	None
Magnetic Field	$[MT^{-2}I^{-1}]$	Tesla (T)	Gauss	None	None
Illuminance	$[JL^{-2}]$	Lux (lx)	Lux (lx)	None	None
Viscosity	$[ML^{-1}T^{-1}]$	Pascal-second (Pa.s)	Poise (P)	None	None

This table provides a comprehensive overview of various physical quantities, including their dimensions and units across different measurement systems.

Cont…

- **Unit Conversions from the SI System to Other Measurement Systems**

Quantity	Unit	Convert to	Conversion Factor
Length	1 *meter* (*m*)	100 centimeters (cm)	1 m = 100 cm
	1 *meter* (*m*)	39.37 inches (in)	1 m ≈ 39.37 in
	1 *kilometer* (*km*)	0.621371 miles (mi)	1 km ≈ 0.621371 mi
	1 *meter* (*m*)	3.28084 feet (ft)	1 m ≈ 3.28084 ft
Mass	1 *kilogram* (*kg*)	1000 grams (g)	1 kg = 1000 g
	1 *kilogram* (*kg*)	2.20462 pounds (lbm)	1 kg ≈ 2.20462 lbm
	1 *pound* (*lbm*)	0.453592 kilograms (kg)	1 lbm ≈ 0.453592 kg
Time	1 *hour* (*h*)	60 minutes (min)	1 h = 60 min
	1 *minute* (*min*)	60 seconds (s)	1 min = 60 s
Temperature	0 *degrees Celsius* (°*C*)	32 degrees Fahrenheit (°F)	°F = (°C × 9/5) + 32

Cont…

	0 degrees Celsius (°C)	273.15 Kelvin (K)	1 bar = 100,000 Pa
Pressure	1 *bar* (*bar*)	100,000 pascals (Pa)	1 bar = 100,000 Pa
	1 *bar* (*bar*)	14.5038 psi	1 bar ≈ 14.5038 psi
Volume	1 *liter* (*L*)	1000 *milliliters* (*mL*)	1 *L* = 1000 *mL*
	1 *liter* (*L*)	0.264172 *gallons* (*gal*)	1 *L* ≈ 0.264172 *gal*
Density	$1\ kg/m^3$	0.06243 pounds/foot³ (lb/ft³)	1 kg/m³ ≈ 0.06243 lb/ft³
Speed	1 *meter/second* (*m/s*)	3.6 kilometers/hour (km/h)	1 m/s = 3.6 km/h
	1 *meter/second* (*m/s*)	2.23694 miles/hour (mph)	1 m/s ≈ 2.23694 mph
Force	1 *newton* (*N*)	0.224809 pound-force (lbf)	1 N ≈ 0.224809 lbf
	1 *kilonewton* (*kN*)	224.809 pound-force (lbf)	1 kN ≈ 224.809 lbf
	1 *newton* (*N*)	100,000 dynes	1 N = 100,000 dyn
	1 *pound* − *force* (*lbf*)	4.44822 newtons (N)	1 lbf ≈ 4.44822 N
	1 *kilogram* − *force* (*kgf*)	9.80665 newtons (N)	1 kgf = 9.80665 N
Mass	1 *pound* (*lbm*)	0.453592 kilograms (kg)	1 lbm ≈ 0.453592 kg
Energy	1 *joule* (*J*)	0.239006 calories (cal)	1 J ≈ 0.239006 cal

This table provides a comprehensive overview of unit conversions between the SI system and various other measurement systems.

Cont…

Difference Between Force in SI and English Systems

- **SI System:** The standard unit of force is the **newton (N)**. One newton is defined as the force required to accelerate a one-kilogram mass by one meter per second squared ($1\ N = 1\ kg.m/s^2$).
- **English System:** The standard unit of force is the **pound-force (lbf)** . One pound-force is defined as the force required to accelerate a one-pound mass by 32.174 feet per second squared ($1\ lbf = 32.174\ lbm \cdot ft/s^2$).

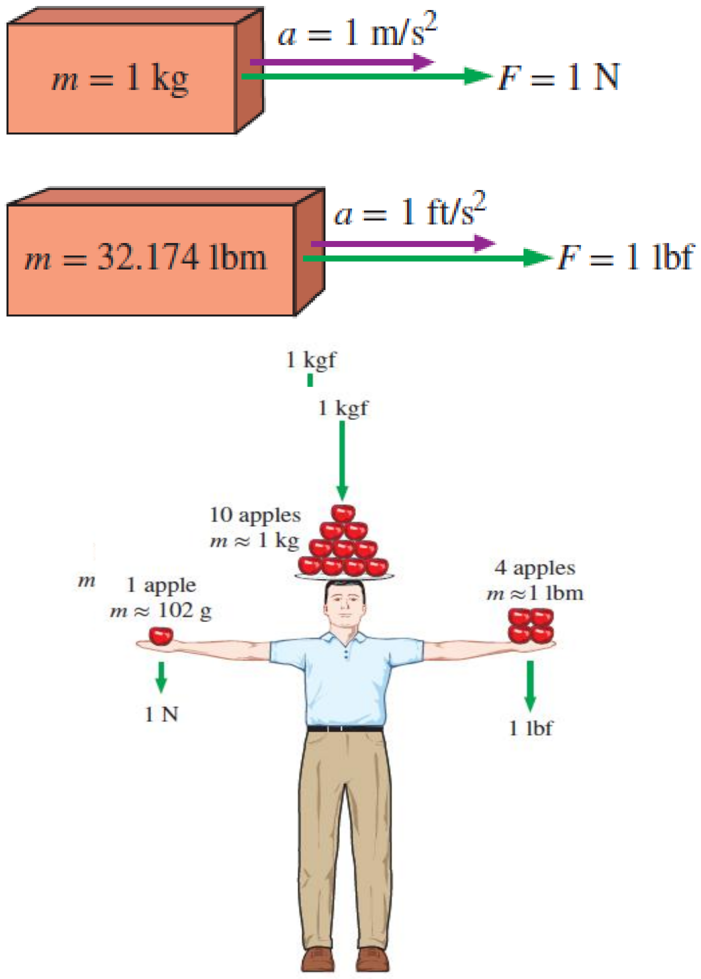
Definition of Kilogram-Force (kgf)

The kilogram-force (kgf) is a unit of force that represents the gravitational force exerted on a mass of one kilogram at standard gravity (approximately 9.80665 m/s²).

- 1 kgf is defined as the force exerted by gravity on a mass of 1 kg.

$$1\ kgf = 9.80665\ N$$

- The kilogram-force is often used in contexts where gravitational force is relevant, such as in engineering, physics, and material testing.



The relative magnitudes of the force units.

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- Example: Weight Calculation on Earth and Moon (SI to English Systems)

Calculate the weight of a human on both Earth and The moon. The individual has a mass of 70 kg.

Required:

1. Calculate the weight of the 70 kg individual on Earth. Use the gravitational acceleration on Earth $\left(g_E \approx 9.81\frac{m}{s^2}\right)$.
2. Calculate the weight of the same individual on the Moon. Use the gravitational acceleration on The Moon $\left(g_{Moon} \approx 1.625\frac{m}{s^2}\right)$.
3. Convert the weights from newtons (N) to pounds-force (lbf). Use the conversion factor $1\ N \approx 0.224809\ lbf$.

A body weighing 154.37 lbf on earth will weigh only 25.6 lbf on the moon.

Cont…

Solution:

1. $W_E = m \cdot g_E = 70\ \text{kg} \cdot 9.81\,\frac{\text{m}}{\text{s}^2} \approx 686.7\ \text{N}$

2. $W_{Moon} = m \cdot g_{Moon} = 70\ \text{kg} \cdot 1.625\,\frac{\text{m}}{\text{s}^2} \approx 113.75\ \text{N}$

3. Weight on Earth:

$$W_{E\,(lbf)} = W_E \cdot 0.224809 \approx 686.7\ N \cdot 0.224809 \approx 154.37\ lbf$$

Weight on Moon:

$$W_{Moon\,(lbf)} = W_{Moon} \cdot 0.224809 \approx 113.75\ N \cdot 0.224809 \approx 25.6\ lbf$$

A body weighing 154.37 lbf on earth will weigh only 25.6 lbf on the moon.

Cont…

- Example: Weight Calculation in English System and Conversion to SI System

Calculate the weight of a human who weighs 1 pounds (lbm) in the English system and convert that weight to the SI system (newtons).

Required:

1. Calculate the weight of the 1 lbm individual in the English system. Use the gravitational acceleration in the English system ($g_{English} \approx 32.174\ \frac{ft}{s^2}$).
2. Convert the weight of the 1 lbm individual from pounds-force (lbf) to newtons (N) to Use the conversion factor 1 $lbf \approx 4.44822\ N$.

Solution:

1. $\mathrm{W_{English}} = \mathrm{m} \cdot \mathrm{g_{English}} = 1\ lbm \cdot 32.174\ \frac{\mathrm{ft}}{\mathrm{s}^2} \approx 1\ lbf$
2. $\mathrm{W_{SI}} = \mathrm{W_{English}} \cdot 4.44822 \approx 1\ lbf \cdot 4.44822 \approx 4.44822\ \mathrm{N}$

A body weighing 1 lbf in English Unit System is equal to 4.44822 N in SI Unit System.

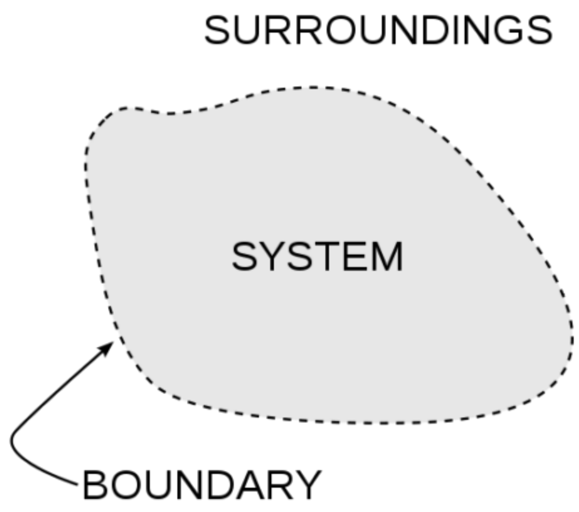
Systems, boundaries and surroundings

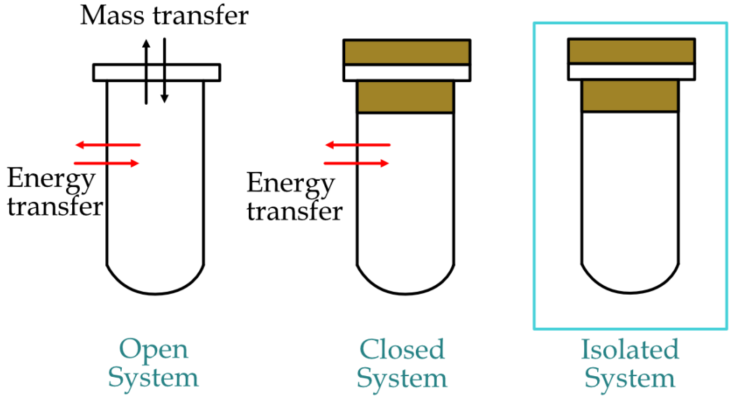
- **Systems**, **Boundaries**, and **Surroundings** are fundamental concepts in thermodynamics that help define and analyze energy interactions. A clear understanding of these components is essential for studying how energy is transferred and transformed in various processes.

Systems

A **system** is defined as a specific portion of the universe that is under consideration for analysis. It can be classified into several types:

- **Open System:** An open system can exchange both energy and matter with its surroundings. An example is a boiling pot of water where steam escapes, and heat is transferred to the water.
- **Closed System:** A closed system can exchange energy (heat and work) with its surroundings but not matter. For example, a sealed container of gas can transfer heat to its environment without allowing gas to escape.
- **Isolated System:** An isolated system can exchange neither energy nor matter with its surroundings. This type of system is theoretical and is used to simplify analysis. An example could be a perfectly insulated thermos that contains hot coffee.





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- Open, closed, and isolated systems can be analyzed in terms of both mass and volume characteristics. Here's how each type fits into those categories:

1. Open System
   - Mass:
     - **Variable Mass System:** An open system can exchange both mass and energy with its surroundings. The mass within the system can change over time (e.g., a boiling pot of water where steam escapes).
   - Volume:
     - **Variable Volume System:** An open system can also have a variable volume, especially in processes where the volume changes due to the influx or outflux of matter.
2. Closed System
   - Mass:
     - **Fixed Mass System:** A closed system can exchange energy (heat and work) but not mass with its surroundings. The total mass within the system remains constant (e.g., a sealed container of gas).
   - Volume:
     - **Variable Volume System or Fixed Volume System :** A closed system can either have a fixed volume (like a rigid container) or a variable volume (like a flexible bag) depending on the context. If the volume can change (as in a flexible bag), it could still be considered a closed system as long as no mass enters or leaves.

Cont…

3. Isolated System

- Mass:
  - **Fixed Mass System:** An isolated system cannot exchange mass or energy with its surroundings. The mass remains constant because there is no mass transfer (e.g., a perfectly insulated thermos).
- Volume:
  - **Fixed Volume System :** An isolated system typically has a fixed volume since it does not allow for any changes in mass or energy exchange.

System Type	Mass Type	Volume System
Open System	Variable Mass	Variable Volume
Closed System	Fixed Mass	Variable or Fixed Volume
Isolated System	Fixed Mass	Fixed Volume

This table provides a summary on systems categorize depending on mass and volume characteristics.

Cont…

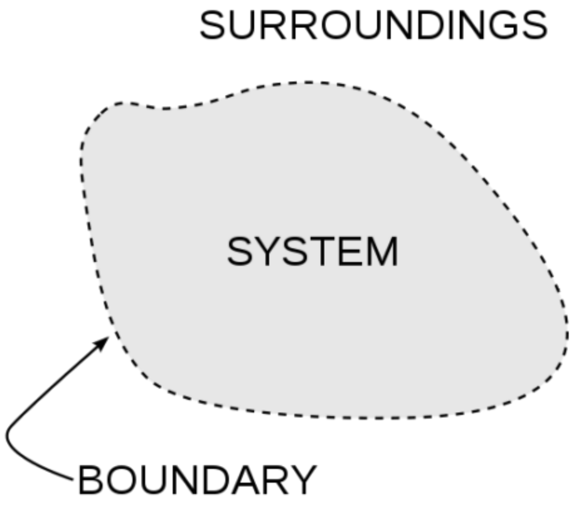
❖ Boundaries

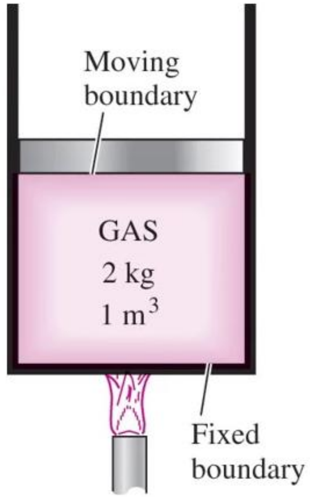
The boundary is the interface that separates the system from its surroundings. It can be:

- **Real boundary:** A physical barrier, such as the walls of a container.
- **Imaginary boundary:** A conceptual line that defines the limits of the system without a physical barrier. This is often used in theoretical models.

Boundaries can also be classified based on their ability to allow energy or matter transfer:

- **Fixed Boundary:** A boundary that does not change in position, such as the walls of a rigid container.
- **Movable Boundary:** A boundary that can change position, allowing for work to be done by the system, such as a piston in an engine.





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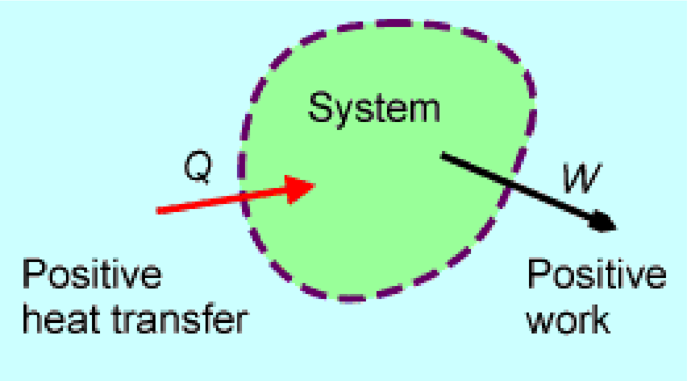
❖Surroundings

The **surroundings** refer to everything outside the system that can interact with it. This includes all matter and energy that can exchange with the system across its boundary. The surroundings can significantly affect the behavior and properties of the system.

❖ Interactions between systems, boundaries and surroundings

The interactions between the system, boundary, and surrounding can be described in terms of:

- **Heat Transfer:** The transfer of thermal energy between the system and surroundings due to temperature differences.
- **Work:** The energy transfer resulting from a force acting over a distance, which can occur through boundary movement (e.g., a piston moving).



❖Importance of systems, boundaries and surroundings in Thermodynamics

Understanding these concepts is critical for analyzing:

- **Thermodynamic Processes**: Such as isothermal, adiabatic, isochoric, and isobaric processes, which describe how systems change under various conditions.

Cont...

- **Energy Conservation:** Applying the first law of thermodynamics, which states that energy cannot be created or destroyed, only transformed, requires a clear definition of the system and its boundaries.
- **Equilibrium:** The state where there are no net changes in the system or its surroundings, which is essential for analyzing thermodynamic cycles.

❖Properties of systems

In thermodynamics, **systems** are defined by a set of properties that help describe their behavior and interactions. Here are some key properties of systems:

1. **Mass:** Represents the amount of matter within the system. It can be constant (in closed and isolated systems) or variable (in open systems).
2. **Volume:** Represents the space occupied by the system. It can be fixed (in closed systems) or variable (in open systems).

$$V = \frac{m}{\rho}$$

3. **Pressure:** The force exerted per unit area within the system. Pressure can change based on variations in volume or temperature.

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

Cont…

4. **Temperature:** Represents the average kinetic energy of the molecules within the system. Temperature is an indicator of the thermal energy state of the system.

$$PV = nR_{\mu}T$$

5. **Internal Energy:** The total energy contained within the system, including both kinetic and potential energy of the molecules. Internal energy changes with heat transfer or work done.

$$\Delta U = Q - W$$

6. **Heat:** A form of energy that transfers between the system and the surroundings due to a temperature difference.

$$Q = mc\Delta T$$

7. **Work:** The energy transferred as a result of applying a force on the system. Work can arise from changes in volume or pressure.

$$W = P\Delta V$$

8. **Entropy:** A measure of the disorder or randomness of a system. Entropy indicates the direction of natural processes and helps determine the system's tendency to change.

$$\Delta S = \frac{Q}{T}$$

Cont…

9. **Density**: the mass of a substance per unit volume. It indicates how much matter is contained within a specific volume of the substance.

$$\rho = \frac{m}{V}$$

10. **State:** Represents a set of specific values for the properties mentioned above (such as pressure, volume, and temperature) at a given moment. These values are used to describe the system's condition.

$$(P, V, T)$$

11. **Equilibrium:** A state where the system's properties do not change over time. It indicates no net flow of energy or matter.

❖ Extensive and Intensive Properties

- **Extensive Properties:** Extensive properties are those properties of a system that depend on the amount or size of the material present. They change when the size of the system changes, such as when mass or volume is increased or decreased.

- **Intensive Properties:** Intensive properties are those properties of a system that do not depend on the amount or size of the material present. They remain constant regardless of how much substance is present in the system.

Cont…

Classification of Properties

Property	Type	Symbol
Mass	Extensive	m
Volume	Extensive	V
Density	Intensive	$\rho = \frac{m}{V}$
Pressure	Intensive	P
Temperature	Intensive	T
Internal Energy	Extensive	U
Heat	Extensive	Q
Work	Extensive	W
Entropy	Extensive	S
State	Intensive	(P, V, T)

Cont…

Equilibrium	Intensive	eq (subscript)
Enthalpy	Extensive	H
Gibbs Free Energy	Extensive	G
Specific Heat	Intensive	c
Specific Volume	Intensive	$v = \frac{V}{m}$
Viscosity	Intensive	μ
Thermal Conductivity	Intensive	k
Refractive Index	Intensive	n

This table provides the classification of the key properties of thermodynamic systems.

Cont...

❖Equilibrium and State

In thermodynamics, equilibrium and state are fundamental concepts that describe the condition and behavior of a system. Here's a detailed explanation of each:

- **Equilibrium**

  Equilibrium refers to a condition where a system's properties remain constant over time, and there are no net changes occurring within the system or between the system and its surroundings.

  Types of Equilibrium:

  1. **Thermal Equilibrium:** Occurs when two systems in thermal contact reach the same temperature. There is no heat transfer between them.
  2. **Mechanical Equilibrium:** Exists when there are no unbalanced forces acting on a system. For example, the pressure is uniform throughout the system, and there is no net flow of matter.
  3. **Chemical Equilibrium:** Achieved when the rates of the forward and reverse chemical reactions are equal, leading to no net change in the concentrations of reactants and products.
  4. **Phase Equilibrium**: Occurs when different phases (solid, liquid, gas) of a substance coexist at equilibrium. Example: Ice and water in a sealed container at 0°C.

Cont…

Characteristics of Equilibrium:

- **Stability:** A system in equilibrium is stable and will not change unless acted upon by an external force or change in conditions.
- **Uniformity:** Properties such as pressure, temperature, and density are uniform throughout the system.

- **State:** The state of a thermodynamic system is defined by a set of properties that describe its condition at a specific moment in time. These properties can include pressure, volume, temperature, mass, and chemical composition.

Key Aspects of State:

1. **State Variables:** These are properties used to describe the state of the system. Common state variables include:
   - Pressure (P)
   - Volume (V)
   - Temperature (T)

Cont…

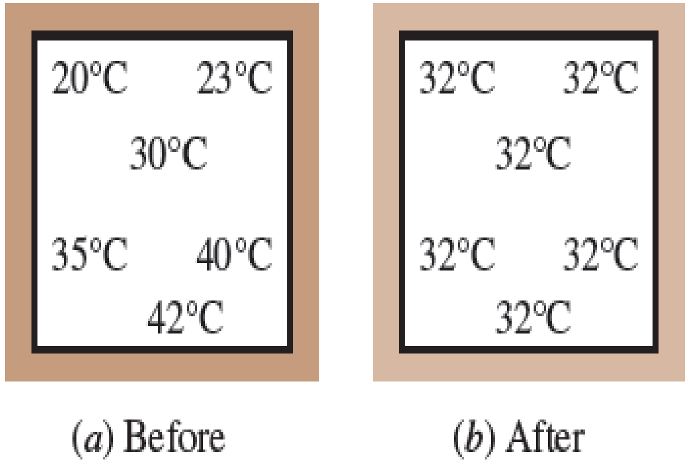
- Internal Energy (U)
- Enthalpy (H)
- Entropy (S)

2. **State Functions:** Properties that depend only on the current state of the system, not on how the system reached that state. For example, internal energy is a state function.

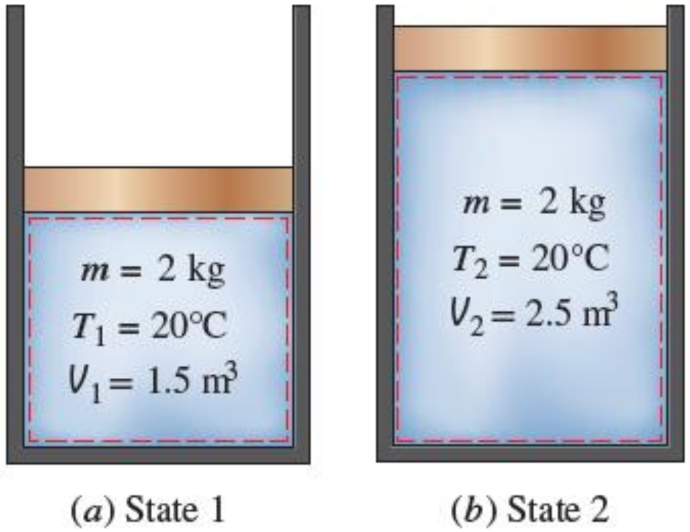
Cont…

3. **Equilibrium State:** When a system is at equilibrium, it is in a specific state where all state variables are constant over time.

4. **Changes in State:** When a system undergoes a process (e.g., heating, cooling, expansion, or compression), it transitions from one state to another. The path taken during this transition may involve changes in various state variables.



A closed system reaching thermal equilibrium.



A system at two different states.

Cont…

Specific Volume and Density

Specific volume and **density** are two important properties in thermodynamics that describe the relationship between the volume of a substance and its mass. Here's a detailed explanation of both, along with their relations:

1. **Specific Volume**

Specific volume is defined as the volume occupied by a unit mass of a substance. It is an intensive property.

$$v = \frac{V}{m}$$

where:

v = specific volume (usually expressed in cubic meter per kilogram, m^3/kg).

V = total volume of the substance (m^3).

m = mass of the substance (kg).

Cont…

2. **Density**

Density is defined as the mass per unit volume of a substance. It is also an intensive property.

$$\rho = \frac{m}{V}$$

where:

ρ = density (usually expressed in kilogram per cubic meter, kg /m³).

m = mass of the substance (kg).

V = total volume of the substance (m³).

❖ **Relationship Between Specific Volume and Density**

From the definitions above, we can derive a direct relationship between specific volume and density:

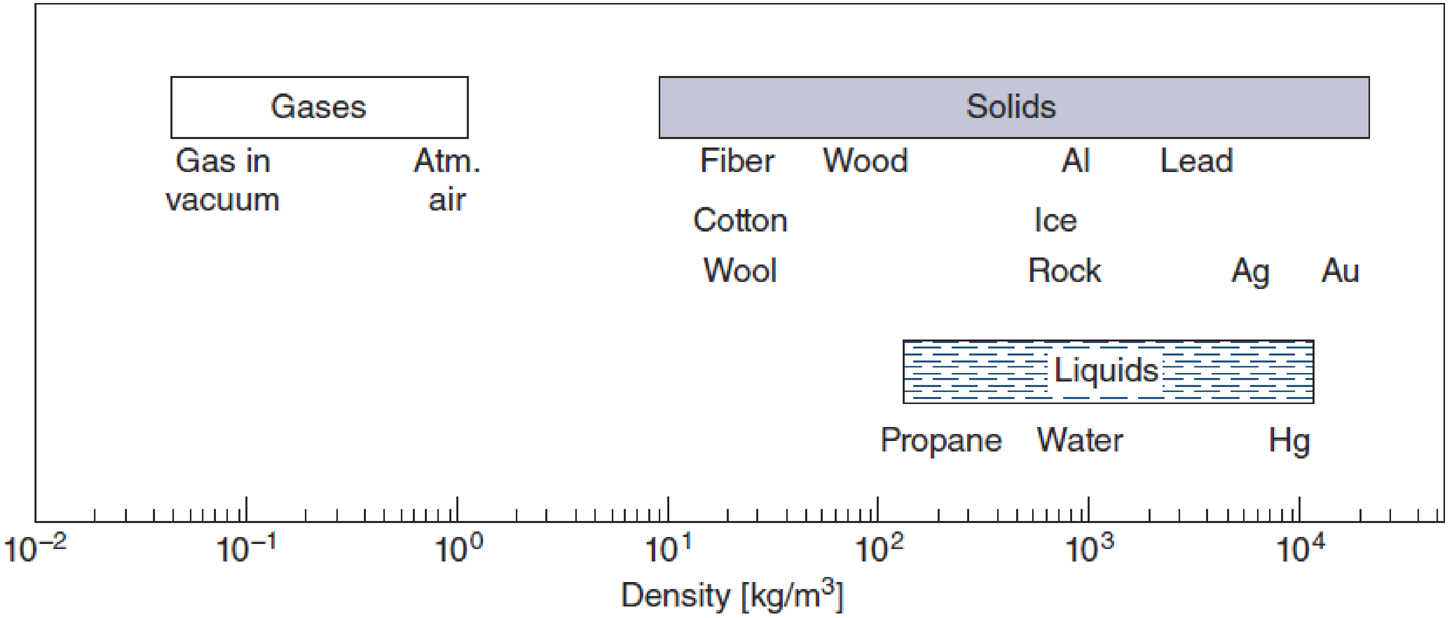
$$v = \frac{1}{\rho}$$

or equivalently,

$$\rho = \frac{1}{v}$$

Cont…

- Both properties are crucial for understanding the behavior of substances in thermodynamic processes, particularly in applications involving gases and liquids.
- **Specific Volume** is particularly important in the analysis of steam tables, refrigerants, and gas mixtures.
- **Density** is often used in calculations related to buoyancy, pressure, and fluid dynamics.



Density of common substances.

Cont…

- Example

A container with a capacity of 1 cubic meter (m^3) is filled with the following materials:

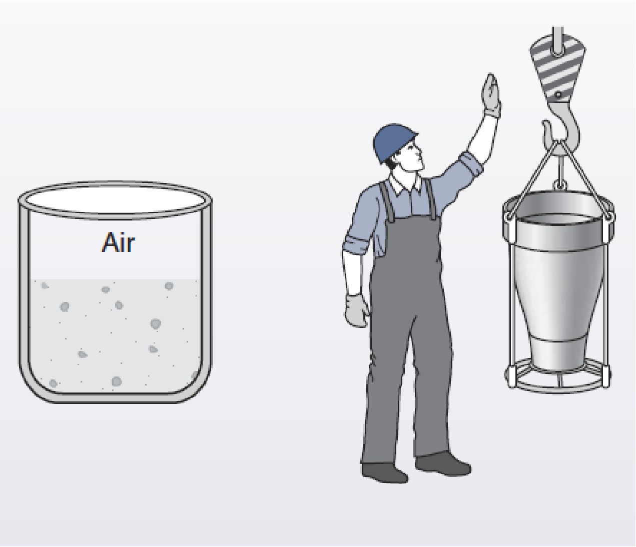
- 0.10 cubic meters of granite
- 0.20 cubic meters of sand
- 0.25 cubic meters of liquid water at 25°C
- The remaining volume, which is 0.45 cubic meters, is air with a density of 1.15 kg/m³

Calculate the Overall specific volume and the overall density of the contents of the container.

Solution

1. Calculate the Mass of Each Material:
   - Granite: $\left(\rho_{granite} = 2750 \frac{kg}{m^3}\right)$ From Table

$$m_{granite} = V_{granite} \cdot \rho_{granite} = 2750 \frac{kg}{m^3} \cdot 0.10\, m^3 = 275\, kg$$



Sketch for Example

Substance	ρ (kg/m3) at 25°C
Granite	2750
Sand	1500
Water	997
Air	1.15

Cont…

- Sand: $\left(\rho_{sand} = 1500 \frac{kg}{m^3}\right)$ From Table

$$m_{sand} = V_{sand} \cdot \rho_{sand} = 1500 \frac{kg}{m^3} \cdot 0.20\ m^3 = 300\ kg$$

- Water: $\left(\rho_{water} = 997 \frac{kg}{m^3}\right)$ From Table

$$m_{water} = V_{water} \cdot \rho_{water} = 997 \frac{kg}{m^3} \cdot 0.25\ m^3 = 249.25\ kg$$

- Air: $\left(\rho_{air} = 1.15 \frac{kg}{m^3}\right)$ From Table

$$m_{air} = V_{air} \cdot \rho_{air} = 1.15 \frac{kg}{m^3} \cdot 0.45\ m^3 = 0.5175\ kg$$

2. Calculate the Total Mass:

$$m_{total} = m_{granite} + m_{sand} + m_{water} + m_{air} = 275 + 300 + 249.25 + 0.5175 = 824.7675\ kg$$

3. Calculate the Overall Specific Volume:

$$v_{Overall} = \frac{V_{total}}{m_{total}} = \frac{1\ m^3}{824.7675\ kg} = 0.0012124\ \frac{m^3}{kg}$$

4. Calculate the Overall Density:

$$\rho_{Overall} = \frac{m_{total}}{V_{total}} = \frac{824.7675\ kg}{1\ m^3} = 824.7675\ \frac{kg}{m^3}$$

Cont…

Pressure

pressure is a fundamental concept that describes the force exerted per unit area by the particles of a substance. It plays a crucial role in understanding the behavior of gases, liquids, and solids under various conditions. Here are some key aspects of pressure in thermodynamics, along with relevant relations:

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

For ideal gases, pressure is related to volume (V), temperature (T), and the number of moles (n) of the gas through the Ideal Gas Law:

$$PV = nR_\mu T$$

where R is the universal gas constant, has a value of:

- $R_\mu = 8.314\ \mathrm{J/(mol \cdot K)}$, usually used in chemistry and thermodynamics, especially when dealing with energy calculations.
- $R_\mu = 0.0821\ \mathrm{L \cdot atm/(mol \cdot k)}$, usually used in gas law calculations, especially in the ideal gas law.

The conversion factor can be done as follows:

$$R_\mu = 8.314 \frac{\mathrm{J}}{\mathrm{mol \cdot K}} \cdot \left(\frac{9.869 \times 10^{-3}\ \mathrm{L \cdot atm}}{1\ \mathrm{J}}\right) \approx 0.0821\ \mathrm{L.atm} \qquad , 1\ \mathrm{J} = 9.869 \times 10^{-3}\ \mathrm{L \cdot atm}$$

Cont…

For various phases of matter, pressure can be described using other equations of state. For example:

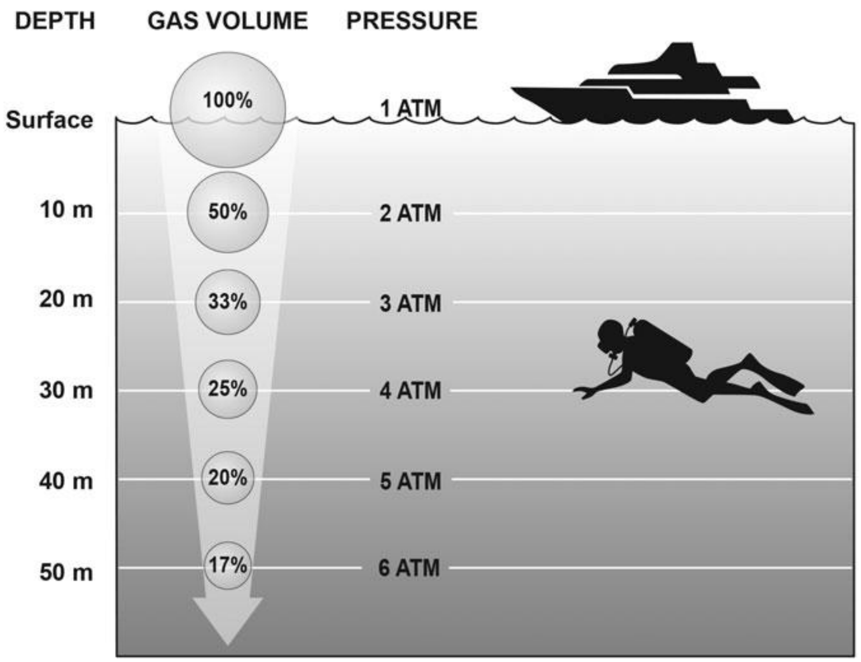
- For liquids, pressure can be affected by factors like temperature and density.
- For solids, pressure can influence phase transitions (e.g., melting, sublimation).

In fluids at rest, pressure varies with depth due to the weight of the fluid above. The hydrostatic pressure is given by:

$$P = P_0 + \rho g h$$

where:

- P_0 is the pressure at the surface.
- ρ is the fluid density.
- g is the acceleration due to the gravity.
- h is the depth below the surface.



Cont…

Pressure is involved in various thermodynamic processes, including:

- Isothermal Process: At constant temperature, the relationship between pressure and volume is given by Boyle's Law:

$$PV = constant$$

- Isobaric Process: At constant pressure, the relationship between volume and temperature is:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

- Isochoric Process: At constant volume, the relationship between pressure and temperature is:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

In thermodynamics, work done by or on the system can be calculated using pressure:

$$W = P\Delta V$$

where ΔV is the change in volume

Cont…

During phase transitions, such as boiling or melting, pressure plays a critical role. The Clapeyron equation relates the pressure and temperature of phase transitions:

$$\frac{dP}{dT} = \frac{L}{T\Delta V}$$

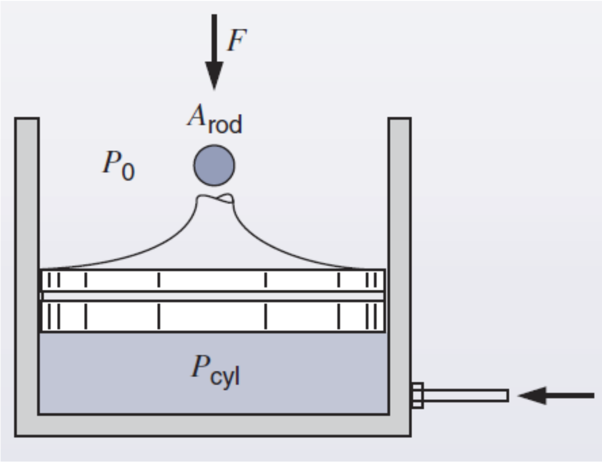
where:

- L is the latent heat.
- ΔV is the change in volume during the transition.

- Example:

In the hydraulic piston/cylinder system shown in Figure, the piston has a diameter of 0.15 m, and the rod has a diameter of 0.01 m. The total mass of the piston and rod is 30 kg. The hydraulic fluid inside the cylinder exerts a pressure of 300 kPa, while the atmospheric pressure outside the rod is 101 kPa. Calculate the maximum upward force that the rod can exert, taking into account the weight of the rod and the effects of atmospheric pressure.

Given Parameter: Piston Diameter (0.15)m, Rod Diameter (0.01)m, Piston and Rod Mass (30) kg, inside pressure (300) kPa, Atmospheric Pressure (101 kPa).



Sketch for Example

Cont...

Solution:

To determine the force that the rod can push upward, we can use the principles of hydraulics. The force exerted by the hydraulic fluid on the piston can be calculated using the following formula:

$$F = P \times A$$

Step 1: Calculate the areas

$$A_{Piston} = \frac{\pi D^2}{4} = \frac{\pi (0.15)^2}{4} \approx 0.017671\ m^2$$

$$A_{rod} = \frac{\pi D^2}{4} = \frac{\pi (0.01)^2}{4} \approx 7.8539 \times 10^{-5}\ m^2$$

Step 2: We will assume a static balance of forces on the piston (positive upward)

$$F_{net} = ma = 0$$

$$= P_{cyl} A_{cyl} - P_0 (A_{cyl} - A_{rod}) - F - m_p g$$

$$F = P_{cyl} A_{cyl} - P_0 (A_{cyl} - A_{rod}) - m_p g$$

$$F = [300\ kPa \times 0.017671\ m^2 - 101\ kPa\ (0.017671 - 7.8539\ \times 10^{-5}) m^2]\ 1000 \frac{Pa}{kPa} - 30\ kg \times 9.81\ \frac{m}{s^2}$$
$$= [5301.3 - 1776.838561 - 294.3] = 3230.16\ N$$

Cont…

❖Absolute Pressure

Absolute pressure is defined as the total pressure exerted on a system, measured relative to a perfect vacuum. It accounts for all atmospheric and additional pressures acting on an object or fluid, providing a complete measure of pressure without reference to the surrounding environment. Absolute pressure formula is:

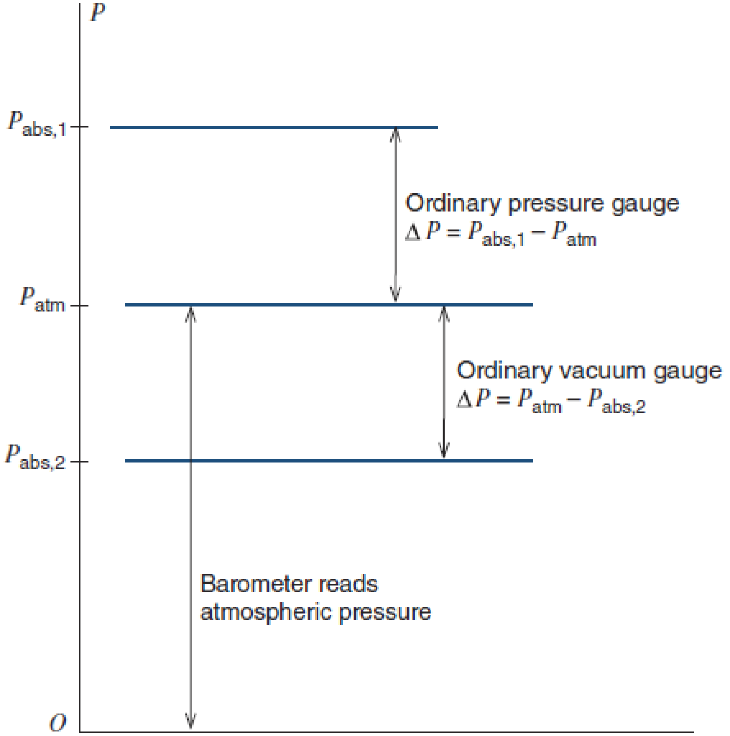
$$P_{abs} = P_{gauge} + P_{atm}$$

where:

P_{abs}: Absolute pressure.

P_{gauge}: Gauge pressure (pressure relative to atmospheric pressure).

P_{atm}: Atmospheric pressure (approximately 101.3 kPa at



Cont...

Manometer Basics

A manometer is a device used to measure the pressure of a fluid by comparing it to the atmospheric pressure. It typically consists of a U-shaped tube filled with a liquid (commonly mercury or water). The difference in the liquid levels in the two arms of the tube indicates the pressure difference.

$$P_B - P_0 = \rho g H$$

- Example:

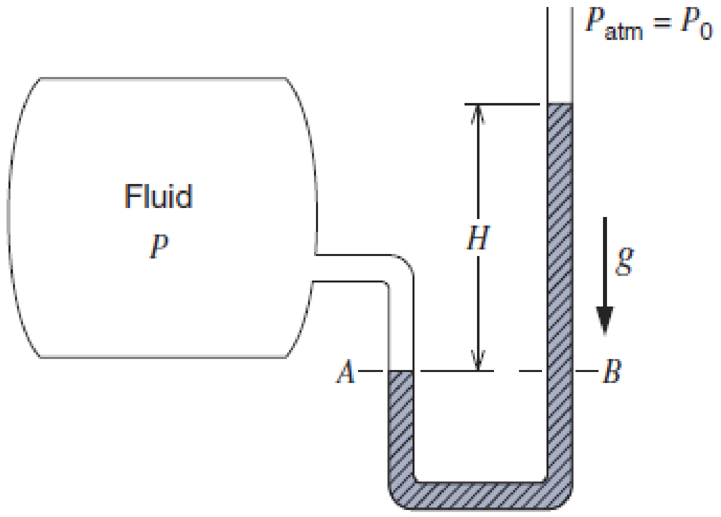
A mercury manometer is connected to a gas line. The height difference between the mercury levels in the two arms of the manometer is measured to be 0.15 m. Given that the density of mercury is approximately 13,600 kg/m^3, calculate the gauge pressure of the gas in the line.

Given: the density of mercury 13,600 kg/m^3, the mercury levels is 0.15 m.

Solution:

$$P_B - P_0 = \rho g H \Rightarrow P_B - 101300 = 13{,}600 \frac{kg}{m^3} \cdot 9.81 \frac{m}{s^2} \cdot 0.15\, m \Rightarrow P_B = 20012.4 + 101300 = 121312.4\, Pa \Rightarrow 121.3124\, kPa$$

$$P_{gauge} = P_B - P_0 = 121.3124 - 101.3 = 20.0124\, kPa$$



Sketch for Example

Cont…

Barometer Basics

barometer is a device used to measure atmospheric pressure using a column of mercury. It consists of a glass tube filled with mercury, which is inverted into a reservoir of mercury. The height of the mercury column provides a direct measurement of atmospheric pressure.

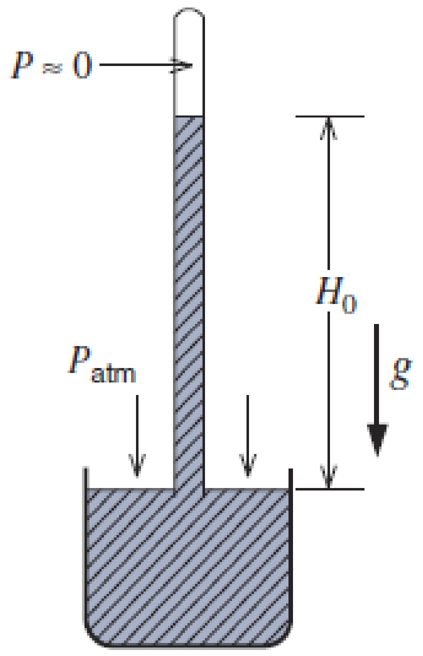
$$P_0 = \rho g H_0$$

- Example:

A mercury barometer located in a room at 25°C has a height of 750 mm. What is the atmospheric pressure in kPa? ($\rho_{mercury} = 13{,}600\ kg/m^3$)

Solution:

$$P_0 = \rho g H_0 \Rightarrow P_0 = 13{,}600 \frac{kg}{m^3} \cdot 9.81\ \frac{m}{s^2} \cdot 0.75\ m = 100.062\ kPa$$



Barometer

Cont…

Pascal Law's

"Any change in pressure applied to an incompressible fluid in a closed container is transmitted equally in all directions."

Applications:

1. Hydraulic Lifts: Used to apply large forces using small forces.
2. Hydraulic Brakes: Where pressure is transmitted from the brake pedal to the brake system.
3. Hydraulic Presses: Used in industry to compress materials.

Equation:

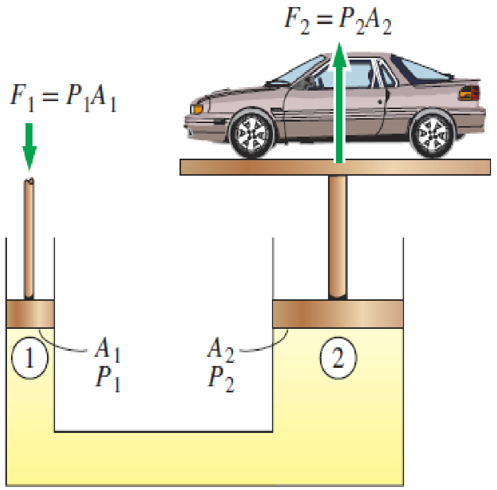
$$P_1 = P_2$$

- Example:

If we effect on the pistion by $F_1 = 14.8\ kn$ on $A_1 = 2\ m^2$ and the $A_2 = 4\ m^2$ what is F_2 ?

Solution:

$$P_1 = P_2 \longrightarrow \frac{F_1}{A_1} = \frac{F_2}{A_2} \longrightarrow F_2 = \frac{F_1 \cdot A_2}{A_1} = \frac{14.8\ kn \cdot 4\ m^2}{2\ m^2} = 29.6\ kn$$



Example on Pascal Principle

Cont…

❖ Energy

Energy is defined as the capacity to do work or produce heat. It exists in various forms, including kinetic, potential and internal energy. Energy can be transformed from one form to another, but it cannot be created or destroyed, as stated by the law of conservation of energy. We write the total energy as

$$E_{total} = E_k + E_p + E_{k,rot} + E_{nuclear} + E_{thermal} + E_{chemical} + E_{electrical} + U$$

where:

E_k *is Kinetic energy* $\left(E_k = \frac{1}{2}mv^2\right)$.

E_p *is Potential energy* $(E_p = mgh)$.

$E_{k,rot}$ *is Rotational kinetic* $\left(E_{k,rot} = \frac{1}{2}I\omega^2\right)$.

$E_{nuclear}$ *is Nuclear energy* $(E_{nuclear} = mc^2)$.

$E_{thermal}$ *is Thermal energy* $(E_{thermal} = mc\Delta T)$.

$E_{chemical}$ *is Chemical energy* $(E_{chemical} = \Delta H)$.

$E_{electrical}$ *is Electrical energy* $(E_{electrical} = V.I.t)$.

U *is Internal energy*.

Cont…

And the specific total energy becomes

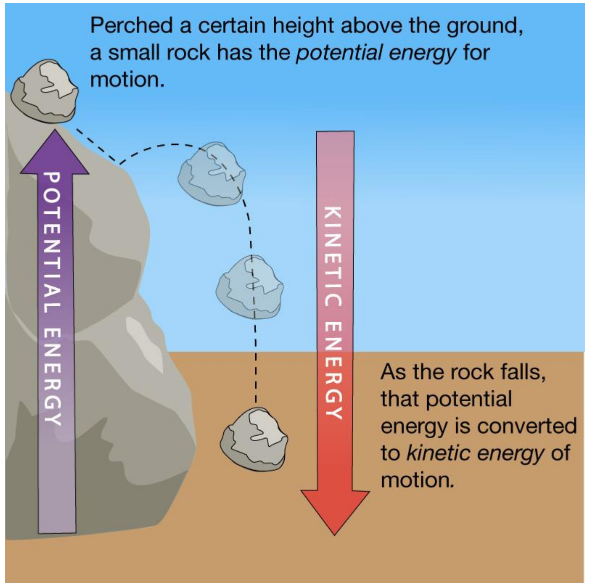
$$e = \frac{E}{m} = e_k + e_p + e_{k,rot} + e_{nuclear} + e_{thermal} + e_{chemical} + e_{electrical} + u$$

- Example: Falling object

  A rock of mass 2 kg is dropped from a height of 10 meters. Calculate the total energy.

  Solution:

  1. Potential energy, $E_p = mgh = 2\,kg \cdot 9.81\frac{m}{s^2} \cdot 10\,m = 196.2$ J
  2. Kinetic energy before impact, $E_k = E_p = 196.2$ J
  3. Internal energy, $U = 0$.
  4. Total energy, $E_{total} = E_k + E_p + U = 196.2 + 0 + 0 = 196.2$ J



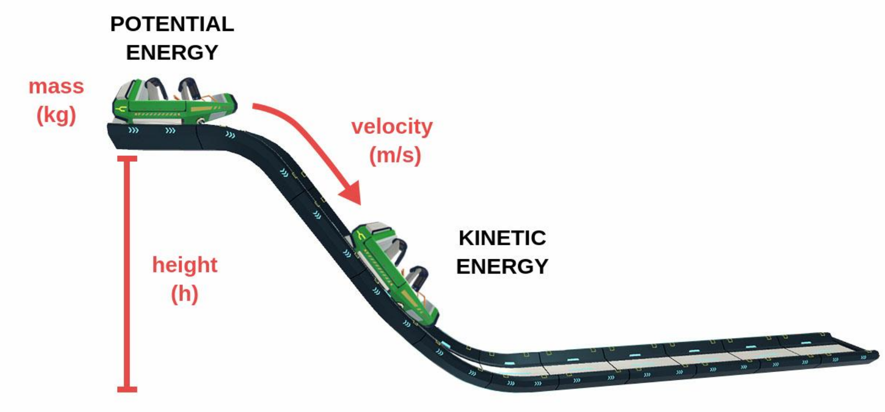
Cont…

- Example: Roller Coaster

A roller coaster car of mass 500 kg reaches a height of 30 meters. Calculate the Total energy.

Solution:

1. Potential energy, $E_p = mgh = 500\ kg \cdot 9.81 \frac{m}{s^2} \cdot 30\ m = 147150$ J
2. Kinetic energy before impact, $E_k = E_p = 147150$ J
3. Internal energy, $U = 0$.
4. Total energy, $E_{total} = E_k + E_p + U = 147150 + 0 + 0 = 147150$ J



Cont…

- Example:

A school is paying \$0.12/kWh for electric power. To reduce its power bill, the school installs a wind turbine shown in figure below. with a rated power of 30 kW. If the turbine operates 2200 hours per year at the rated power, determine the amount of electric power generated by the wind turbine and the money saved by the school per year.

Solution:

$$Total\ energy = (Energy\ per\ unit\ time\ ) \cdot (Time\ interval) = 30\ kW \cdot 2200\ h$$
$$= 66{,}000\ kWh$$

The money saved per year

$$Money\ saved\ = (Total\ energy) \cdot (Unit\ cost\ of\ energy)$$
$$= 66{,}000\ kWh \cdot \$0.12/\text{kWh} = \$7920$$

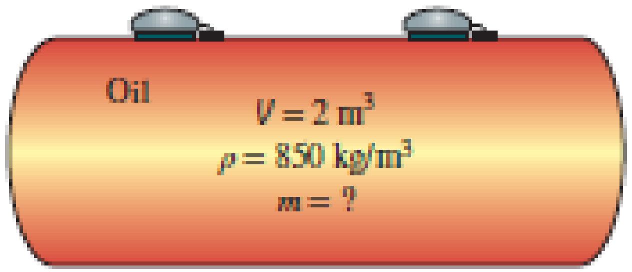
Cont…

- Example:

A tank is filled with oil whose density is $\rho = 850\ kg/m^3$. If the volume of the tank is $V = 2\ m^3$, determine the amount of mass m in the tank.

Solution:

$$m = \rho \cdot V = 850 \frac{kg}{m^3} \cdot 2\ m^3 = 1700\ kg$$



Cont...

- Example:

Humans are most comfortable when the temperature is between 65°F and 75°F. Express these temperature limits in °C. Convert the size of this temperature range (10°F) to K, °C, and R. Is there any difference in the size of this range as measured in relative or absolute units ?

Solution:

$$T(°C) = \frac{T(°F) - 32}{1.8} = \frac{65 - 32}{1.8} = 18.3°C$$

$$T(°C) = \frac{T(°F) - 32}{1.8} = \frac{75 - 32}{1.8} = 23.9°C$$

A temperature change of 10°F in various units are

$$\Delta T(R) = \Delta T(°F) = 10\ R$$

$$\Delta T(°C) = \frac{\Delta T(°F)}{1.8} = \frac{10}{1.8} = 5.6°C$$

Cont…

- Example:

A vacuum gage connected to a chamber reads 5.8 psi. at a location where the atmospheric pressure is 14.5 psi. Determine the absolute pressure in the chamber.

Solution:

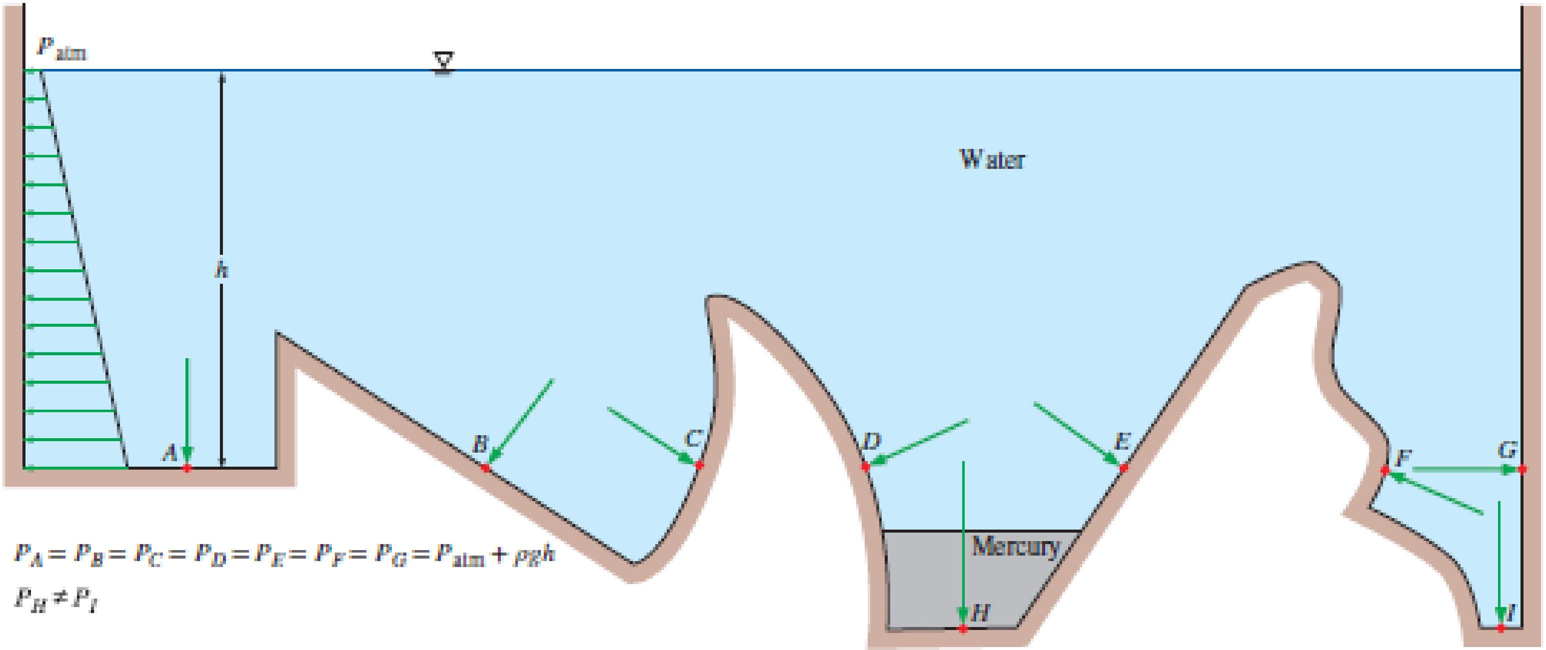
$$P_{abs} = P_{atm} - P_{vac} = 14.5 - 5.8 = 8.7\ psi$$

Cont…

❖A matter for discussion:

Is the pressure equal at A, B, C, D, E, F, G?

Is the pressure equal at H, I? Why?



$P_A = P_B = P_C = P_D = P_E = P_F = P_G = P_{atm} + \rho g h$

$P_H \neq P_I$

Cont…

❖ Example:

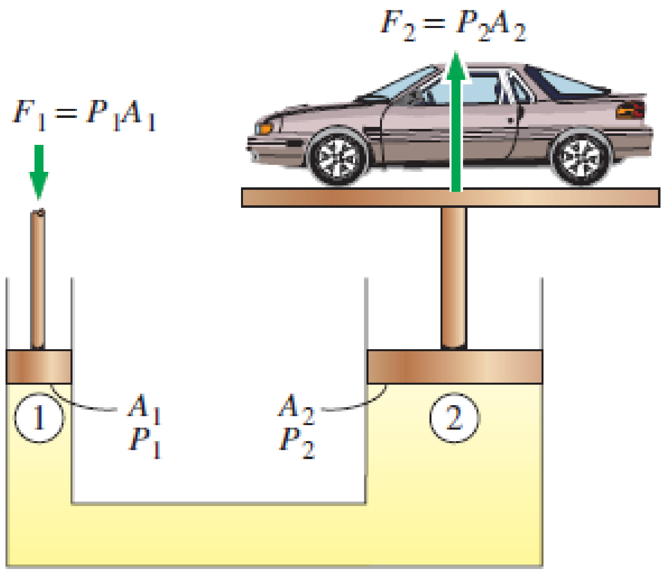
If $P_1 = P_2$, and we effect on the piston by $F_1 = 14.8\ kn$ on $A_1 = 2\ m^2$ and the $A_2 = 4\ m^2$ what is F_2 ?

Solution:

$$P_1 = \frac{F_1}{A_1}$$

$$P_2 = \frac{F_2}{A_2}$$

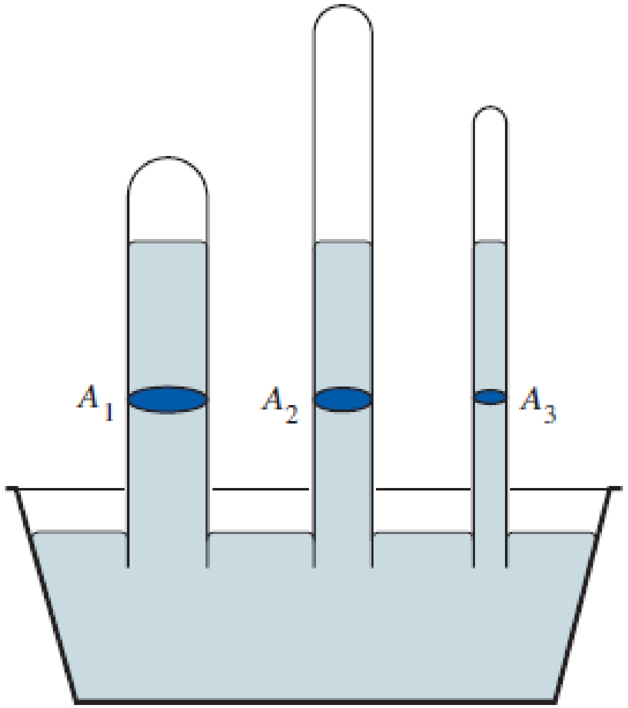
$$F_2 = \frac{F_1 A_2}{A_1} = \frac{14.8\ kn \cdot 4\ m^2}{2\ m^2} = 29.6\ kn$$



Cont…

- A matter for discussion:

Is the area effect on the height of the fluid column?



Cont…

- Example:

Determine the atmospheric pressure at a location where the barometric reading is 740 mmHg and the gravitational acceleration is $g = 9.805\ m/s^2$. Assume the temperature of mercury to be 10℃, at which its density is 13,570 kg/m^3.

Solution:

$$P_{atm} = \rho g h = 13{,}570 \frac{kg}{m^3} \cdot 9.805 \frac{m}{s^2} \cdot 0.740\ m = 98459.849\ Pa = 98.5\ kPa$$

Cont...

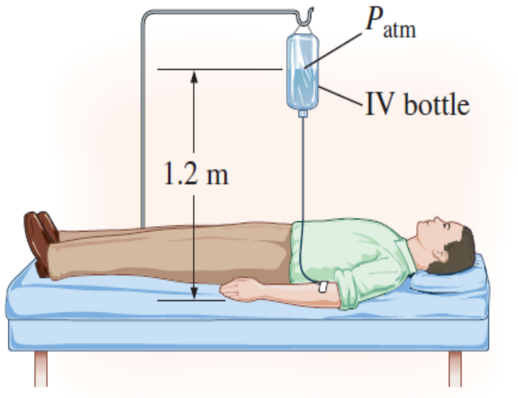
- Example:

Intravenous infusions usually are driven by gravity by hanging the fluid bottle at sufficient height to counteract the blood pressure in the vein and to force the fluid into the body (shown in figure below). The higher the bottle is raised, the higher the flow rate of the fluid will be. (*a*) If it is observed that the fluid and the blood pressures balance each other when the bottle is 1.2 m above the arm level, determine the gage pressure of the blood. (*b*) If the gage pressure of the fluid at the arm level needs to be 20 kPa for sufficient flow rate, determine how high the bottle must be placed. Take the density of the fluid to be 1020 kg/m^3.

Solution:

(a) $P_{gage,arm} = P_{abs} - P_{atm} = \rho g h_{arm-bottle}$

$$P_{gage,arm} = \left(1020\frac{kg}{m^3}\right)\left(9.81\frac{m}{s^2}\right)(1.20\ m) = 12{,}000\ Pa = 12\ kPa$$



(b) $h_{arm-bottle} = \frac{P_{gage,arm}}{\rho g}$

$$h_{arm-bottle} = \frac{(20 \cdot 1000)\ Pa}{(1020\frac{kg}{m^3})(9.81\frac{m}{s^2})} = 2\ m$$

Cont…

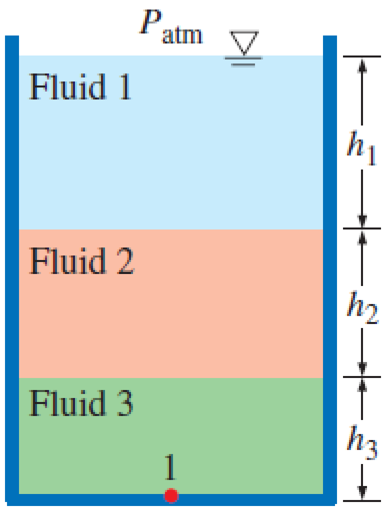
- Example:

Calculate the pressure at point 1, which fluid 1 water, fluid 2 oils ($\rho = 850\ kg/m^3$) and fluid 3 is mercury. Also, $h1 = 5\ m$, $h2 = 10\ m$ and $h3 = 15\ m$.

Solution:

$$P_1 = P_{fluid\ 1} + P_{fluid\ 2} + P_{fluid\ 3} + P_{atm} = \rho g h_1 + \rho g h_2 + \rho g h_3 + P_{atm}$$

$$= 1000\frac{kg}{m^3}\cdot 9.81\frac{m}{s^2}\cdot 5\ m + 850\frac{kg}{m^3}\cdot 9.81\frac{m}{s^2}\cdot 10\ m + 13600\frac{kg}{m^3}\cdot 9.81\frac{m}{s^2}\cdot 15\ m + 101300$$
$$= 2234975\ Pa = 2234.975\ kPa$$



Cont…

❖ Example:

The water in a tank is pressurized by air, and the pressure is measured by a multifluid manometer as shown in Fig. The tank is located on a mountain at an altitude of 1400 m where the atmospheric pressure is 85.6 kPa. Determine the air pressure in the tank if $h_1 = 0.1$ m, $h_2 = 0.2$ m, and $h_3 = 0.35$ m. Take the densities of water, oil, and mercury to be 1000 kg/m^3, 850 kg/m^3, and 13,600 kg/m^3, respectively.

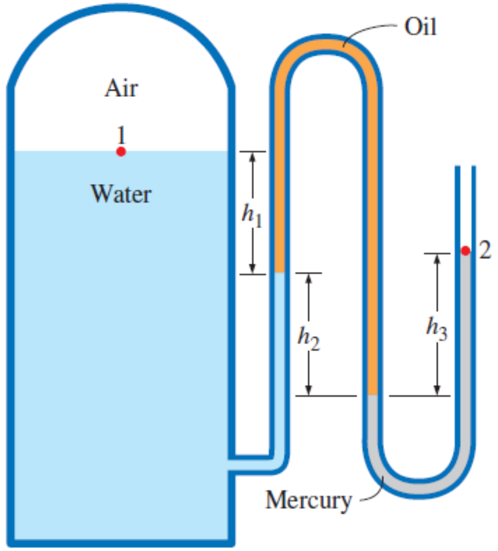
Solution:

$$P_1 + \rho_{water} g h_1 + \rho_{oil} g h_2 - \rho_{mercury} g h_3 = P_{atm}$$

$$P_1 = P_{atm} - \rho_{water} g h_1 - \rho_{oil} g h_2 + \rho_{mercury} g h_3$$

$$= P_{atm} + g(\rho_{mercury} g h_3 - \rho_{water} g h_1 - \rho_{oil} g h_2)$$

$$= (85.6 \cdot 1000) Pa$$
$$+ \left(9.81 \frac{m}{s^2}\right)\left[\left(13{,}600 \frac{kg}{m^3}\right)(0.35\ m) - \left(1000 \frac{kg}{m^3}\right)(0.1\ m) - \left(850 \frac{kg}{m^3}\right)(0.2\ m)\right]$$
$$= 130\ kPa$$



Cont…

- **Example:** The gage pressure of the air in the tank shown in Figure is measured to be 65 kPa. Determine the differential height *h* of the mercury column.

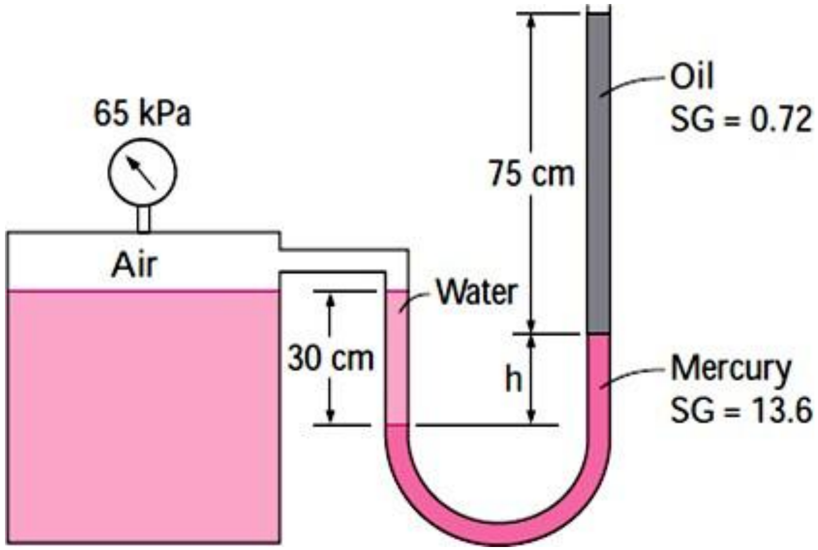
Sol:

$$P_1 - P_{atm} + \rho_{water} g h_1 - \rho_{oil} g h_2 - \rho_{mercury} g h_3 = 0$$

$$65000 + 1000 \cdot 0.3 \cdot 9.81 - 720 \cdot 0.75 \cdot 9.81 - 13600 \cdot h \cdot 9.81 = 0$$

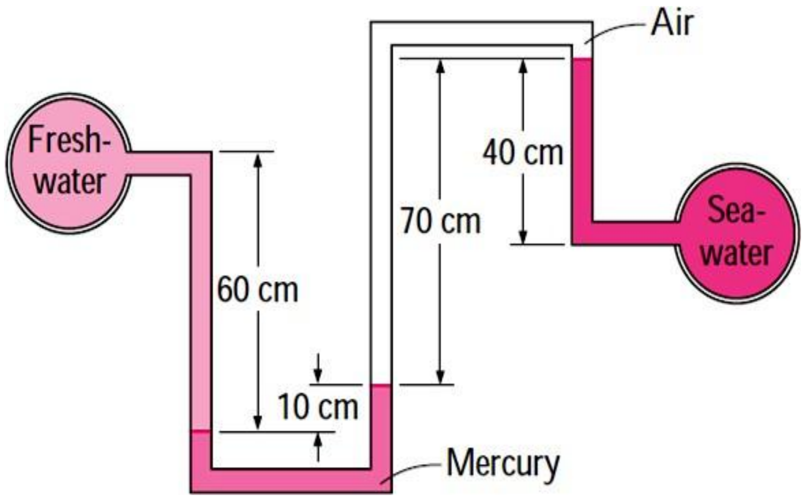
$$65000 + 2943 - 5297.4 = 13600 \cdot h \cdot 9.81$$

$$h = 0.47\ m$$



Cont…

- **Exercise:** Freshwater and seawater flowing in parallel horizontal pipelines are connected to each other by a double U-tube manometer, as shown in the Fig. Determine the pressure difference between the two pipelines. Take the density of seawater at that location to be ρ = 1035 kg/m3. Can the air column be ignored in the analysis?



Cont…

- **Example:** Two water tanks are connected to each other through a mercury manometer with inclined tubes, as shown in the Fig. below. If the pressure difference between the two tanks is 20 kPa, calculate a and θ.

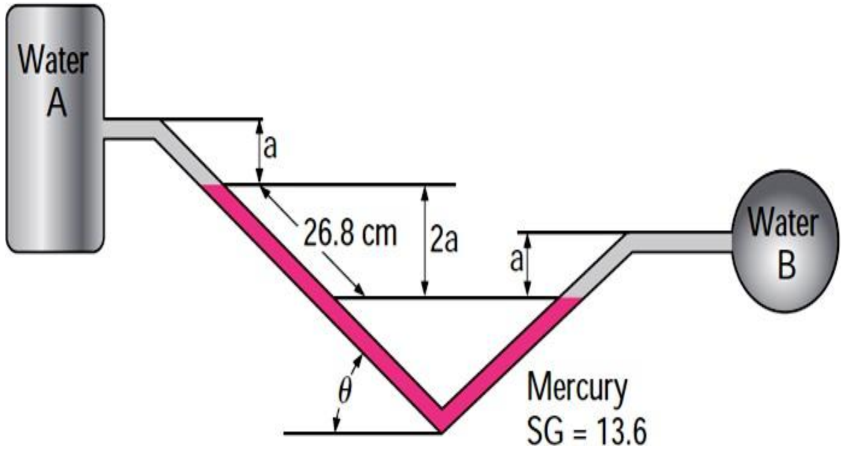
Sol:

$$P_B + \rho_{water} g a - \rho_{mercury} g 2a - \rho_{water} g a = P_A$$

$$P_B - P_A = \rho_{mercury} g \cdot 2a$$

$$20 \cdot 1000 = 13600 \cdot 9.81 \cdot 2a$$

$$a = 0.074\, m$$



For θ,

$$2a = s \cdot sin\theta$$

$$2 \cdot 0.074 = 0.268 \cdot sin\theta \rightarrow sin\theta = 0.5522 \rightarrow \theta = 34°$$

Thermal Process

Thermal processes refer to the various ways heat energy is transferred and transformed within a system. These processes are central to understanding how energy is converted and conserved in physical systems. Here are the types of thermal process in thermodynamics:

- **Isothermal Process**: Occurs at constant temperature. The internal energy of the system remains unchanged, and all heat added to the system is converted to work. For an ideal gas undergoing an isothermal process, the following relation holds:

$$PV = constant$$

The work done by the gas during an isothermal expansion can be calculated as:

$$W = nR_\mu T ln\left(\frac{V_f}{V_i}\right)$$

- **Adiabatic Process**: No heat exchange occurs with the surroundings. Any change in the internal energy of the system is solely due to work done on or by the system. For an ideal gas the relation between pressure and volume is given by:

$$PV^k = constant$$

Where $\mathrm{k} = \frac{C_p}{C_v}$ (the ratio of specific heats).

Cont…

The relation between temperature and volume is:

$$TV^{k-1} = constant$$

The work done in an adiabatic process can be calculated using:

$$W = \frac{C_v(T_i - T_f)}{k-1}$$

- **Isobaric Process**: Takes place at constant pressure. Heat added or removed results in work done by or on the system, leading to a change in volume. For an ideal gas, the relation is:

$$P = constant$$

The work done during an isobaric process is given by:

$$W = P\Delta V$$

The heat add can also be expressed as:

$$Q = nC_p\Delta T$$

- **Isochoric Process**: Occurs at constant volume. Any heat added to the system increases its internal energy, leading to a rise in temperature. Since the volume is constant, no work is done ($W = 0$).

The change in internal energy is equal to the heat added:

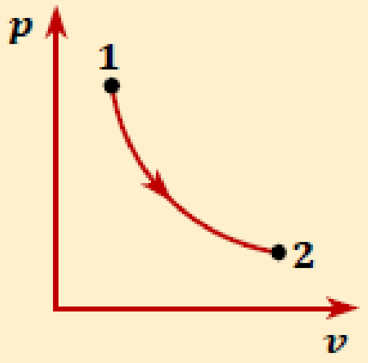
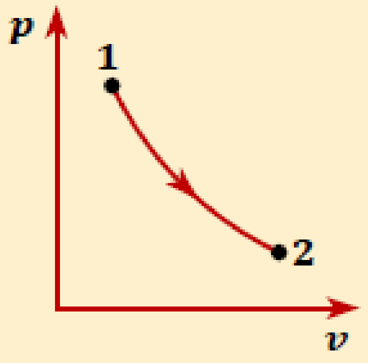
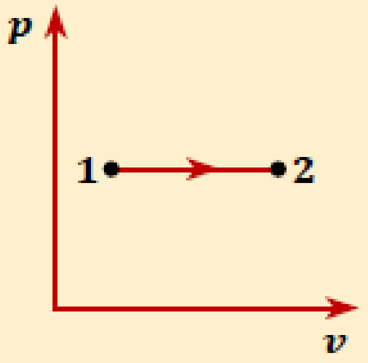
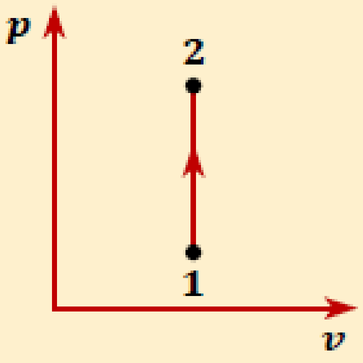
$$\Delta U = Q$$

Cont…

Process Type	Definition	Relation for Ideal Gas	Work done	Heat Transfer
Isothermal	Occurs at constant temperature	$PV = constant$	$W = nR_\mu T ln\left(\frac{V_f}{V_i}\right)$	$Q = W$
Adiabatic	No heat exchange occurs with the surroundings	$PV^k = constant$	$W = \frac{C_v(T_i - T_f)}{\mathrm{k} - 1}$	$Q = 0$
Isobaric	Occurs at constant pressure	$P = constant$	$W = P\Delta V$	$Q = nC_p\Delta T$
Isochoric	Occurs at constant volume	$V = constant$	$W = 0$	$Q = \Delta U$

Tabulated Summary for Thermal Process

Cont…

Adiabatic	Isothermal	Isobaric	Isochoric
			
$\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^k$	$\frac{p_2}{p_1} = \frac{v_1}{v_2}$	$\frac{v_2}{v_1} = \frac{T_2}{T_1}$	$\frac{p_2}{p_1} = \frac{T_2}{T_1}$
$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1}$			
$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}$			

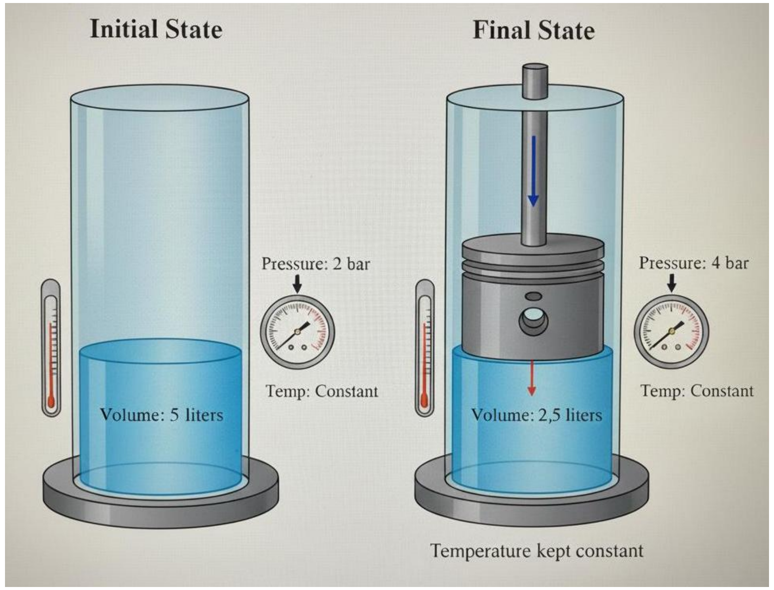
Cont…

- Example:

If you have a gas trapped in a piston with a volume of 5 liters at a pressure of 2 bar, what will the pressure be if the volume is reduced to 2.5 liters, while keeping the temperature constant?

Sol:

$$P_1 \cdot V_1 = P_2 \cdot V_2$$



Where:

$$P_1 = 2\ bar$$

$$V_1 = 5\ liters$$

$$V_2 = 2.5\ liters$$

Finding P_2:

$$P_2 = \frac{P_1 \cdot V_1}{V_2} = \frac{2 \cdot 5}{2.5} = 4\ bar$$

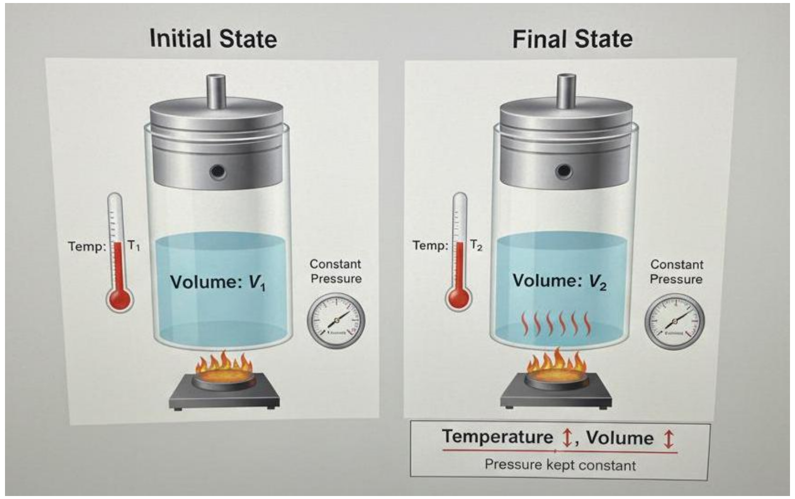
Cont…

- Example:

If you have a gas at a pressure of 1 bar and a volume of 10 liters at a temperature of 300 K, what will the volume of the gas be at a temperature of 600 K, while keeping the pressure constant?

Sol:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$



Where:

$$V_1 = 10\ liters, T_1 = 300\ K$$

$$T_2 = 600\ k$$

Finding V_2:

$$V_2 = V_1 \cdot \frac{T_2}{T_1} = 10 \cdot \frac{600}{300} = 20\ liters$$

Cont…

- Example:

If you have 1 mole of gas at a temperature of 273 K and a pressure of 1 bar, what volume will the gas occupy?

Sol:

$$PV = nR_\mu T$$

Where:

$$R_\mu = 0.0821\ L.bar/(mol \cdot K)$$

$$n = 1\ mole$$

$$P = 1\ bar, T = 273\ K$$

Finding V:

$$V = \frac{nR_\mu T}{P} = \frac{1 \cdot 0.0821 \cdot 273}{1} = 22.4\ liters$$

Cont…

- Example:

If you have a gas in an adiabatic process where the volume decreases from 8 liters to 4 liters, and the initial pressure is 1.5 bar, what is the final pressure? (use $k = 1.4$)

Sol:

$$P_1 \cdot V_1^k = P_2 \cdot V_2^k$$

Finding P_2:

$$P_2 = P_1 \left(\frac{V_1}{V_2}\right)^k = 1.5 \left(\frac{8}{4}\right)^{1.4} = 3.96\ bar$$

Cont…

❖ Example:

If you have 2 moles of an ideal gas in a container with a volume of 10 liters at a temperature of 300 K, what is the initial pressure of the gas? Then, if the gas is expanded to a volume of 20 liters while keeping the temperature constant, calculate the final pressure.

Sol:

1. Initial pressure:

$$PV = nR_\mu T$$

$$P = \frac{nR_\mu T}{V} = \frac{2 \cdot 0.0821 \cdot 300}{10} = 4.926\ bar$$

2. Final pressure:

$$P_2 = P_1 \frac{V_1}{V_2} = 4.926 \cdot \frac{10}{20} = 2.463\ bar$$

Cont…

- Example:

Calculate the work done on the gas when 1 mole of an ideal gas is compressed from a volume of 10 liters to 5 liters at a temperature of 300 K.

Sol:

$$W = -nR_{\mu}Tln\left(\frac{V_f}{V_i}\right) = -1 \cdot 0.0821 \cdot 300 \ln\left(\frac{5}{10}\right) = 17.05\, J$$

Cont...

❖ Example:

Calculate the change in internal energy of an ideal gas if it is heated from 250 K to 500 K, given that the gas contains 2 moles and has $c_v = \frac{3}{2}R_\mu$.

Sol:

$$\Delta U = nc_v\Delta T$$

$$c_v = \frac{3}{2}R_\mu = \frac{3}{2} \cdot 0.0821 = 0.123\ L.bar/(mol.k)$$

$$\Delta T = 500 - 250 = 250\ K$$

$$\Delta U = nc_v\Delta T = 2 \cdot 0.123 \cdot 250 = 61.5\ J$$

Cont…

- Example:

If you have a piston with a volume of 10 liters at a pressure of 2 bar, and the gas expands to a volume of 20 liters, calculate the work done during this expansion if the process is isothermal.

Sol:

$$W = P\Delta V = 2 \cdot (20 - 10) = 20 \cdot 100 = 2000\, J$$

Cont…

- Example:

If gas is compressed in a piston from 10 liters to 5 liters, with an initial pressure of 1 bar, calculate the work done on the gas.

Sol:

$$W = -\int_{V_1}^{V_2} P\, dV$$

$$W = P_{avg} \cdot \Delta V$$

Where:

$$P_{avg} = \frac{P_i + P_f}{2}$$

$$P_f = \frac{P_i V_i}{V_f} = \frac{1 \cdot 10}{5} = 2\ bar$$

Cont…

$$P_{avg} = \frac{P_i + P_f}{2} = \frac{1+2}{2} = 1.5\ bar$$

$$\Delta V = V_f - V_i = 5 - 10 = -5\ liters$$

$$W = 1.5 \cdot (-5) = -7.5\ bar.liters \cdot 100 = 750\ J$$

Cont…

❖ Example:

A gas in a piston undergoes three processes:

1. It contracts from 20 liters to 10 liters at a constant pressure of 1 bar.
2. The gas is heated from 10 liters to 15 liters at a constant pressure of 2 bar.
3. The gas expands from 15 liters to 20 liters at a constant pressure of 1 bar.

Calculate the work done in each process. Calculate the total work.

Sol:

1. Process one (pressure 1 bar):

$$W_1 = P\Delta V = 1 \cdot (10 - 20) = -10\ bar.liters\ \cdot 100 = -1000\ J$$

Cont...

2. Process two (pressure 2 bar):

$$W_2 = 2 \cdot (15 - 10) = 2 \cdot 5 = 10\ bar.liters \cdot 100 = 1000\ J$$

3. Process three (pressure 1 bar):

$$W_3 = 1 \cdot (20 - 15) = 1 \cdot 5 = 5\ bar.liters \cdot 100 = 500\ \ J$$

Total Work:

$$W_{total} = W_1 + W_2 + W_3 = -1000 + 1000 + 500 = 500$$

The Ideal Gases

- **Ideal Gas**: An ideal gas is composed of elastic molecules with negligible mass and volume, where intermolecular forces (intermolecular attractions) do not affect the interactions between its particles.

- **Ideal Gases Laws:**

1. **Boyle's Law:** Boyle's Law states that at constant temperature ($T = const$), the pressure of a given mass of gas is inversely proportional to its volume. Mathematically, it can be expressed as:

$$\frac{P_2}{P_1} = \frac{V_1}{V_2}$$

2. **Gay-Lussac's Law:** Gay-Lussac's Law states that the Volume of a given mass of gas is directly proportional to its absolute temperature when the Pressure is held constant ($\mathrm{P} = const$). Mathematically, it can be expressed as:

$$\frac{V_2}{V_1} = \frac{T_2}{T_1}$$

Cont…

3. **Charles's Law:** Charles's Law states that the Pressure of a given mass of gas is directly proportional to its absolute temperature when the Volume is held constant ($V = const$). Mathematically, it can be expressed as:

$$\frac{P_2}{P_1} = \frac{T_2}{T_1}$$

4. **Avogadro's Law:** Avogadro's Law states that equal volumes of gases, at the same temperature and pressure, contain an equal number of molecules. Mathematically, it can be expressed as:

$$V \, \alpha \, n$$

or

$$\frac{V_1}{n_1} = \frac{V_2}{n_2}$$

Where is n equal number of molecules.

- The molar mass and the molar volume:

$$\mu = \frac{m}{n}$$

$$V_\mu = \frac{V}{n}$$

Cont…

The mass of an ideal gas, based on Avogadro, is directly proportional to its molar mass. Therefore, the density of a gas is directly proportional to its molar mass:

$$\frac{m_2}{m_1} = \frac{\mu_1}{\mu_2} = \frac{\rho_2}{\rho_1}$$

At Standard temperature and pressure (STP):

$$T = 273\ K\ \&\ t = 0℃$$

$$P = 1\ atm = 101325\ Pa = 760\ mmHg$$

$$V_\mu = 22.4\ \frac{m^3}{kmol}$$

The Specific Volume and density at STP for any ideal gas:

$$v_0 = \frac{V_\mu}{\mu} = \frac{22.4}{\mu}$$

$$\rho_0 = \frac{1}{v_0} = \frac{\mu}{22.4}$$

- The equation of state for an ideal gases:

$$PV = nR_\mu T$$

Cont...

- The equation of state for an ideal gases is the relation between the three thermal parameters (P, V, T):

$$PV = nR_\mu T$$

$$PV = mRT$$

$$Pv = RT$$

$$PV_\mu = R_\mu T$$

$$R = \textbf{Ideal Gas Constant}$$
$$= 8.21 \times 10^{-5}\, m^3 \cdot \frac{atm}{mol \cdot K}$$
$$= 8.314\, J/(mol \cdot k)$$
$$= 0.0821\, L \cdot \frac{atm}{mol \cdot K}$$
$$= 1.987\, cal/(mol \cdot K)$$

The Universal gas constant:

$$R_\mu = \frac{PV_\mu}{T} = \frac{101325\, Pa \cdot 22.4\, \frac{m^3}{kmol}}{273\, K} = 8.314\, \frac{\text{J}}{kmol \cdot K}$$

$$R = \frac{R_\mu}{\mu} \qquad \frac{\text{J}}{kg \cdot K}$$

$R = 287.05 \frac{\text{J}}{kg \cdot K}$ *for dry air, where* $\mu = 0.029\, kg/mol.$

$R = 461.5 \frac{\text{J}}{kg \cdot K}$ *for water vapor, where* $\mu = 0.018\, kg/mol.$

Cont…

- Example:

750 ml of nitrogen gas at a temperature of 75℃ and under a pressure of 850 Torr. Calculate the volume of the gas at standard conditions (STP).

Solution:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$V_2 = \frac{P_1V_1T_2}{P_2T_1} \Longrightarrow V_2 = \frac{850\ Torr \cdot 750\ ml \cdot 273.15\ K}{760\ Torr \cdot 348.15\ K} = 658\ ml$$

Note: $1\ atm = 760\ Torr$

Cont…

- Example:

A quantity of methane gas occupies a volume of 260 ml, at 305 K under a pressure of 0.5 atmospheres. Calculate the temperature at which a gas with a volume of 500 ml and a pressure of 1200 Torr will be reached.

Solution:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$T_2 = \frac{P_2V_2T_1}{P_1V_1} \Longrightarrow T_2 = \frac{1200\,Torr \cdot 500\,ml \cdot 305\,K}{380\,Torr \cdot 260\,ml} = 1852\,K \approx 1580\,℃$$

Cont…

- Example:

Calculate the pressure exerted by 1.67 moles of 25 liters of ethane gas at 25℃.

Solution:

$$P = \frac{nR_{\mu}T}{V}$$

$$P = \frac{1.67\ moles \cdot 0.0821\ L \cdot atm\ /(mol \cdot K)\ \cdot 298.15\ K}{25\ L} = 1.63\ atm$$

Cont…

- Example:

A balloon contains 1.2×10^7 liters of helium at a pressure of 737 mm Hg at a temperature of 25℃. Calculate the mass of the gas.

Solution:

$$737 \cdot \frac{1}{760} = 0.970\, atm$$

$$PV = nR_\mu T$$

$$PV = \frac{m}{\mu} R_\mu T$$

$$m = \frac{PV\mu}{R_\mu T} \Longrightarrow m = \frac{0.970\, atm \cdot 1.2 \times 10^7 liters \cdot 4 \frac{g}{mol}}{0.0821 L \cdot atm/(mol \cdot K) \cdot 298.15K} = 1.9 \times 10^6\ g$$

Heat Capacity

- **Heat Capacity** refers to the amount of heat required to change the temperature of an entire object or substance by one degree Celsius (or one Kelvin).

$$C = \frac{Q}{\Delta T}$$

Heat Capacity is divided into:

1. **Mass Heat Capacity:** It is the amount of heat required to change the temperature of a given mass of a substance by one degree Celsius (or one Kelvin), it can be expressed as:

$$C = \frac{Q}{\Delta T} \qquad \textit{where is } C = mc_m,$$

2. **Volumetric heat capacity:** It is the amount of heat required to change the temperature of a given Volume of that material by one degree Celsius (or one Kelvin). Mathematically, it can be expressed as:

$$C = \frac{Q}{\Delta T} \qquad \textit{where is } C = Vc_V,$$

Cont…

3. **Molar Heat Capacity:** It is the amount of heat required to change the temperature of one mole of a substance by one degree Celsius (or one Kelvin), it can be expressed as:

$$C = \frac{Q}{\Delta T} \qquad \textit{where is } C = nc_{\mu},$$

- **Equations that relate heat capacities:**

  - **Relation between mass and molar heat capacity:**

$$c_m = \frac{c_\mu}{\mu}$$

  - **Relation between mass and volume heat capacity:**

$$c_V = \rho c_m$$

  - **Relation between molar and volume heat capacity:**

$$c_V = \rho \frac{c_\mu}{\mu}$$

Cont…

- **The two types of heat capacity most in demand in thermodynamics:**

  1. Heat capacity at constant Pressure (c_p).
  2. Heat capacity at constant volume (c_v).

The relation between c_p and c_v:

$$c_p = c_v + R$$

$$c_{p\mu} = c_{v\mu} + R_\mu$$

Heat capacity ratio:

$$k = \frac{c_p}{c_v}$$

Also, we can use:

$$c_v = \frac{R}{k-1}$$

$$c_p = \frac{kR}{k-1}$$

Cont…

- **Calculating heat capacities from thermodynamic tables:**

1. Heat capacity is constant, it's not related to temperature or according to the partial kinetic theory (acceptable accuracy):

$$C = \frac{c_\mu}{\mu} \Longrightarrow \begin{cases} c_v = \dfrac{c_{\mu v}}{\mu} \\ c_p = \dfrac{c_{\mu p}}{\mu} \end{cases}$$

2. Heat capacity is linearly related to temperature (accuracy is good):

$$C = a + bt \Longrightarrow \begin{cases} c_v = a + bt \\ c_p = a + bt \end{cases}$$

3. Heat capacity is related to temperature non-linearly (The most accurate):

$$C\Big|_{t_1}^{t_2} = \frac{C\Big|_0^{t_2} \cdot t_2 - C\Big|_0^{t_1} \cdot t_1}{t_2 - t_1} \Longrightarrow \begin{cases} c_v\Big|_{t_1}^{t_2} = \dfrac{c_v\Big|_0^{t_2} \cdot t_2 - c_v\Big|_0^{t_1} \cdot t_1}{t_2 - t_1} \\ c_p\Big|_{t_1}^{t_2} = \dfrac{c_p\Big|_0^{t_2} \cdot t_2 - c_p\Big|_0^{t_1} \cdot t_1}{t_2 - t_1} \end{cases}$$

Cont…

❖ Example: Calculating the Heat Capacity of a Body

we have a mass of 2 kilograms with an applied heat energy of 500 joules, resulting in a temperature change of 20 degrees Celsius. Calculate the mass capacity.

Solution:

To find the heat capacity, we use the formula:

$$c_m = \frac{Q}{m \cdot \Delta T}$$

Substituting the given values, we calculate:

$$c_m = \frac{500\,J}{2\,kg\ \cdot 20℃}$$

$$c_m = \frac{500}{40} = 12.5\left(\frac{J}{kg.℃}\right)$$

Cont…

❖ Example: Heat Capacity of a Different Body

You have 2 kilograms of water (with a specific heat capacity of 4184 $J/(kg \cdot °C)$) and 3 kilograms of iron (with a specific heat capacity of 450 $J/(kg \cdot °C)$). The water is heated to 80 °C, and the iron is heated to 120 °C. If the water is mixed with the iron, calculate the final temperature (T_f) of the mixture, assuming no heat loss.

Solution:

We use the principle of conservation of energy,

$$Q_{lost} = Q_{gained}$$

For the iron, the heat lost can be expressed as:

$$Q_{lost} = m_{iron} \cdot c_{iron} \cdot (T_{i,iron} - T_f)$$

For the water, the heat gained can be expressed as:

$$Q_{gained} = m_{water} \cdot c_{water} \cdot (T_f - T_{initial,water})$$

Substituting the values, we have:

$$3 \cdot 450 \cdot \left(120 - T_f\right) = 2 \cdot 4184 \cdot (T_f - 80)$$

Cont…

$$3 \cdot 450 \cdot (120 - T_f) = 2 \cdot 4184 \cdot (T_f - 80)$$

Expanding this gives:

$$1350 \cdot (120 - T_f) = 8368 \cdot (T_f - 80)$$

Simplifying further:

$$162000 - 1350T_f = 8368T_f - 668480$$

Combining terms yields:

$$830480 = 9718T_f$$

$$T_f \approx 85.5℃$$

$$3 \cdot 450 \cdot (120 - T_f) = 2 \cdot 4184 \cdot (T_f - 80)$$

Cont...

❖ Example: Heat Added to a system

You have 1.5 kilograms of aluminum (with a specific heat capacity of 900 J/(kg·°C)) and 2 kilograms of water. The amount of heat added to the system is 2000 J. The temperature of the aluminum changes from 25 °C to 55 °C. If the initial temperature is 25 °C, Calculate the final temperature of the water after heat is added.

Solution:

First, we calculate the amount of heat gained by the aluminum:

$$Q_{aluminum} = m_{aluminum} \cdot c_{aluminum} \cdot \Delta T_{aluminum}$$

where:

$$\Delta T_{aluminum} = 55 - 25 = 30°\text{C}$$

Substituting the values gives:

$$Q_{aluminum} = 1.5 \cdot 900 \cdot 30 = 40500\,J$$

Cont…

Since the total heat added to the system is only 2000 J, we find the heat gained by the water:

$$Q_{water} = Q_{added} - Q_{aluminum}$$

$$Q_{water} = 2000 - 40500 = -38500\,J$$

This indicates that the water lost heat. We now calculate the change in temperature of the water:

$$Q_{water} = m_{water} \cdot c_{water} \cdot \Delta T_{water}$$

Substituting gives:

$$-38500 = 2 \cdot 4184 \cdot \Delta T_{water}$$

Calculating ΔT results in:

$$\Delta T_{water} \approx -4.6℃$$

If the initial temperature of the water was 25 °C, then:

$$T_{final,water} \approx 25 - 4.6 \approx 20.4℃$$

Cont…

❖ Example: Calculating Heat Capacity Using Volume

You have 500 mL of water. The initial temperature of the water is 20 °C, and you add 2000 joules of heat. Calculate the final temperature.

Solution:

First, we need to calculate the mass using volume: (for water, 1000 ml = 1 kg)

$$m = V \cdot \rho = 500\, ml \cdot \frac{1}{1000000}\frac{m^3}{ml} . 1000\, \frac{kg}{m^3} = 0.5\, kg$$

Second, we need to calculate the change in temperature (ΔT) using the formula:

$$Q = m.c.\Delta T$$

$$2000\, J = 0.5\, kg. 4184\, J/(kg \cdot ℃). \Delta T$$

$$\Delta T = 0.95℃$$

Thus, the final temperature is:

$$T_{final} = 20 + 0.95 \approx 20.95\, ℃$$

Cont...

- Example: Calculating Heat Capacity Using Moles

You have 2 moles of oxygen gas (O_2). The gas is heated by 50 °C, and the amount of heat gained is 1250 joules. Calculate the heat capacity.

Solution:

We use the formula:

$$Q = n.c.\Delta T$$

Substituting the values in:

$$1250\,J = 2\,mole.c.50\,°C$$

$$c = \frac{1250}{2 \cdot 50} = 12.5\,J/(mol \cdot °C)$$

Cont…

- Example:

You have an ideal gas with a molar heat capacity at constant pressure $\left(c_{p\mu}\right)$ of 29 $J/(mol \cdot ℃)$. Calculate the molar heat capacity at constant volume $\left(c_{v\mu}\right)$.

Solution:

For ideal gases, there is a relationship between c_p and c_v :

$$c_{p\mu} = c_{v\mu} + R_\mu$$

Where R is the ideal gas constant (approximately 8.31 $J/(mol \cdot ℃)$.

Substituting the values:

$$29 = c_{v\mu} + 8.31$$

Solving for c_v:

$$c_{v\mu} = 29 - 8.31 = 20.69\, J/(mol \cdot ℃)$$

Cont…

❖Example:

You have 2 moles of nitrogen gas (N_2) with a molar heat capacity at constant pressure ($c_{p\mu}$) of 29 J/(mol·°C) and at constant volume ($c_{v\mu}$) of 20.8 J/(mol·°C). The gas is heated from 25 °C to 75 °C at constant pressure. Calculate the heat required (Q).

Solution:

When heating the gas at constant pressure, the heat required is calculated using the equation:

$$Q = n \cdot c_{p\mu} \cdot \Delta T$$

Substituting the values:

$$Q = 2 \cdot 29 \cdot 50 = 2900\, J$$

Cont…

- Example: Heat Capacity of a gas

Let's assume we have a hypothetical gas, and its heat capacity at constant pressure c_p can be approximated by the following polynomial equation:

$$c_p(T) = a + bT + cT^2$$

Given Constants:

- $a = 1\ kJ/(kg.K)$
- $b = 0.02\ kJ/(kg.K^2)$
- $c = 0.0001 \frac{kJ}{kg.K^3}$

Calculate the heat capacity at 20, 50 and 80 ℃.

Cont…

Sol:

At $T = 20°\text{C}$:

$$c_p(20) = 1 + 0.02 \cdot (20 + 273.15) + 0.0001 \cdot (20 + 273.15)^2$$

$$c_p(20) = 1 + 5.863 + 8.5936 = 15.4566\ kJ/(kg.K)$$

At $T = 50°\text{C}$:

$$c_p(50) = 1 + 0.02 \cdot (50 + 273.15) + 0.0001 \cdot (50 + 273.15)^2$$

$$c_p(50) = 1 + 6.463 + 10.442 = 17.905\ kJ/(kg.K)$$

At $T = 80°\text{C}$:

$$c_p(80) = 1 + 0.02 \cdot (80 + 273.15) + 0.0001 \cdot (80 + 273.15)^2$$

$$c_p(80) = 1 + 7.063 + 12.4714 = 20.5344\ kJ/(kg.K)$$

Cont…

❖ Example: Calculate Heat transfer (Q)

The heat transfer Q can be calculated using the following integral:

$$Q = m \int_{T_1}^{T_2} c_p(T)\, dT$$

$$Q = m \left[aT + \frac{b}{2} T^2 + \frac{c}{3} T^3 \right]_{T_1}^{T_2}$$

Given Constants:

- $a = 1 \frac{kJ}{kg.K}, \quad b = 0.02 \frac{kJ}{kg.K^2}, \quad c = 0.0001 kJ/(kg.K^3)$

Calculate the heat transfer at 80 and 20 ℃. Calculate the total heat transfer. $m\ is\ 5\ kg$.

Cont…

Sol:

At $T = 80°C$:

$$Q_{80} = m\left[aT + \frac{b}{2}T^2 + \frac{c}{3}T^3\right]$$
$$= 5 \cdot \left[1 \cdot (80 + 273.15) + \frac{0.02}{2}(80 + 273.15)^2 + \frac{0.0001}{3}(80 + 273.15)^3\right]$$
$$= 15342\ kJ$$

At $T = 20°C$:

$$Q_{20} = m\left[aT + \frac{b}{2}T^2 + \frac{c}{3}T^3\right]$$
$$= 5 \cdot \left[1 \cdot (20 + 273.15) + \frac{0.02}{2}(20 + 273.15)^2 + \frac{0.0001}{3}(20 + 273.15)^3\right]$$
$$= 9961.33\ kJ$$

Total heat transfer:

$$Q = Q_{80} - Q_{20} = 15342 - 9961.33 = 5380.67\ kJ$$

Cont…

❖ Example: Heat Capacity of Air

- Assume we have air, and its heat capacity at constant pressure c_p can be modeled by the following polynomial equation:

$$c_p(T) = a + bT + cT^2 + dT^3$$

Given Constants of Air from Tables:

- $a = 28.11\ kJ/(kmol.K)$
- $b = 0.1967 \times 10^{-2}\ kJ/(kmol.K^2)$
- $c = 0.4802 \times 10^{-5}\ kJ/(kmol.K^3)$
- $d = -1.966 \times 10^{-9}\ kJ/(kmol.K^4)$

- Calculate the average heat capacity for air if $T_2 = 1526.85$ and $T_1 = 0\ ℃$.

Cont…

Sol:

To find c_p for Air we will use Average heat capacity $\overline{c_p}$:

$$\overline{c_{\mu p}} = \frac{\int_{T_1}^{T_2} c_p(T)dT}{T_2 - T_1} = \frac{\left[\left(aT_2 + \frac{b}{2}T_2^2 + \frac{c}{3}T_2^3\right) - \left(aT_1 + \frac{b}{2}T_1^2 + \frac{c}{3}T_1^3\right)\right]}{T_2 - T_1}$$

At $T = 0°\text{C} \Longrightarrow 273.15\ K$:

$$c_p(273.15) = 28.11 \cdot 273.15 + \frac{0.1967 \times 10^{-2}}{2} \cdot 273.15^2 + \frac{0.4802 \times 10^{-5}}{3} \cdot 273.15^3 + \frac{-1.966 \times 10^{-9}}{4} \cdot 273.15^4\ kJ/(kmol.K)$$

$$c_{\mu p}(273.15) = 7678.2465 + 73.3798 + 32.6215 - 2.74 = 7781.5078\ kJ/(kmol.K)$$

Cont…

At $T = 1526.85°C \Longrightarrow 1800\ K$:

$$c_{\mu p}(1800) = 28.11 \cdot 1800 + \frac{0.1967\ \times\ 10^{-2}}{2} \cdot 1800^2 + \frac{0.4802\ \times\ 10^{-5}}{3} \cdot 1800^3 + \frac{-1.966\ \times\ 10^{-9}}{4} \cdot 1800^4\ kJ/(kmol.K)$$

$$c_p(1800) = 50598 + 3186.54 + 9335.088 - 5159.5704 = 57960.0576\ kJ/(kmol.K)$$

$$\overline{c_{\mu p}} = \frac{\left[\left(aT_2 + \frac{b}{2}T_2^2 + \frac{c}{3}T_2^3\right) - \left(aT_1 + \frac{b}{2}T_1^2 + \frac{c}{3}T_1^3\right)\right]}{T_2 - T_1} = \frac{57960.0576 - 7781.5078}{1800 - 273.15} = 32.864\ kJ/(kmol.K)$$

$$\bar{c_p} = \frac{\overline{c_{\mu p}}}{\mu_{air}} = \frac{0.032864\ kJ/(mol.K)}{0.02896\ kg/mol} = 1.1367 kJ/(kg \cdot K)$$

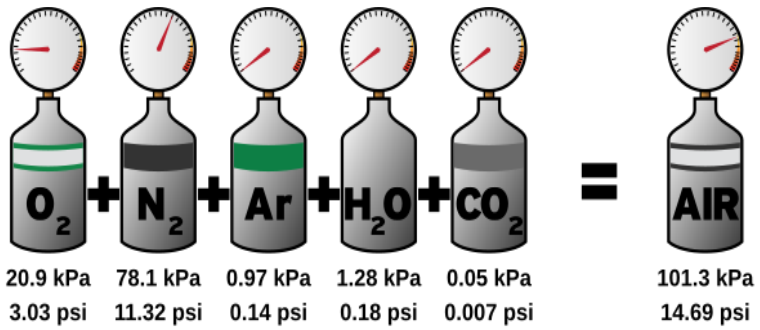
Dalton's Law of Partial Pressures

- **Dalton's Law of Partial Pressures** states that the total pressure of a mixture of gases is equal to the sum of the partial pressures of each individual gas in the mixture.
- In other words, if we have a mixture of gases, the pressure exerted by that mixture can be calculated by adding the pressures contributed by each gas separately.
- This law can be expressed mathematically as:

$$P_{total} = P_1 + P_2 + P_3 + \cdots + P_n$$

where,

$$P_1 = X_1 \cdot P_{total}$$



X_1 is the Mole Fraction, which equal:

$$\left(\frac{n_i}{n_{total}}\right)$$

which n is number of moles.

Cont…

- Example: A Mixture of Gases

Imagine you are in a room containing three gases:

- Oxygen (O_2) has a partial pressure of 0.2 atm.
- Nitrogen (N_2) has a partial pressure of 0.8 atm.
- Carbon Dioxide (CO_2) has a partial pressure of 0.1 atm.

Calculate the total pressure.

Solution:

Total pressure:

$$P_{total} = P_{o_2} + P_{N_2} + P_{co_2} = 0.2\ atm + 0.8\ atm + 0.1\ atm = 1.1\ atm$$

Cont…

- Example: Pressure Change When Adding a Gas

If you have a tank containing one gas, such as nitrogen with a partial pressure of 0.5 atm, and then you add oxygen with a partial pressure of 0.3 atm.

Calculate the total pressure

Solution:

Total Pressure After Addition:

$$P_{total} = P_{o_2} + P_{N_2} = 0.5\ atm + 0.3\ atm = 0.8\ atm$$

Cont...

❖ Example: Gas Mixture in Equilibrium

Imagine you are working in a laboratory and preparing a gas mixture consisting of: (Assume the temperature is 300 K , $R = 0.0821\ L \cdot atm\ /(K \cdot mol)$ and $V = 10\ L$:

- 1 mole of Oxygen (O_2).
- 2 moles of Nitrogen (N_2).
- 0.5 moles of Carbon Dioxide (CO_2).

Solution:

1. Calculate Total Moles:

$$n_{total} = n_{o_2} + n_{N_2} + n_{co_2} = 2 + 1 + 0.5 = 3.5\ mol$$

2. Calculate Total Pressure:

$$P_{total} = \frac{nR_\mu T}{V} = \frac{3.5 \cdot 0.0821 \cdot 300}{10} = 8.61\ atm$$

Cont...

3. Calculate Partial Pressure for each gas:

$$P_{N_2} = \frac{n_{N_2}}{n_{total}} \times P_{total} = \frac{2}{3.5} \times 8.61 \approx 4.92\ atm$$

$$P_{o_2} = \frac{n_{o_2}}{n_{total}} \times P_{total} = \frac{1}{3.5} \times 8.61 \approx 2.46\ atm$$

$$P_{co_2} = \frac{n_{co_2}}{n_{total}} \times P_{total} = \frac{0.5}{3.5} \times 8.61 \approx 1.23\ atm$$

Example: Chemical Reactions with Gases

Assume you are studying a reaction between nitrogen (N_2) and hydrogen (H_2) to produce ammonia (NH_3) according to the equation:

$$N_2 + 3H_2 \rightarrow 2NH_3$$

If you start with 1 mole of nitrogen and 3 moles of hydrogen in a closed container, and as a result of the reaction, 2 moles of ammonia are produced. (Assume Temperature is 298 K and Volume is 5 L)

1. Calculate Remaining Moles.
2. Calculate Total Moles.
3. Calculate Total Pressures.

Cont…

4. Calculate Partial Pressures.

Solution:

1. $Remainig\ nitrogen = n_{N_2} - \frac{n_{N_2}}{n_{NH_3}} \Longrightarrow Remainig\ nitrogen = 1 - \frac{1}{2} = 0.5\ mol$

$Remainig\ hydrogen = n_{H_2} - \frac{n_{H_2}}{n_{NH_3}} \Longrightarrow Remainig\ nitrogen = 3 - \frac{3}{2} = 1.5\ mol$

$Ammonia\ produced: 2\ mol$

2. $n_{total} = 0.5 + 1.5 + 2 = 4\ mol$

3. $P_{total} = \frac{nR_{\mu}T}{V} = \frac{4 \times 0.0821 \times 298}{5} \approx 19.54\ atm$

4. $P_{N_2} = X_{N_2} \cdot P_{total} = \frac{n_{N_2}}{n_{total}} \cdot P_{total} = \frac{0.5}{4} \cdot 19.54 = 2.44\ atm$

$P_{H_2} = X_{H_2} \cdot P_{total} = \frac{n_{H_2}}{n_{total}} \cdot P_{total} = \frac{1.5}{4} \cdot 19.54 = 7.31\ atm$

$P_{NH_3} = X_{NH_3} \cdot P_{total} = \frac{n_{NH_3}}{n_{total}} \cdot P_{total} = \frac{2}{4} \cdot 19.54 = 9.77\ atm$

Cont…

- Example: Decomposition of Ammonium Dichromate

Reaction Equation:

$$(NH_4)_2Cr_2O_7(s) \rightarrow Cr_2O_3(s) + 2NH_3(g) + H_2O\ (g)$$

Calculate Total moles after reaction and calculate partial pressure for decomposition. ($P_{total} = 100\ kPa$)

Sol:

Total moles after reaction:

$$n_f = 1 + 2 + 1 = 4\ moles$$

Cont...

We must calculate the mole fractions:

$$X_{NH3} = \frac{2}{4} = 0.5$$

$$X_{H_2O} = \frac{1}{4} = 0.25$$

$$X_{Cr_2O_3} = \frac{1}{4} = 0.25\ (though\ it\ is\ a\ solid\ and\ does\ not\ contribute\ to\ pressure)$$

Partial pressure:

We only consider gases,

$$P_{NH3} = X_{NH3} \cdot P_{total} = 0.5 \cdot 100\ kPa = 50\ kPa$$

$$P_{H_2O} = X_{H_2O} \cdot P_{total} = 0.25 \cdot 100\ kPa = 25\ kPa$$

The Zeroth Law in Thermodynamics

- **The zeroth law of thermodynamics** is a fundamental concept in thermodynamics that expresses the relationship between the temperatures of different bodies. Here's a summary of this law:

  " The zeroth law of thermodynamics states that if there are three bodies (A, B, and C) such that the temperature of body A is equal to the temperature of body B, and the temperature of body B is equal to the temperature of body C, then the temperature of body A will be equal to the temperature of body C. "

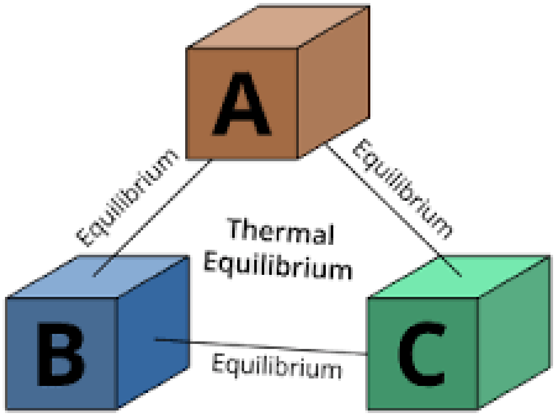
- **Symbolic Expression**

  If we have three bodies A, B and C, then:

  If $T_A = T_B$ and $T_B = T_C$

  Then $T_A = T_C$

- **Applications**
  - This law is used in the design of temperature measuring devices such as thermometers.
  - It contributes to the understanding of thermal equilibrium between bodies.



Zeroth law of Thermodynamics

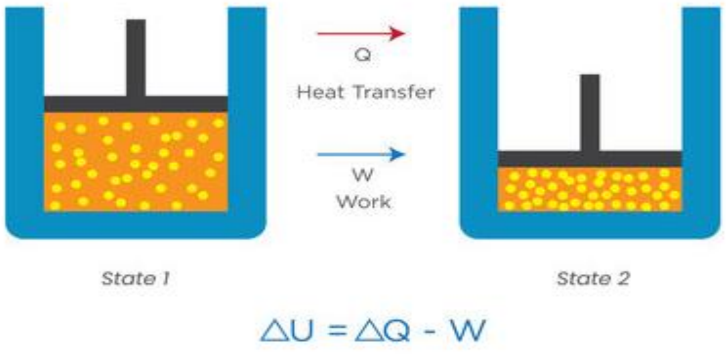
The First Law in Thermodynamics

- The first law of thermodynamics can be stated in various forms, but a common text for this law is:

- "The increase in the internal energy of a closed system is equal to the amount of heat added to the system minus the work done by the system on its surroundings.“

- In mathematical terms, this is expressed as:

$$\Delta U = Q - W$$



Where:

ΔU: Change in internal energy of the system.

Q: Heat added to the system (positive if added, negative if removed).

W: Work done by the system (positive if done by the system, negative if done on the system).

Cont…

- Types of Thermodynamic Processes:
  1. Isothermal Process: Temperature remains constant ($T = constant$).
     - Work Done (W):

$$W = nR_{\mu}Tln\left(\frac{V_f}{V_i}\right)$$

     - Heat Transfer (Q):

$$Q = W, \qquad since\ \Delta U = 0$$

  2. Adiabatic Process: no heat exchange with surroundings ($Q = 0$).
     - Work Done (W):

$$W = \Delta U$$

     - Heat Transfer (Q):

$$Q = 0$$

Cont…

3. Isochoric Process: Volume remains constant ($V = constant$).
   - Work Done (W):
   $$W = 0$$
   - Heat Transfer (Q):
   $$Q = \Delta U$$
4. Isobaric Process: Pressure remains constant ($P = constant$).
   - Work Done (W):
   $$W = P\Delta V, \qquad where\ \Delta V = V_f - V_i$$
   - Heat Transfer (Q):
   $$Q = \Delta U + P\Delta V$$

Cont…

❖ Work

There are two types of work:

1. **Volume Change Work (Mechanical Work):** is the work done when the volume of a system changes under the volume of a system changes under the influence of a certain pressure.

$$W_m = \int_{V_i}^{V_f} PdV$$

2. **Technical Work (Technical Work):** is the work done when the pressure of a system changes under the pressure of a system changes under the influence of a certain volume.

$$W_t = -\int_{P_i}^{P_f} VdP$$

Cont…

There are two types of work process:

1. **Expansion Work**: is the work done through expansion process; it's positive work.

2. **Compression Work**: is the work done through Compression process; it's negative work.

❖ **Internal energy**

Internal energy U is a fundamental concept in thermodynamics that represents the total energy contained within a system. It is particularly useful in processes that occur at constant volume.

$$\Delta U = mc_v \Delta T$$

Cont…

- **Enthalpy**

Enthalpy H is a thermodynamic property that represents the total heat content of a system. It is particularly useful in processes that occur at constant pressure, such as chemical reactions and phase changes. Enthalpy combines the internal energy of a system with the product of its pressure and volume. The enthalpy of a system is defined mathematically as:

$$H = U + PV$$

Change in Enthalpy

The change in enthalpy ΔH during a process is given by:

$$\Delta H = \Delta U + \Delta(PV)$$

At constant pressure:

$$\Delta H = \Delta U + P\Delta V$$

$$\Delta H = Q_p = mc_p\Delta T$$

Cont...

At constant Volume:

$$\Delta H = \Delta U + V\Delta P$$

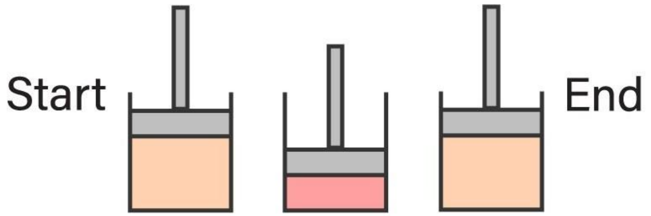
$$\Delta U = Q_V = mc_v\Delta T$$

$$\Delta H = mc_v\Delta T + V\Delta P$$

❖ **Reversible and Irreversible Process**

❑ **Reversible Processes**

A reversible process is an idealized process that occurs in such a way that the system can be returned to its original state without any net change in the system or its surroundings. In a reversible process, the system is always in equilibrium.



Cont…

Characteristics:

1. **Equilibrium:** The system is in thermodynamic equilibrium at all stages.

2. **No Dissipation of Energy:** There are no energy losses due to friction, turbulence, or other irreversible phenomena.

3. **Path Dependency:** The work done and heat exchanged depends only on the initial and final states, not on the path taken.

Examples:

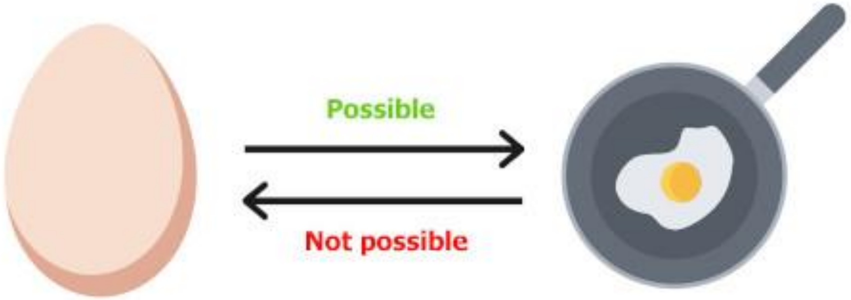
Isothermal Expansion of an Ideal Gas: When an ideal gas expands slowly and reversibly at a constant temperature, it can be compressed back to its original volume without any changes in the surroundings.

Phase Changes: Melting and freezing of ice at 0 °C under constant pressure can be considered reversible processes.

Cont…

❑ Irreversible Process

An irreversible process is one that cannot return to its initial state without changes occurring in the surroundings. These processes involve non-equilibrium states and often involve energy dissipation.



Cont...

Characteristics:

1. **Non-Equilibrium:** The system is not in equilibrium throughout the process.
2. **Dissipation of Energy:** Energy losses occur due to factors like friction, turbulence, and other forms of dissipation.
3. **Path Dependency:** The work done and heat exchanged depend on the specific pathway taken during the process.

Examples:

Free Expansion of a Gas: When a gas expands into a vacuum, it does so without doing work and cannot be returned to its original state without external intervention.

Combustion: The burning of fuel in an engine is an irreversible process that generates heat and work but cannot be reversed without changes to the fuel and the environment.

Heat Transfer: Heat flowing from a hot object to a cold one is an irreversible process.

Cont…

Summary of difference:

Feature	Reversible Process	Irreversible Process
Equilibrium	Always in equilibrium.	Not in equilibrium.
Energy Dissipation	No energy loss.	Energy lost due to friction, etc.
Path Dependency	Depends only on initial and final states.	Depends on the specific path.
Examples	Isothermal expansion, phase changes.	Free expansion, combustion.

Cont…

Quasi-Static and Non-Quasi Static Processes

Quasi-Static Processes

A quasi-static process is one that occurs very slowly, allowing the system to remain in thermodynamic equilibrium at all times.

Relation to Reversibility:

- Reversible Processes: Quasi-static processes are often reversible because they allow the system to adjust to changes gradually, ensuring that any infinitesimal change in state can be reversed without any net change in the system or its surroundings.

Example: A slow compression or expansion of a gas in a piston-cylinder arrangement, where the gas pressure and temperature adjust gradually, is an example of a quasi-static and reversible process.

Cont…

- **Non-Quasi Static Processes**

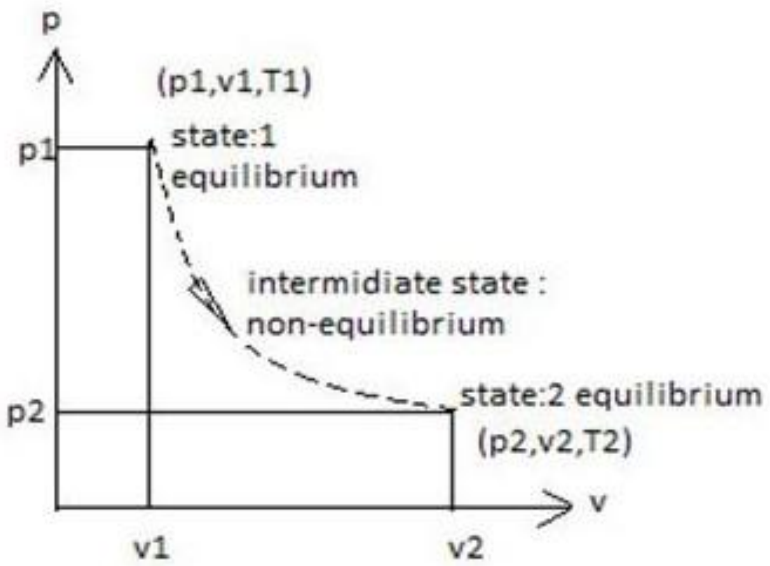
A non-quasi-static process occurs rapidly or in such a way that the system does not remain in equilibrium.

Relation to Reversibility:

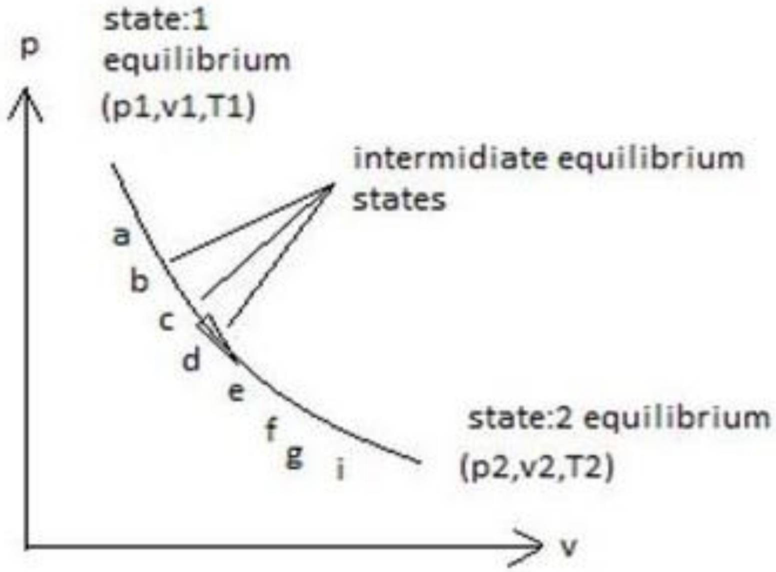
- Irreversible Processes: Non-quasi-static processes are typically irreversible because they involve rapid changes, friction, turbulence, or other factors that prevent the process from returning to its initial state without external work or changes in the surroundings.

Example: A sudden expansion of gas into a vacuum or the rapid combustion in an engine is considered a non-quasi-static and irreversible process.

Cont…



Non-quasi-static process



Quasi-static process

Cont…

Summary of Relationship:

Feature	Quasi-Static	Non-Quasi Static
Equilibrium	Always in equilibrium.	Not in equilibrium.
Reversibility	Often reversible	Typically irreversible
Speed of Change	Very slow	Rapid or sudden
Energy Losses	Minimal energy losses	Significant energy losses
Example	Slow gas expansion/compression	Rapid gas expansion into vacuum

Cont...

- **Phase Change**

Phase Change (or phase transition) in thermodynamics refers to the process in which a substance transitions from one state of matter to another due to changes in temperature or pressure. The primary states of matter involved in phase changes are solid, liquid, and gas.

- **Types of Phase Changes:**

Melting: Transition from solid to liquid (e.g., ice to water).

Freezing: Transition from liquid to solid (e.g., water to ice).

Vaporization: Transition from liquid to gas (e.g., water to steam).

Condensation: Transition from gas to liquid (e.g., steam to water).

Sublimation: Transition from solid to gas without passing through the liquid phase (e.g., dry ice to carbon dioxide gas).

Cont…

Deposition: Transition from gas to solid without passing through the liquid phase (e.g., frost formation).

- **Energy Changes:**

During a phase change, the temperature of the substance remains constant while heat is added or removed. This heat is referred to as latent heat.

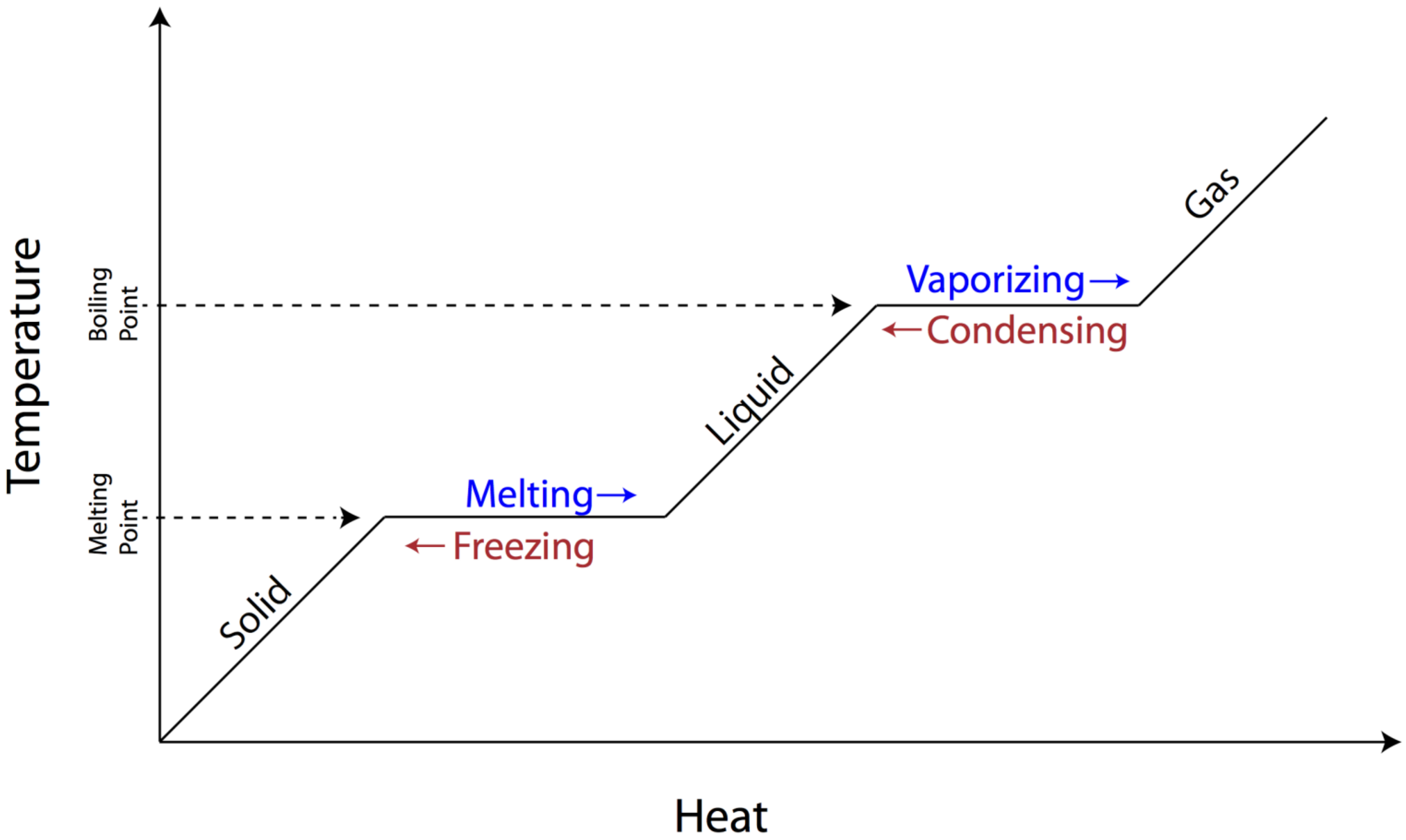
Examples include latent heat of fusion (for melting/freezing) and latent heat of vaporization (for vaporization/condensation).

- **Thermodynamic Implications:**

Phase changes are associated with changes in entropy. For instance, when a substance transitions from a solid to a gas, the entropy increases because the gas has more microstates available than the solid.

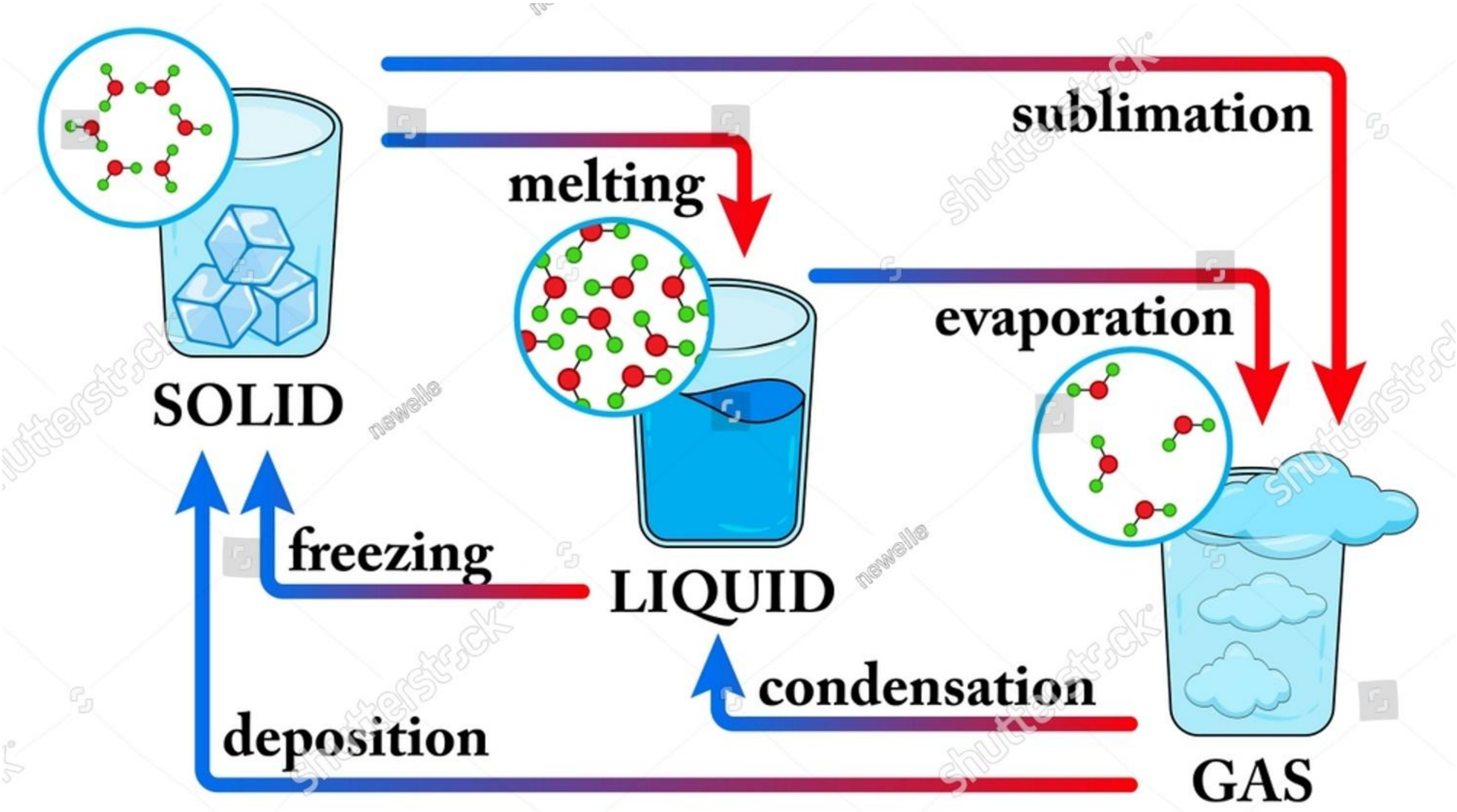
The laws of thermodynamics apply during phase changes, particularly the first and second laws.

Cont…



Temperature
Boiling Point
Melting Point
Solid
Melting→
←Freezing
Liquid
Vaporizing→
←Condensing
Gas
Heat

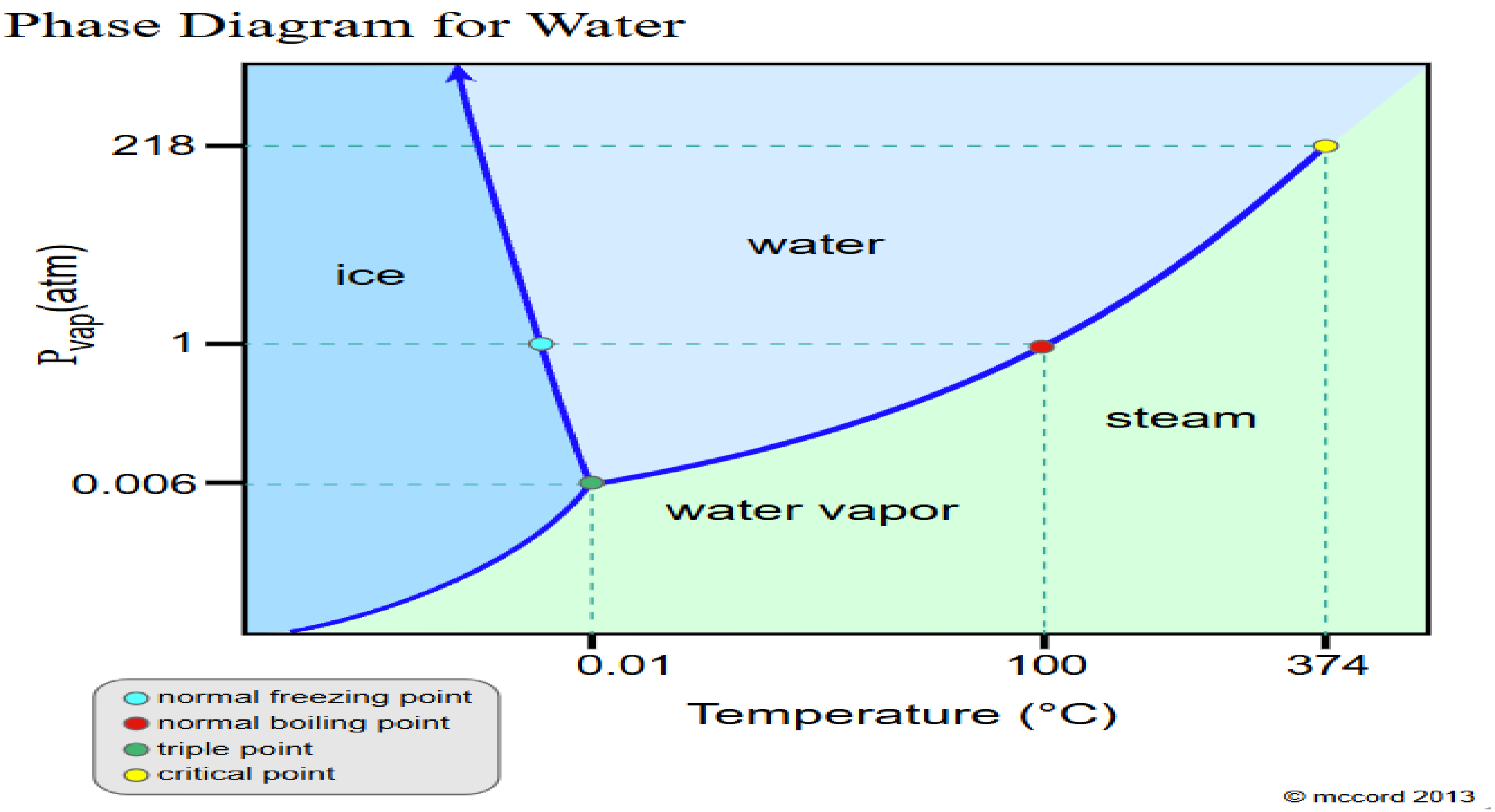
Cont…



sublimation
melting
evaporation
SOLID
freezing
LIQUID
condensation
deposition
GAS

Cont…

Phase Diagram for Water:



Cont…

- **Phase Diagram Consist of:**

1. **Lines:**

- **Melting Line:** Separates the solid phase from the liquid phase. Represents the conditions (pressure and temperature) at which a substance melts (transitions from solid to liquid).

- **Vaporization Line:** Separates the liquid phase from the gas phase. Represents the conditions at which a substance boils (transitions from liquid to gas).

- **Sublimation Line:** Separates the solid phase from the gas phase. Represents the conditions at which a substance sublimates (transitions from solid to gas without passing through the liquid phase).

2. **Points:**

- **Triple Point:** The point where all three lines intersect, allowing the substance to exist in all three phases (solid, liquid, gas) simultaneously.

Cont…

- **Critical Point:** The point beyond which the substance cannot be distinguished as a liquid or gas.

❖ Sensible and Latent Heat

In thermodynamics, latent heat and sensible heat are two important concepts related to the transfer of heat energy in a substance. Both play crucial roles in phase changes and temperature changes, respectively.

1. **Sensible Heat:** is the heat energy that causes a change in the temperature of a substance without changing its phase. It is the heat that can be sensed or measured with a thermometer.

$$Q = m \cdot c \cdot \Delta T$$

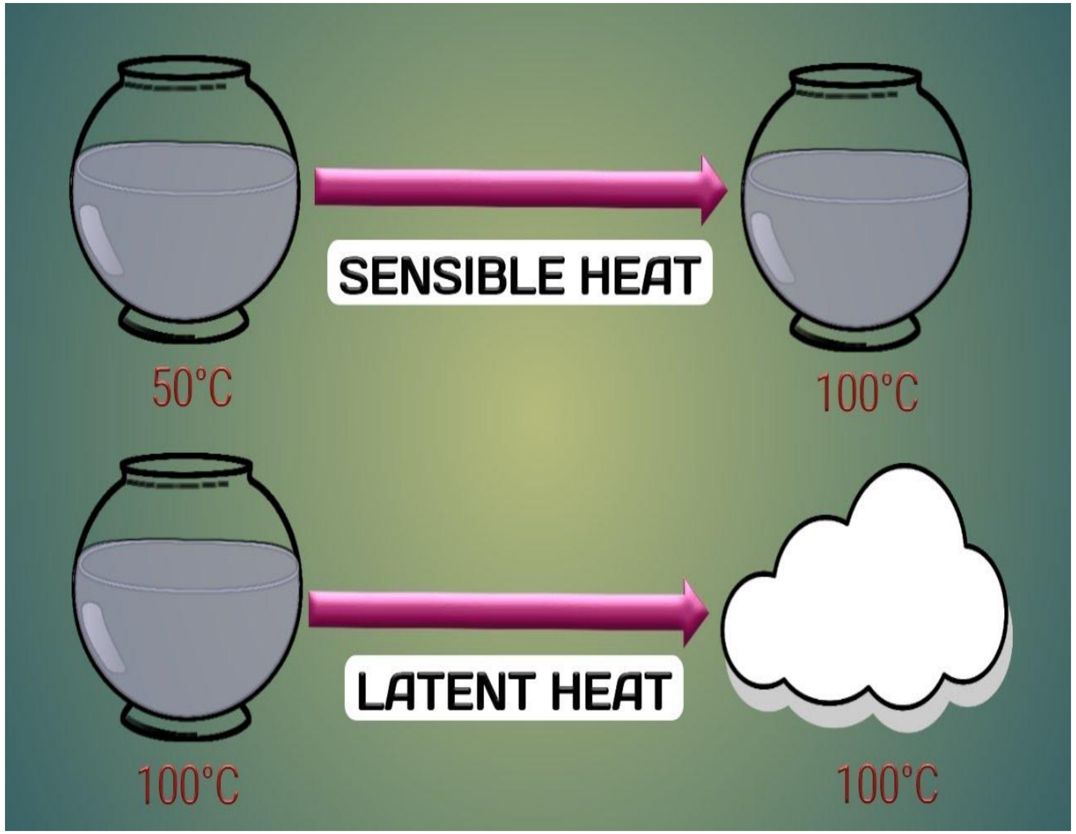
Cont…

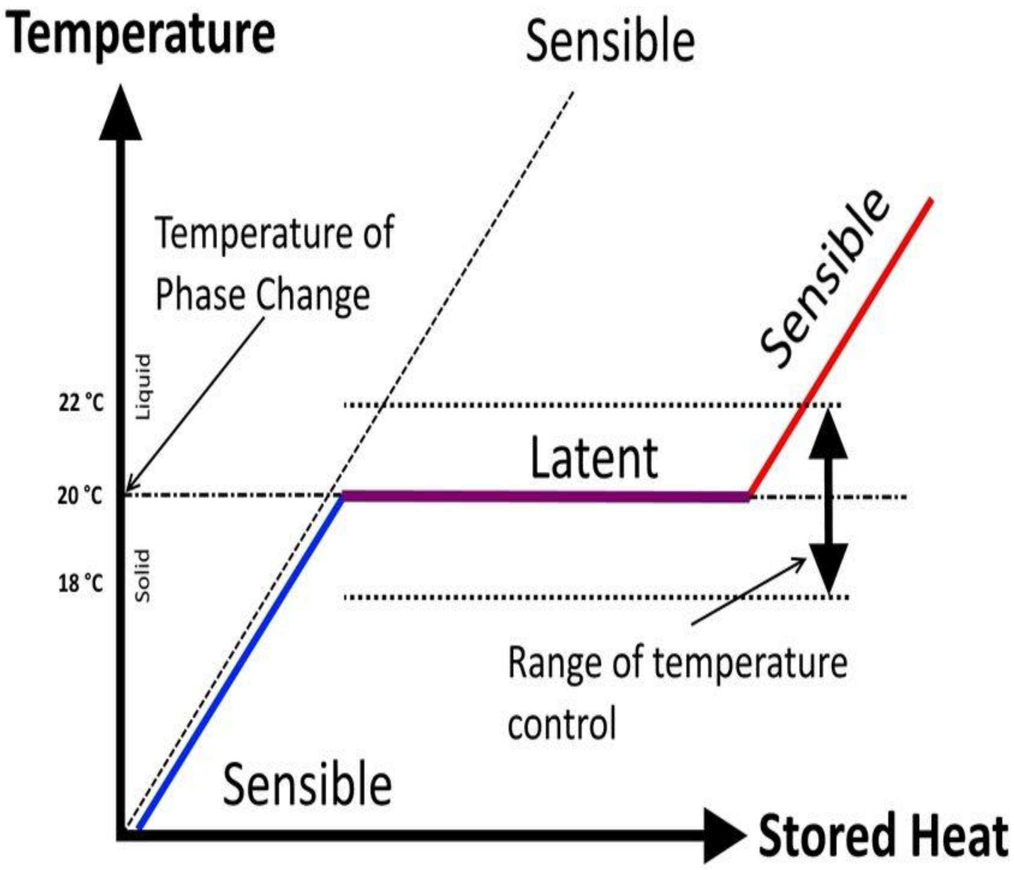
2. **Latent Heat:** is the heat energy absorbed or released by a substance during a phase change at constant temperature and pressure. This heat does not result in a temperature change but rather in a change of state.

$$Q = m \cdot L$$

Where L is latent heat (either of fusion or vaporization).

Cont…


SENSIBLE HEAT
50°C
100°C
LATENT HEAT
100°C
100°C


Temperature
Sensible
Temperature of
Phase Change
Sensible
Liquid
22 °C
Latent
20 °C
Solid
18 °C
Range of temperature
control
Sensible
Stored Heat

Cont...

Summary of Differences:

Aspect	Sensible Heat	Latent Heat
Definition	Heat Causing a temperature change	Heat Causing a phase change
Temperature change	Yes	No
Phase change	No	Yes
Examples	Heating water from $20°C$ to 100℃	Melting ice or boiling water
Formula	$Q = m \cdot c \cdot \Delta T$	$Q = m \cdot L$

Cont…

- **Example:** Heating an Ideal Gas

You have 2kg of an ideal gas that is heated from an initial temperature of 300k to a final temperature of 600k. The specific heat capacity at constant volume c_v is 500 $J/(kg.K)$, and the specific heat capacity at constant pressure c_p is 700 $J/(kg.K)$. The gas expands during this heating process. Calculate the Work Done by the System W.

Sol:

Calculate the Change in Internal Energy ΔU at Constant Volume

$$\Delta U = m \cdot c_v \cdot \Delta T = 2 \cdot 500 \cdot (600 - 300) = 300{,}000\,J$$

Calculate the Heat Added to the System Q_p at Constant Pressure

$$Q_p = m \cdot c_p \cdot \Delta T = 2 \cdot 700 \cdot 300 = 420{,}000J$$

Calculate the Work Done by the System W

$$W = P\Delta V$$

Cont…

But here we will use the first law of thermodynamics at Constant Pressure:

$$\Delta U = Q_p - W \Longrightarrow W = Q_p - \Delta U = 420{,}000 - 300{,}000 = 120{,}000 J$$

- **Example:** Heating Water at Constant Pressure

  You have 1kg of water at 25℃ and you want to heat it to 75℃. The c_p for water is 4,186 $J/(kg.℃)$. Calculate the change of enthalpy ΔH.

Sol:

Calculate the Heat Added to the System Q_p

$$Q_p = m \cdot c_p \cdot \Delta T = 1 \cdot 4{,}186 \cdot (75 - 25) = 209{,}300\ J$$

Calculate the change of enthalpy ΔH

$$\Delta H = Q_p = 209{,}300\ J$$

Cont…

❖ Example: Phase Change (Melting Ice)

You have 0.5kg of ice at 0℃ that you want to melt into water at 0℃ .The latent heat of fusion for ice is 334,000 J/kg. Calculate the change of enthalpy ΔH.

Sol:

Calculate the Heat Required for Melting Q_p

$$Q_p = m \cdot L_f = 0.5 \cdot 334{,}000 = 167{,}000\ J$$

Calculate the change of enthalpy ΔH

$$\Delta H = Q_p = 167{,}000\ J$$

Cont…

❖Example: Phase Change with Sensible Heat

You have 1kg of ice at -10°C that you want to heat to steam at 100°C. Calculate the Total energy required. (The latent heat of fusion for ice is 334,000 J/kg and 2,260,000 for Vaporization of water)

$c_{p\ for\ ice} = 2{,}090\ J/(kg.°C)$

$c_{p\ for\ water} = 4{,}186\ \ J/(kg.°C)$

Sol:

Sensible Heat to Heat the Ice to 0°C:

$$Q_1 = m \cdot c_p \cdot \Delta T = 1 \cdot 2{,}090 \cdot \big(0 - (-10)\big) = 20{,}900\ J$$

Latent Heat for Melting Ice:

$$Q_2 = m \cdot L_f = 1 \cdot 334{,}000 = 334{,}000\ J$$

Cont...

Sensible Heat to Heat water to 100℃:

$$Q_3 = m \cdot c_p \cdot \Delta T = 1 \cdot 4.186 \cdot (100 - 0) = 418{,}600\ J$$

Latent Heat for Vaporization:

$$Q_4 = m \cdot L_v = 1 \cdot 2{,}260{,}000 = 2{,}260{,}000\ J$$

Total energy required:

$$Q_{total} = Q_1 + Q_2 + Q_3 + Q_4 = 20{,}900 + 334{,}000 + 418{,}600 + 2{,}260{,}000 = 3{,}033{,}500\ J$$

Cont…

❖ Example: Heating gas with work done

You have $1\,m^3$ of an ideal gas in a rigid container initially at $300K$ and 100 Kpa. The gas is heated, causing the pressure to increase to 400 Kpa. Calculate the heat added to the gas.

$$c_{v\ for\ air} = 718\frac{J}{kg.K}, \qquad \mu_{air} = 0.029\ kg/mol$$

Sol:

Calculate the work done,

$$W = \Delta P \cdot V = (400 - 100) \cdot 1 = 300{,}000\ j$$

Calculating the change in internal energy

First, we must calculate the moles from Ideal Gas law

$$n = \frac{PV}{R_\mu T} = \frac{100{,}000\ J \cdot 1m^3}{8.314\ J/(mol.K) \cdot 300k} = 40.093$$

Cont…

$$m = n \cdot \mu = 40.093 \cdot 0.029 = 1.162\ kg$$

Second, we find T_f

$$T_f = \frac{400{,}000 \cdot 1}{40.093 \cdot 8.314} = 1200\ K$$

Then,

$$\Delta U = m \cdot c_v \cdot \Delta T = 1.162 \cdot 718 \cdot (1200 - 300) = 750884.4\ J$$

Calculate the heat added to the gas

$$Q_p = \Delta U + W = 750884.4 + 300000 = 1050884.4\ J$$

Cont…

- **Entropy**

Entropy (S) is a measure of the disorder or randomness in a given system. In thermodynamics, entropy is an important property that determines the natural direction of processes. The greater the disorder of the system, the higher its entropy value.

Basic Laws

1. **Reversible and Irreversible Process:**
   - **Reversible Process:** Occur without any changes in entropy.
   - **Irreversible Process:** Lead to an increase in entropy.
2. **Second Law of Thermodynamics:** it states that the entropy of an isolated system can never decrease. In other words, natural processes tend to increase entropy.

Cont…

Calculating Entropy

The change in entropy (ΔS) can be calculated using the equation:

$$\Delta S = \frac{Q}{T}$$

where:

- Q is the heat added or removed in a Thermal process.
- T is the absolute temperature (in Kelvin).

Entropy for reversible process

1. **General Formula for Entropy Change**

In a reversible process, the change in entropy ΔS can be calculated using the heat exchanged reversibly Q_{rev} at a constant temperature T:

Cont…

$$\Delta S = \frac{Q_{rev}}{T}$$

2. **Heat Transfer in Reversible Processes**

- **Reversible Heating:** if a system absorbs heat Q_{rev} at a constant temperature T**,** the change in entropy is:

$$\Delta S = \frac{Q_{rev}}{T}$$

- **Reversible Cooling:** Conversely, if a system loses heat Q_{rev} at the same temperature, the change in entropy becomes negative:

$$\Delta S = -\frac{Q_{rev}}{T}$$

3. **Total Entropy Change**

For reversible processes involving both the system and the surroundings, the total change in entropy can be considered as follows:

Cont…

$$\Delta S_{total} = \Delta S_{system} + \Delta S_{surroundings}$$

In a reversible process, the total entropy change is zero when considering the entire universe (system plus surroundings):

$$\Delta S_{total} = 0$$

Entropy for irreversible process

1. **Entropy Change of the System**

The entropy change of the system can be calculated using the heat transfer involved in the process. However, since the process is irreversible, the calculation may not be straightforward:

- **Heat Absorption**: If the system absorbs heat Q, the change in entropy can be expressed as:

$$\Delta S_{system} = \frac{Q}{T_{effective}}$$

Cont...

Here, $T_{effective}$ is the average temperature during the heat transfer, which may vary throughout the process due to the lack of equilibrium.

- **Heat Loss**: Conversely, if the system loses heat, the entropy change becomes negative:

$$\Delta S_{system} = -\frac{Q}{T_{effective}}$$

2. **Entropy Change of the Surroundings**

- **Heat Loss**: if the system loses heat, the Surroundings gain that heat:

$$\Delta S_{surroundings} = \frac{Q}{T_{surroundings}}$$

- **Heat Absorption**: If the system absorbs heat Q, the Surroundings lose that heat:

$$\Delta S_{surroundings} = -\frac{Q}{T_{surroundings}}$$

Cont…

3. **Total Entropy Change**

In irreversible processes, the total change in entropy ΔS_{total} is the sum of the entropy changes of the system and the surroundings:

$$\Delta S_{total} = \Delta S_{system} + \Delta S_{surroundings}$$

For irreversible processes, this total change will always be greater than zero:

$$\Delta S_{total} > 0$$

This reflects the second law of thermodynamics, which states that the entropy of an isolated system tends to increase over time.

Entropy for Ideal Gas

1. **Change in Entropy for an Ideal Gas:** For an ideal gas, the change in entropy between two states can be calculated using the formula:

Cont…

$$\Delta S = nc_v \ln\left(\frac{T_2}{T_1}\right) + nR_\mu ln\left(\frac{V_2}{V_1}\right)$$

2. **Entropy Change During Isothermal Processes:** For an ideal gas undergoing an isothermal (constant temperature) process, the change in entropy can be simplified. Since temperature remains constant, the equation reduces to:

$$\Delta S = nR_\mu ln\left(\frac{V_2}{V_1}\right)$$

3. **Entropy Change During Isobaric Processes:** For isobaric (constant pressure) processes, the change in entropy can be calculated as:

$$\Delta S = nc_p \ln\left(\frac{T_2}{T_1}\right)$$

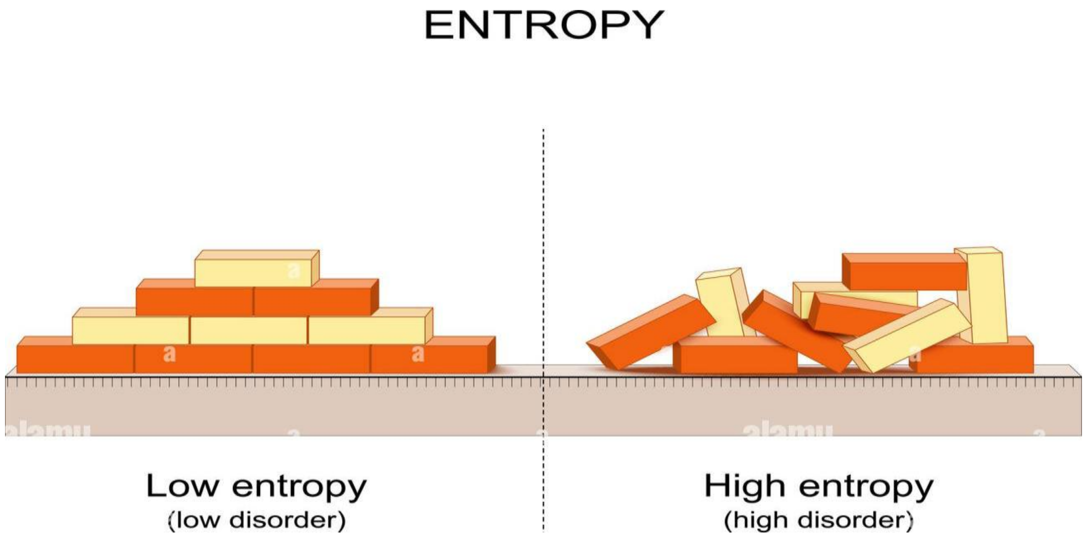
4. **Entropy Change During Isochoric Processes:** The change in entropy for an ideal gas undergoing an isochoric process (constant volume) can be expressed as:

Cont…

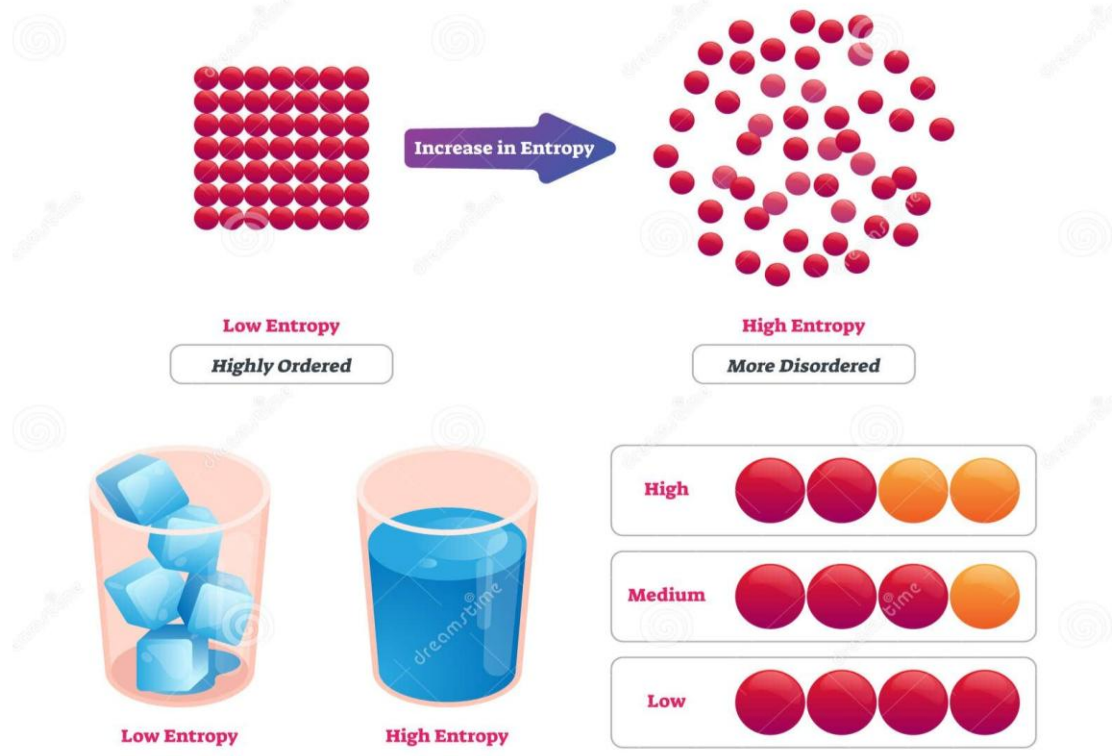
$$\Delta S = nc_v \ln\left(\frac{T_2}{T_1}\right)$$

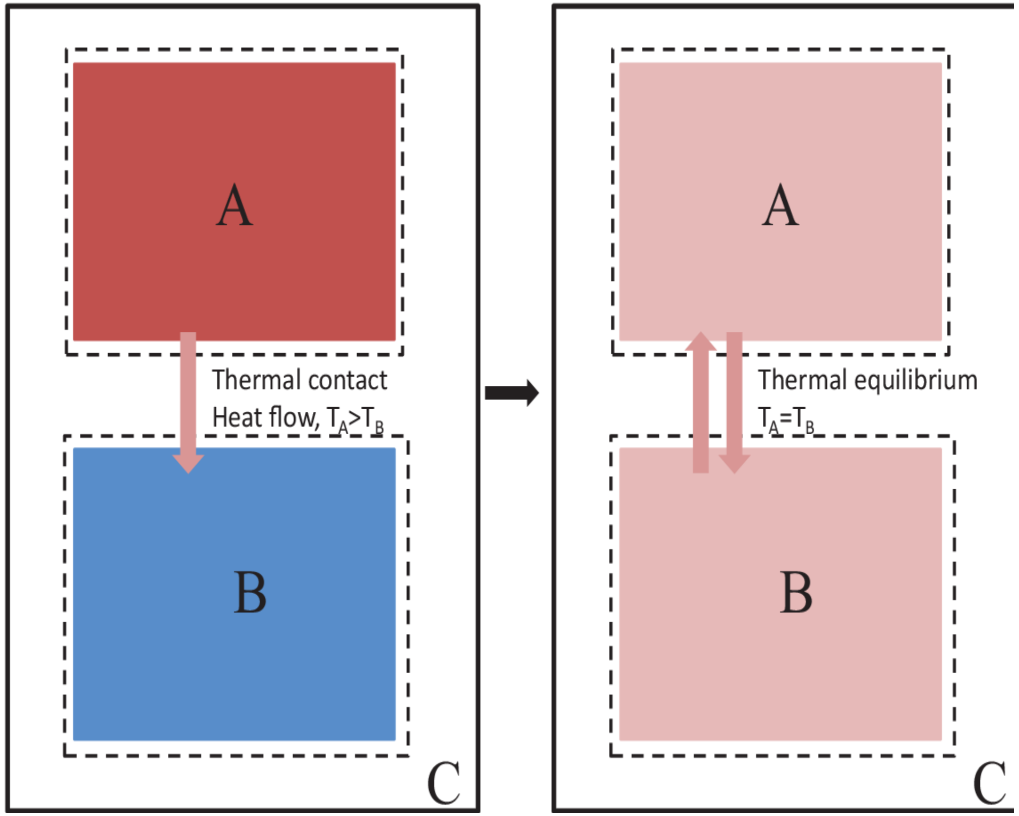
Entropy Change During Adiabatic Processes: The change in entropy for an ideal gas undergoing an Adiabatic Processes can be expressed as:

$$\Delta S = 0$$



Cont…


Increase in Entropy
Low Entropy
Highly Ordered
High Entropy
More Disordered
Low Entropy
High Entropy
High
Medium
Low


A
Thermal contact
Heat flow, T_A>T_B
B
C
A
Thermal equilibrium
T_A=T_B
B
C

Cont…

- Example: Reversible Isothermal Expansion of an Ideal Gas

Consider an ideal gas expanding isothermally (at constant temperature T from volume V_i to V_f.

Sol:

- **Heat Absorption:** During this process, the gas absorbs heat Q_{rev} from the surroundings. The change in entropy for the gas is:

$$\Delta S_{system} = \frac{Q_{rev}}{T}$$

- **Entropy Change of the surroundings:**

$$\Delta S_{surroundings} = -\frac{Q_{rev}}{T}$$

- **Total Entropy Change:**

$$\Delta S_{total} = \Delta S_{system} + \Delta S_{surroundings} = \frac{Q_{rev}}{T} - \frac{Q_{rev}}{T} = 0$$

Cont…

❖ Example: Irreversible Heat Transfer

Consider a hot object placed in a cooler environment.

Sol:

- **Heat Losses:** During this process, the gas losses heat Q from the surroundings. The change in entropy for the object is:

$$\Delta S_{system} = -\frac{Q}{T_{hot}}$$

- **Entropy Change of the surroundings:**

$$\Delta S_{surroundings} = \frac{Q}{T_{cold}}$$

- **Total Entropy Change:**

$$\Delta S_{total} = \Delta S_{system} + \Delta S_{surroundings} = -\frac{Q}{T_{hot}} + \frac{Q}{T_{cold}}, \qquad where\ T_{cold} < T_{hot}, so\ \frac{Q}{T_{cold}} > -\frac{Q}{T_{hot}}, \Delta S_{total} > 0$$

Cont…

❖ Example: Heat transfer

Consider a system where 100 J of heat flows from a hot reservoir at 400 K to a cold reservoir at 300 K. Find the Total change of entropy ΔS_{total}.

Sol:

- **For the hot reservoir:**

$$\Delta S_{hot} = -\frac{Q}{T_{hot}} = -\frac{100}{400} = -0.25\ J/K$$

- **For the cold reservoir:**

$$\Delta S_{cold} = \frac{Q}{T_{cold}} = \frac{100}{300} = 0.33\ J/K$$

- **The total change in entropy:**

$$\Delta S_{total} = \Delta S_{cold} + \Delta S_{hot} = 0.33 - 0.25 = 0.08\ J/K$$

Process Type	Isothermal	Adiabatic	Isobaric	Isochoric
Work at Change Volume	$W_m = P_1V_1 \ln\frac{V_2}{V_1}$ $W_m = P_1V_1 \ln\frac{P_1}{P_2}$ $w_m = RT \ln\frac{V_2}{V_1}$ $w_m = RT \ln\frac{P_1}{P_2}$	$W_m = \frac{1}{k-1}(P_1V_1 - P_2V_2)$ $w_m = \frac{R}{k-1}(T_1 - T_2)$ $W_m = \frac{P_1V_1}{k-1}\left[1 - \left(\frac{V_1}{V_2}\right)^{k-1}\right]$ $W_m = \frac{P_1V_1}{k-1}\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right]$ $w_m = \frac{RT_1}{k-1}\left[1 - \left(\frac{V_1}{V_2}\right)^{k-1}\right]$ $w_m = \frac{RT_1}{k-1}\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right]$	$W_m = P(V_2 - V_1)$ $w_m = R(T_2 - T_1)$	$w_m = 0$
Work at Change Pressure	$w_t = w_m$	$w_t = kw_m$	$w_t = 0$	$W_t = V(P_1 - P_2)$ $w_t = R(T_1 - T_2)$

Change in Internal energy	$\Delta \mathrm{u} = 0$	$\Delta \mathrm{u} = c_v(T_2 - T_1)$ $\Delta \mathrm{u} = -w_m$	$\Delta \mathrm{u} = c_v(T_2 - T_1)$	$\Delta \mathrm{u} = c_v(T_2 - T_1)$
Change in Enthalpy	$\Delta \mathrm{h} = 0$	$\Delta \mathrm{h} = c_p(T_2 - T_1)$ $\Delta \mathrm{u} = -w_t$	$\Delta \mathrm{h} = c_p(T_2 - T_1)$	$\Delta \mathrm{h} = c_p(T_2 - T_1)$
Change in Heat Transfer	$\Delta \mathrm{q} = w_m$	$\Delta \mathrm{q} = 0$	$\Delta \mathrm{q} = \Delta \mathrm{h}$	$\Delta \mathrm{q} = \Delta \mathrm{u}$
Change in entropy	$\Delta s = Rln\left(\frac{V_2}{V_1}\right)$ $\Delta s = -Rln\left(\frac{P_2}{P_1}\right)$ $\Delta s = c_v \ln\left(\frac{P_2}{P_1}\right) + c_p ln\left(\frac{V_2}{V_1}\right)$	$\Delta s = 0$	$\Delta s = c_v \ln\left(\frac{T_2}{T_1}\right) + Rln\left(\frac{V_2}{V_1}\right)$ $\Delta s = c_p \ln\left(\frac{T_2}{T_1}\right)$ $\Delta s = c_p \ln\left(\frac{V_2}{V_1}\right)$	$\Delta s = c_v \ln\left(\frac{T_2}{T_1}\right)$ $\Delta s = c_p \ln\left(\frac{T_2}{T_1}\right) - Rln\left(\frac{P_2}{P_1}\right)$ $\Delta s = c_v \ln\left(\frac{P_2}{P_1}\right)$

Cont…

❖ Example: Calculating work done in an isothermal Expansion

5kg of an ideal gas undergoes an isothermal expansion at a constant temperature. The initial conditions are as follows:

- Initial Pressure P_1 : 100 kPa

- Initial Volume V_1 : 0.1 m³

- Final Volume V_2 : 0.3 m³.

calculate the work done W during this expansion.

Sol:

$$W_m = P_1 V_1 \ln\left(\frac{V_2}{V_1}\right) = 100 \cdot 1000 \cdot 0.1 \cdot \ln\left(\frac{0.3}{0.1}\right) = 10{,}986\, J \Longrightarrow for\ 5kg, w_m = \frac{10{,}986\, J}{5\ kg} = 2{,}197.2\ J/kg$$

Cont…

- Example: Calculating work done in an isothermal Expansion

5kg of an ideal gas undergoes an isothermal expansion at a constant temperature. The initial conditions are as follows:

- Initial Pressure P_1 : 150 kPa

- Initial Volume V_1 : 0.05 m³

- Final Pressure P_2 : 75 kPa.

calculate the work done W during this expansion.

Sol:

$$W_m = P_1 V_1 \ln\left(\frac{P_1}{P_2}\right) = 150 \cdot 1000 \cdot 0.05 \cdot \ln\left(\frac{150{,}000}{75{,}000}\right) = 150{,}000 \cdot 0.05 \cdot 0.6931 = 7{,}000.65\,J \Longrightarrow for\ 5kg, w_m$$
$$= \frac{7{,}000.65\,J}{5\,kg} = 1400.13\,J/kg$$

Cont...

- Example: Calculating work done in an Adiabatic Process

5kg of an ideal gas undergoes an Adiabatic Process where the initial and final states are defined as follows:

- Initial Pressure P_1 : 200 kPa

- Initial Volume V_1 : 0.1 m^3

- Final Pressure P_2 : 100 kPa.

- Final Volume V_2 : 0.2 m^3.

- Adiabatic exponent k : 1.4.

calculate the work done W during this process.

Cont…

Sol:

$$W_m = \frac{1}{k-1}(P_1V_1 - P_2V_2) = \frac{1}{1.4-1}(200 \cdot 1000 \cdot 0.1 - 100 \cdot 1000 \cdot 0.2) = \frac{1}{0.4} \cdot 0 \Longrightarrow W_m = 0$$

❖ Example: Calculating work done in an Adiabatic Process

5kg of an ideal gas undergoes an Adiabatic Process where the initial and final states are defined as follows:

- Initial Temperature T_1 : 350 K.

- Final Temperature T_2 : 300 K.

- Ideal Gas Constant R : $287\ J/(kg \cdot K)$.

- Adiabatic exponent k : 1.4.

calculate the work done W during this process.

Cont...

Sol:

$$w_m = \frac{R}{k-1}(T_1 - T_2) = \frac{287}{1.4-1}(350-300) = 717.5 \cdot (50) = 35{,}875\, J/kg \Longrightarrow for\ 5kg, W_m = 35{,}875 \cdot 5 = 7{,}175\, J$$

- Example: Calculating work done in an Adiabatic Process

5kg of an ideal gas undergoes an Adiabatic Process where the initial and final states are defined as follows:

- Initial Pressure P_1 : 150 kPa

- Initial Volume V_1 : 0.3 m³

- Final Pressure P_2 : 50 kPa.

- Adiabatic exponent k : 1.4.

calculate the work done W during this process.

Cont…

Sol:

$$W_m = \frac{P_1V_1}{k-1}\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right] = \frac{150\cdot 1000\cdot 0.3}{1.4-1}\left[1-\left(\frac{150\cdot 1000}{50\cdot 1000}\right)^{\frac{1.4-1}{1.4}}\right] = 112{,}500\cdot[1-1.367] = -41{,}287.5\,J$$

$$\Rightarrow for\ 5kg, w_m = \frac{-41{,}287.5\,J}{5\,kg} = -8{,}257.5\,J/kg$$

- Example: Calculating work done in an Isobaric Process

5kg of an ideal gas expands from an initial volume to a final volume at constant pressure. The conditions are as follows:

- Pressure P : 150 kPa

- Initial Volume V_1 : 0.1 m³

Cont...

- Final Volume V_2 : 0.25 m³.

calculate the work done W during an expansion at constant pressure.

Sol:

$$W_m = P(V_2 - V_1) = 150 \cdot 1000 \cdot (0.25 - 0.1) = 22{,}500\, J \Rightarrow for\ 5kg, w_m = \frac{22{,}500\ J}{5\ kg} = 4{,}500\, J/kg$$

❖ Example: Calculating work done during a constant pressure process

5kg of an ideal gas is heated from an initial temperature to a final temperature at constant pressure. The conditions are as follows:

- Initial Temperature T_1 : 300 K.

- Final Temperature T_2 : 400 K.

Cont…

- Ideal Gas Constant R : $287\, J/(kg \cdot K)$.

calculate the work done W during an expansion at constant pressure.

Sol:

$$w_m = R(T_2 - T_1) = 287 \cdot (400 - 300) = 28{,}700 \text{ J/kg} \Longrightarrow for\ 5kg, W_m = 28{,}700 \cdot 5 = 143{,}500\ J$$

❖ Example: Calculating Change in Internal Energy of an Ideal Gas

5kg of an ideal gas undergoes a heating process at constant volume. The conditions are as follows:

- Initial Temperature T_1 : 300 K.

- Final Temperature T_2 : 400 K.

- Specific Heat at Constant Volume c_v : $718\, J/(kg \cdot K)$.

Cont…

calculate Change in Internal Energy ΔU during an expansion at constant pressure.

Sol:

$$\Delta \text{u} = c_v(T_2 - T_1) = 718 \cdot (400 - 300) = 71{,}800\, J/kg \Longrightarrow for\ 5kg, \Delta \text{U} = 71{,}800 \cdot 5 = 359{,}000\ \ J$$

- Example: Calculating Change in Internal Energy of an Ideal Gas

5kg of an ideal gas undergoes a heating process at constant pressure. The conditions are as follows:

- Initial Temperature T_1 : 250 K.

- Final Temperature T_2 : 350 K.

- Specific Heat at Constant Pressure c_p : $1005\, J/(kg \cdot K)$.

Cont…

Calculate the Change in Enthalpy ΔH during an expansion at constant pressure.

Sol:

$$\Delta \text{h} = c_p(T_2 - T_1) = 1005 \cdot (350 - 250) = 100{,}500\, J/kg \Longrightarrow for\ 5kg, \Delta \text{H} = 100{,}500 \cdot 5 = 502{,}500\ J$$

- Example: Calculating Change in Entropy of an Ideal Gas

5kg of an ideal gas undergoes an isothermal expansion from an initial volume to a final volume. The conditions are as follows:

- Initial Volume V_1 : 0.1 m³

- Final Volume V_2 : 0.3 m³.

- Ideal Gas Constant R : $287\, J/(kg \cdot K)$.

Cont…

calculate the Change in Entropy ΔS during an expansion at isothermal process.

Sol:

$$\Delta s = Rln\left(\frac{V_2}{V_1}\right) = 287 \cdot \ln 3 = 315.3\ J/kg \Longrightarrow for\ 5kg, \Delta S = 315.3 \cdot 5 = 1576.5\ J$$

- Example: Calculating Change in Entropy of an Ideal Gas

5kg of an ideal gas undergoes a process where both pressure and volume change at isothermal process. The conditions are as follows:

- Initial Pressure P_1 : 200 kPa

- Initial Volume V_1 : 0.1 m³

- Final Pressure P_2 : 100 kPa.

Cont...

- Final Volume V_2 : 0.2 m³.

- Specific Heat at Constant Volume c_v : $718\, J/(kg \cdot K)$.

- Specific Heat at Constant Pressure c_p : $1005\, J/(kg \cdot K)$.

calculate the Change in Entropy ΔS during an expansion at isothermal process.

Sol:

$$\Delta s = c_v \ln\left(\frac{P_2}{P_1}\right) + c_p ln\left(\frac{V_2}{V_1}\right) = 718 \cdot \ln 0.5 + 1005 \cdot \ln 2 = 199.1\, J/kg \cdot K \Longrightarrow for\ 5kg, \Delta \mathrm{S} = 199.1 \cdot 5 = 995.5\ J$$

Cont…

- **Steam Tables & Charts**

Steam tables & charts are primarily used in the study of thermodynamics, specifically in relation to the law of energy conservation and the ideal gas law. These tables and charts provide information about various properties of steam, such as temperature, pressure, and volume, which assists in analyzing thermal processes.

Steam tables and charts are particularly utilized in:

1. **Thermal Cycles:** Such as the Carnot cycle and Rankine cycle.

2. **Energy Calculations:** To analyze the efficiency of thermal machines.

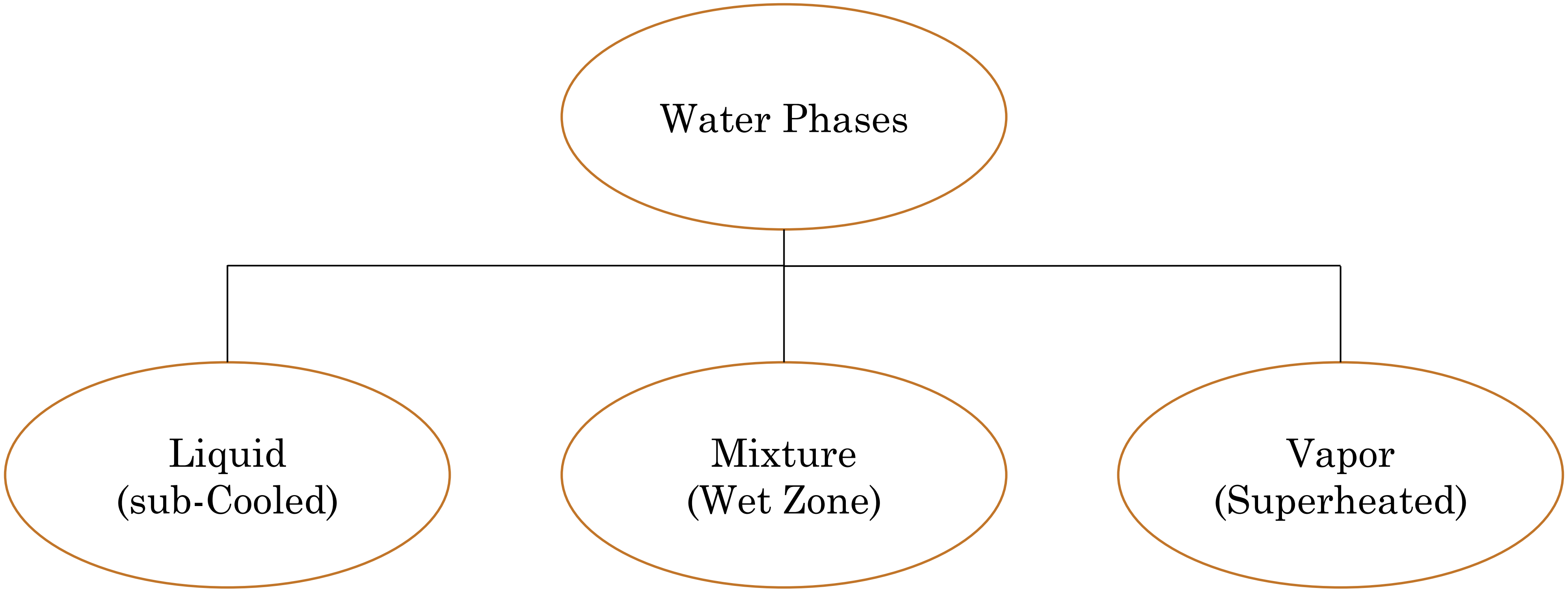
3. **System Design:** Such as turbines and boilers.

Steam tables and charts are tables that contain data about the properties of steam at various pressures and temperatures. These properties include:

Cont…

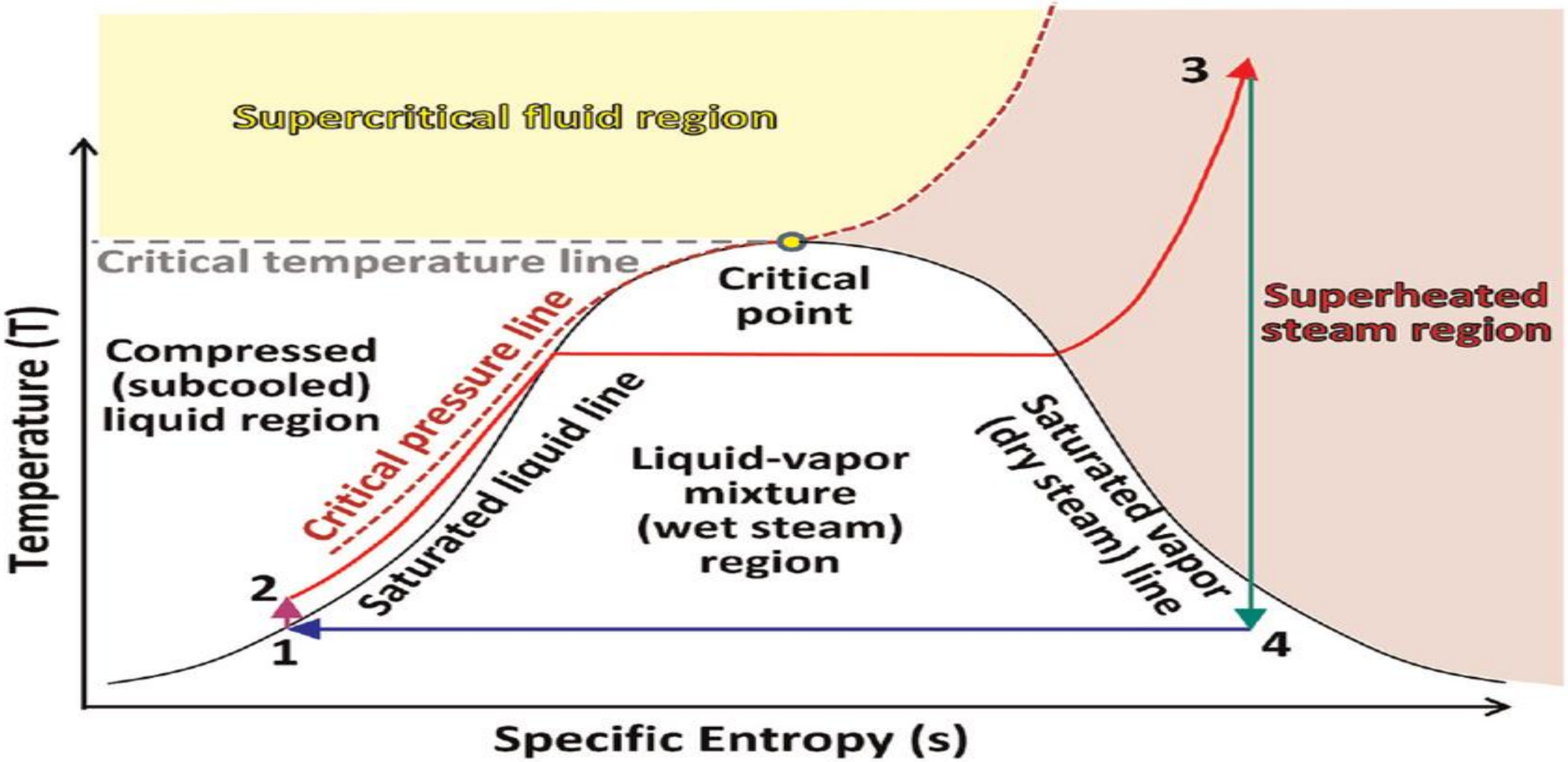
Property	Symbol	Unit	
Temperature	T	**K**, ℃	$T[K] = ℃ + 273$
Pressure	P	Bar, Kpa	$1\ MPa = 10\ bar$ $1\ bar = 100\ KPa$ $1\ MPa = 1000\ KPa$
Volume	V	m^3	Specific Volume (v) $\left[\frac{m^3}{kg}\right]$
Internal Energy	U	KJ	Specific Internal (u) $\left[\frac{kJ}{kg}\right]$
Enthalpy	H	KJ	Specific Enthalpy (h) $\left[\frac{kJ}{kg}\right]$
Entropy	S	KJ/K	Specific Entropy (s) $\left[\frac{kJ}{kg \cdot K}\right]$

Cont…



Water Phases
Liquid
(sub-Cooled)
Mixture
(Wet Zone)
Vapor
(Superheated)

Cont…



Supercritical fluid region
3
Critical temperature line
Critical point
Superheated steam region
Compressed (subcooled) liquid region
Critical pressure line
Saturated liquid line
Liquid-vapor mixture (wet steam) region
Saturated vapor (dry steam) line
Temperature (T)
2
1
4
Specific Entropy (s)

Cont…

Tables and Charts

- **Tables:**
  1. Compressed liquid water
  2. Saturated water—Temperature table
  3. Saturated water—Pressure table
  4. Superheated water
  5. Saturated ice–water vapor
  6. Saturated refrigerant-134a—Temperature table
  7. Saturated refrigerant-134a—Pressure table
  8. Superheated refrigerant-134a

Note: All properties in tables are specific.

Cont…

- **Charts:**
  1. T-S diagram for Water
  2. H-S diagram for Water
  3. *P-h* diagram for refrigerant-134a.

Note: All properties in charts are specific.

Cont…

Saturated Liquid and Gas

Saturated liquid and **saturated vapor** are two states of a substance that differ in their physical and chemical properties. Here's a detailed explanation of the differences between them:

1. **Saturated Liquid:** A saturated liquid is a liquid at its boiling point for a given pressure and temperature, existing in equilibrium with its vapor. The saturated liquid can coexist with its vapor.

Properties:

Temperature: The temperature of a saturated liquid depends on the pressure. For example, at atmospheric pressure (101.3 kPa), water boils at 100 °C.

Latent Heat of Vaporization: If heat is added to the saturated liquid, it begins to convert to vapor without an increase in temperature.

Cont…

2. **Saturated Gas:** A saturated vapor is a vapor that exists at the condensation point for a given pressure and temperature, in equilibrium with a saturated liquid. If heat is removed or pressure is reduced, the vapor can condense into a liquid.

Properties:

Temperature: Like the saturated liquid, the temperature of a saturated vapor depends on the pressure. At atmospheric pressure, saturated steam is at 100 °C.

Latent Heat of Vaporization: If heat is removed from the saturated vapor, it begins to convert back to liquid without decreasing in temperature.

Cont…

Summary of Differences:

Property	Saturated Liquid	Saturated Vapor
State	Liquid	Gas (Vapor)
Equilibrium	In equilibrium with vapor	In equilibrium with liquid
Phase Transition Heat	Transitions to vapor with added heat	Transitions to liquid with removed heat
Pressure and Temperature	Depends on boiling point	Depends on condensation point

Cont...

Saturated Water and mixture ratio

Saturated water, or saturated steam, refers to the state of water at which it exists in equilibrium between liquid and vapor phases. This state is characterized by specific properties that depend on temperature or pressure. Below are some key relationships and properties associated with saturated water:

Key Properties of Saturated Water

1. **Saturation Temperature (T_s)**
2. **Saturation Pressure (P_s)**
3. **Specific Volume (v_f, v_g, v_{fg}):**
   - v_f: specific volume of saturated fluid.
   - v_g: specific volume of saturated vapor.
   - v_{fg}: difference in specific volume of saturated between saturated vapor v_g and saturated liquid v_f.

Cont…

4. **Enthalpy (h_f, h_g, h_{fg}):**
   - h_f: Enthalpy of saturated fluid.
   - h_g: Enthalpy of saturated vapor.
   - $h_{fg} = h_g - h_f$: Latent heat of phase change.
5. **Entropy (s_f, s_g, s_{fg}):**
   - s_f: Entropy of saturated fluid.
   - s_g: Entropy of saturated vapor.
   - $s_{fg} = s_g - s_f$: change in entropy during phase change.

Mixture Ratio or Quality (x)

Quality is defined as the ratio of the mass of vapor to the total mass of the mixture:

$$x = \frac{m_g}{m_f + m_g} = \frac{P - P_f}{P_g - P_f} = \frac{v - v_f}{v_g - v_f} = \frac{h - h_f}{h_g - h_f} = \frac{s - s_f}{s_g - s_f}$$

$$, \quad if\ x = 0, saturated\ liquid, if\ x = 1, saturated\ vapor$$

Cont…

Calculating Properties of Mixtures:

For a mixture of saturated liquid and vapor, properties can be calculated using the quality (x):

- Specific volume:

$$v = v_f + x(v_g - v_f)$$

- Enthalpy:

$$h = h_f + xh_{fg}$$

- Entropy:

$$s = s_f + xs_{fg}$$

Note: in general, in saturation water the given is usually one property. (T or V or P or S or H)

Cont…

- Example: you have a saturated vapor at $T = 35°C$, Using steam Tables Find each of:
  - Saturated Pressure.
  - Specific Volume
  - Specific Enthalpy
  - Specific Entropy

  Sol:

  Saturated Pressure: 5.6291 kPa

  Specific Volume: 25.205 $\frac{m^3}{kg}$

  Specific Enthalpy: 2564.6 $\frac{kJ}{kg}$

  Specific Entropy: 8.3517 $\frac{kJ}{kg \cdot k}$

Cont…

- Example: Suppose we have saturated water at a temperature of 100 °C. From steam tables, find the following properties: (Assume the mixture enthalpy h is 1500 $\frac{kJ}{kg}$).
  - Quality (x).
  - Specific Volume
  - Specific Entropy

  Sol:

Saturated Liquid:

- $h_f = 419.04\ kJ/kg$
- $v_f = 0.00104\ m^3/kg$
- $s_f = 1.307\ kJ/(kg.K)$

Saturated Vapor:

- $h_g = 2676.1\ kJ/kg$
- $v_g = 1.673\ m^3/kg$
- $s_g = 7.354\ kJ/kg$

Cont...

Calculate Quality (x)

$$x = \frac{h - h_f}{h_g - h_f} = \frac{1500 - 419.04}{2676.1 - 419.04} \approx 0.479$$

Calculate Specific Volume:

$$v = v_f + x(v_g - v_f) = v_f + xv_{fg} = 0.00104 + 0.479(1.673 - 0.00104) = 0.8019\, m^3/kg$$

Calculate the entropy:

$$s = s_f + x(s_g - s_f) = 1.307 + 0.479(7.354 - 1.307) = 4.2035\, KJ/(kg.K)$$

Cont…

- Example: determine properties of superheated steam at $P = 300\ kPa\ and\ T = 150℃$.

Sol:

Pressure (kPa)	**Temperature (℃)**	**Enthalpy *h* (kJ/kg)**	**Entropy *s* (kJ/kg.K)**	**Specific Volume *v* (m^3/kg)**
300	150	2761.2	7.0792	0.63402

Cont…

- Example: determine the region for water at $P = 100\ kPa\ and\ T = 99.61℃$.

Sol:

By Using Tables, The region for water is saturated water (mix-region).

- Example: if you have 3 points A,B and C, for Point A the pressure and temperature is $P = 100\ kPa\ and\ T = 133.52℃$. For Point B the pressure and temperature is $P = 300\ kPa\ and\ T = 133.52℃$ and for point C the pressure and Specific volume is $P = 300\ kPa\ and\ v = 2\ m^3/kg$. determine the region for water at each Point.

Sol:

First of all, we have to go for saturated water – Pressure table:

for Point A at $P = 100\ kPa$:

$$T = 133.52℃, and\ T_{sat} = 99.61, \quad so\ T > T_{sat}, \quad Thats\ mean\ Superheated\ Vapor\ table$$

for Point B at $P = 300\ kPa$:

$$T = 133.52℃, and\ T_{sat} = 133.52, \quad so\ T = T_{sat}, \quad Thats\ mean\ Saturated\ Water\ table$$

for Point C at $P = 300\ kPa$:

$$v = 2m^3/kg, and\ v_g = 0.60582, \quad so\ v > v_g, \quad Thats\ meanSuperheated\ Vapor\ table$$

Cont…

Interpolation in thermodynamics

Interpolation is a method used to estimate values between two known points. In thermodynamics, interpolation can be useful when you need to obtain specific properties of a substance between two points in tables or diagrams. We can express as:

$$\frac{Value_{Required} - Value_{Initial}}{Value_{final} - Value_{Initial}} = \frac{Value_{Required} - Value_{Initial}}{Value_{final} - Value_{Initial}}$$

- Example: Suppose you are working with water and need to calculate the enthalpy h at a pressure of 175 kPa with an unknown temperature. You have the following property table for water:

Pressure (kPa)	Enthalpy ***h*** (kJ/kg)
150	340
200	504

Sol:

$$\frac{175 - 150}{200 - 150} = \frac{h - 340}{504 - 340} \Rightarrow h = 422\ kJ/kg$$

Cont…

- Example: if you have H_2O at $T = 180°C\ and\ v = 0.9\ m^3/kg$, Find the phase and pressure

Sol:

First of all, we have to go for saturated water – Temperature table:

At $T = 180°C$:

$$v = 0.9\frac{m^3}{kg}\ and\ v_g = 0.19384, \qquad so\ v > v_g, \qquad Thats\ mean\ Superheated\ Vapor\ table$$

For pressure at $T = 180°C$:

We have to do Interpolation:

From $Superheated\ Vapor\ table$ At $P = 0.20\ MPa$

$$T = 150°C, v = 0.95986$$

$$T = 180°C, v = ??$$

$$T = 200°C, v = 1.08049$$

$$\frac{200 - 150}{1.08049 - 0.95986} = \frac{180 - 150}{v - 0.95986} \Rightarrow v = 1.032238\ m^3/kg$$

Cont…

From *Superheated Vapor table* At $P = 0.30\ MPa$

$$T = 150℃, v = 0.63402$$

$$T = 180℃, v = ??$$

$$T = 200℃, v = 0.71643$$

$$\frac{200 - 150}{0.71643 - 0.63402} = \frac{180 - 150}{v - 0.63402} \Longrightarrow v = 0.683466\ m^3/kg$$

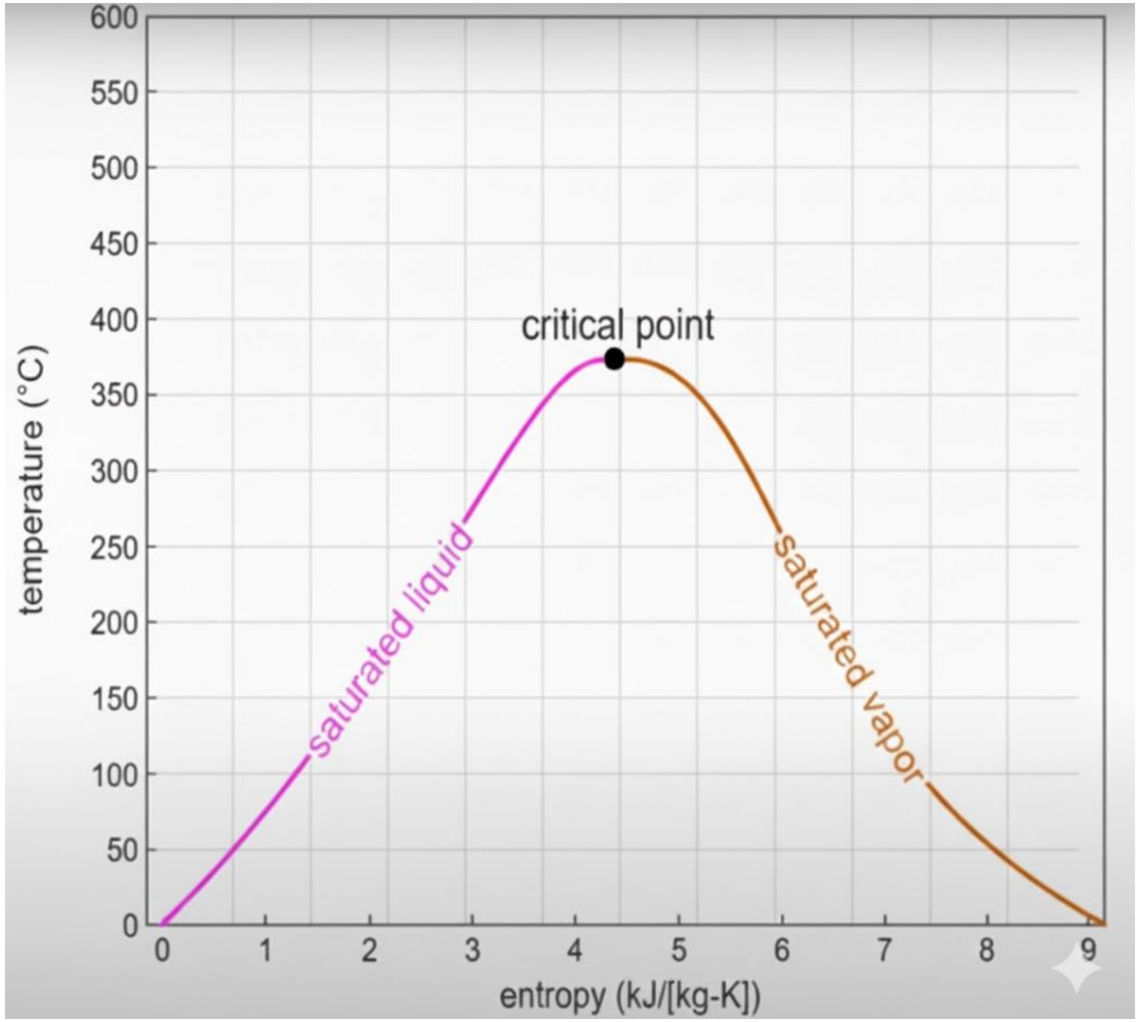
As you know, $v = 0.9\ m^3/kg$, so we have to do interpolation between $P = 0.30\ MPa$ and $P = 0.20\ MPa$.

$$\frac{300 - 200}{0.683466 - 1.032238} = \frac{P - 200}{0.9 - 1.032238} \Longrightarrow P = 237.9153\ kPa$$

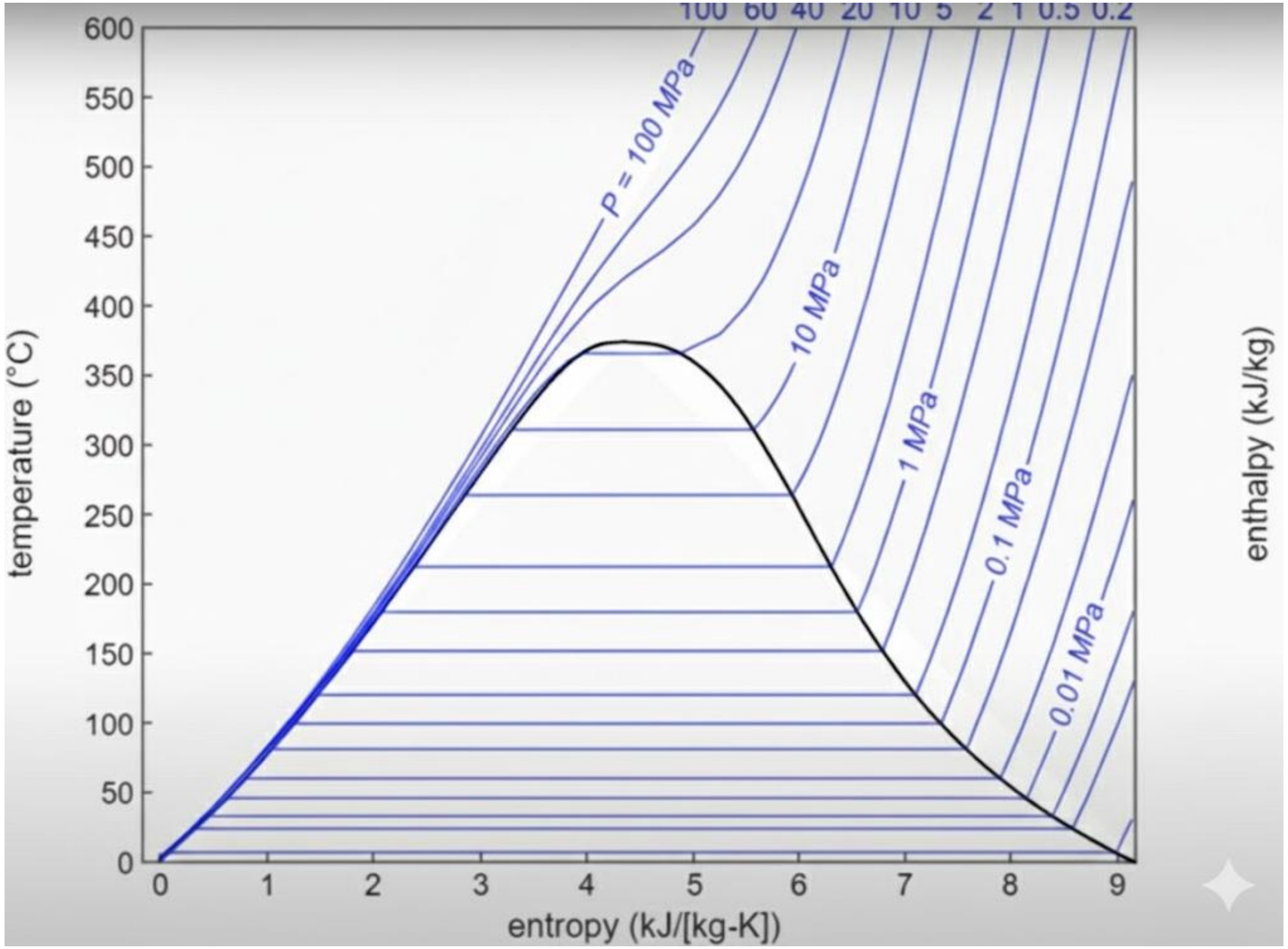
Cont…

T-S diagram

A **T-S diagram**, or **Temperature-Entropy diagram**, is a graphical representation used in thermodynamics to illustrate the relationship between temperature (T) and entropy (S) for a substance during various thermodynamic processes.

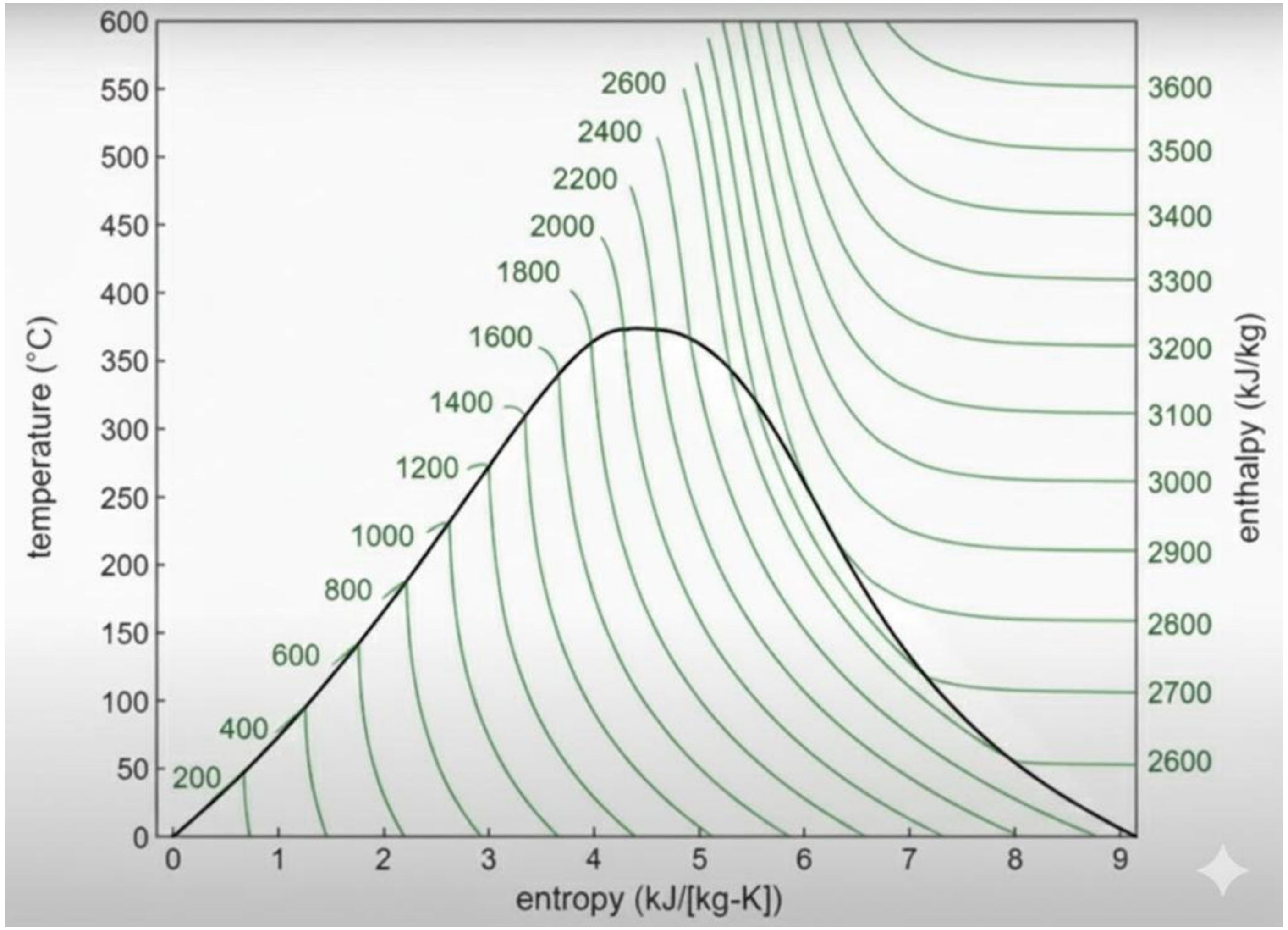


Cont…



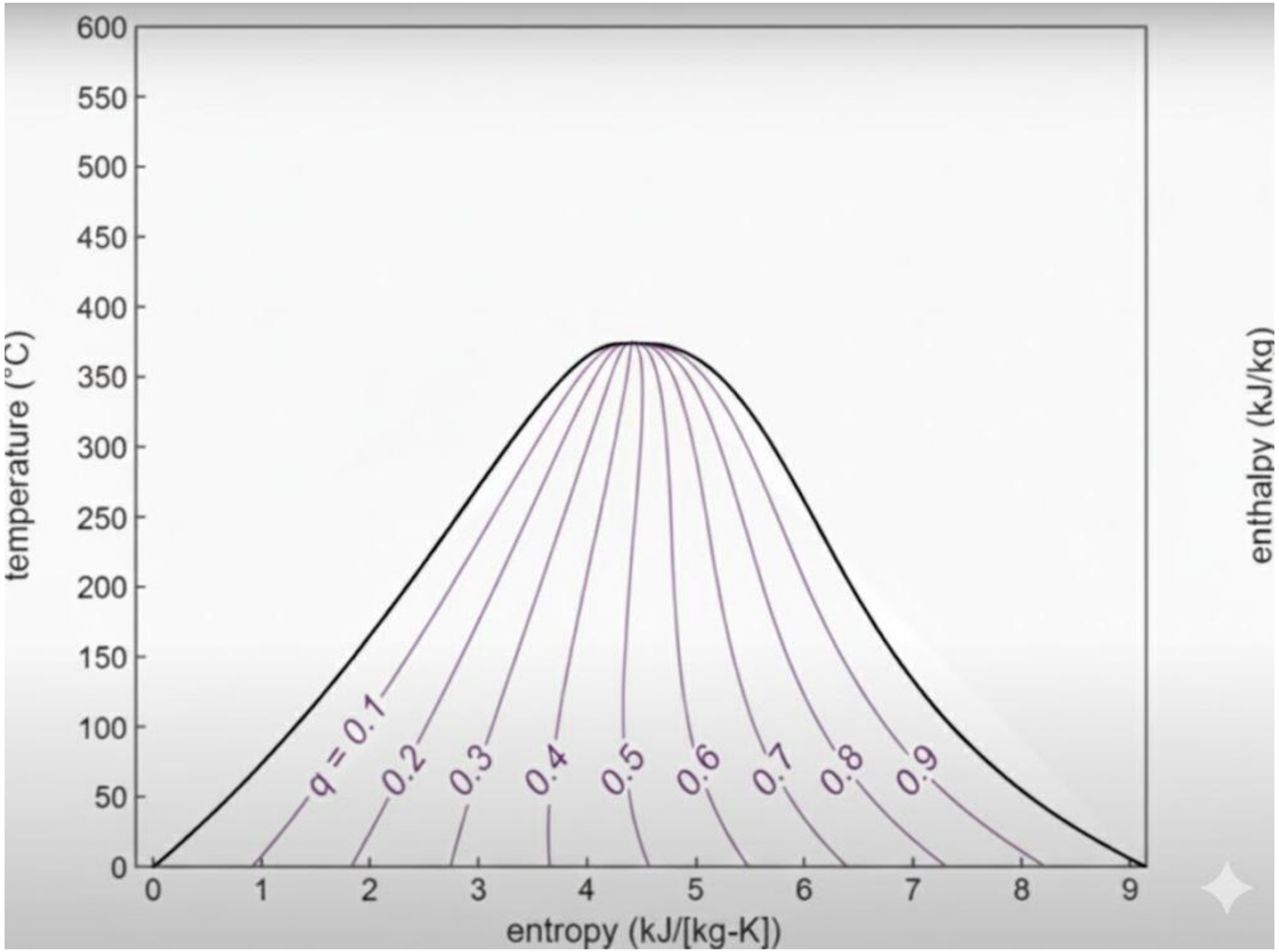
100 60 40 20 10 5 2 1 0.5 0.2
P = 100 MPa
10 MPa
1 MPa
0.1 MPa
0.01 MPa
temperature (°C)
entropy (kJ/[kg-K])
enthalpy (kJ/kg)
600
550
500
450
400
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9

Cont…



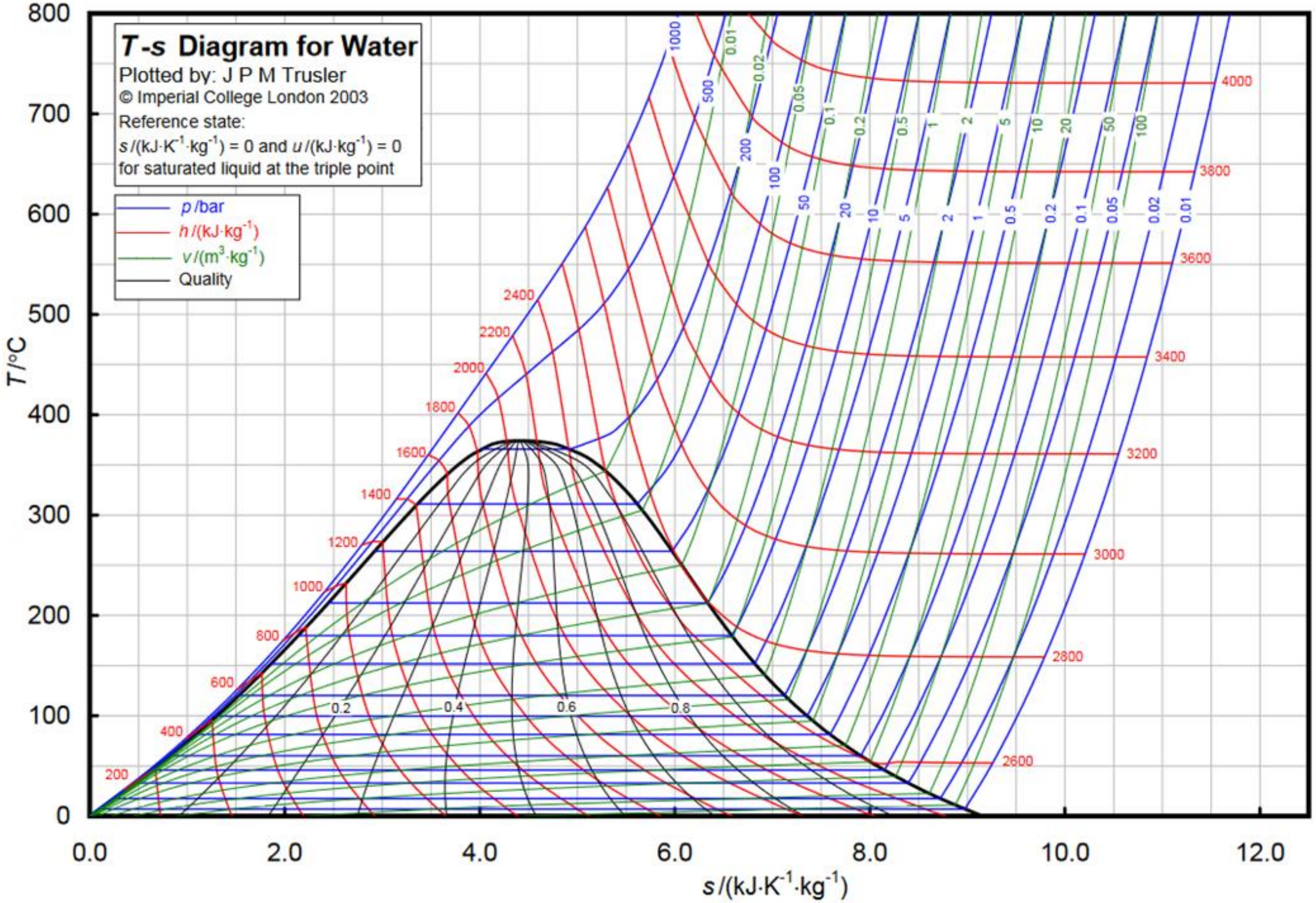
600
550
500
450
400
350
300
250
200
150
100
50
0
temperature (°C)
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1
2
3
4
5
6
7
8
9
entropy (kJ/[kg-K])
3600
3500
3400
3300
3200
3100
3000
2900
2600
2700
2600
enthalpy (kJ/kg)

Cont...



600
550
500
450
400
350
300
250
200
150
100
50
0
temperature (°C)
0
1
2
3
4
5
6
7
8
9
entropy (kJ/[kg-K])
enthalpy (kJ/kg)
q = 0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Cont…


T-s Diagram for Water
Plotted by: J P M Trusler
© Imperial College London 2003
Reference state:
s /(kJ·K⁻¹·kg⁻¹) = 0 and u /(kJ·kg⁻¹) = 0
for saturated liquid at the triple point
p /bar
h /(kJ·kg⁻¹)
v /(m³·kg⁻¹)
Quality
T /°C
s /(kJ·K⁻¹·kg⁻¹)

Cont…

- Example: you have a saturated water at $P = 50\,Bar$ with quality 80%, Using steam Charts Find each of:
  - Saturated Temperature.
  - Specific Enthalpy

Sol:

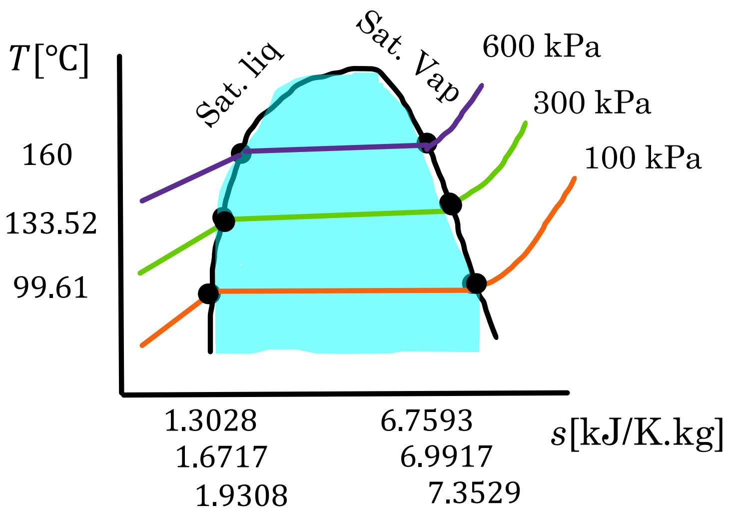
Saturated Temperature : 260℃

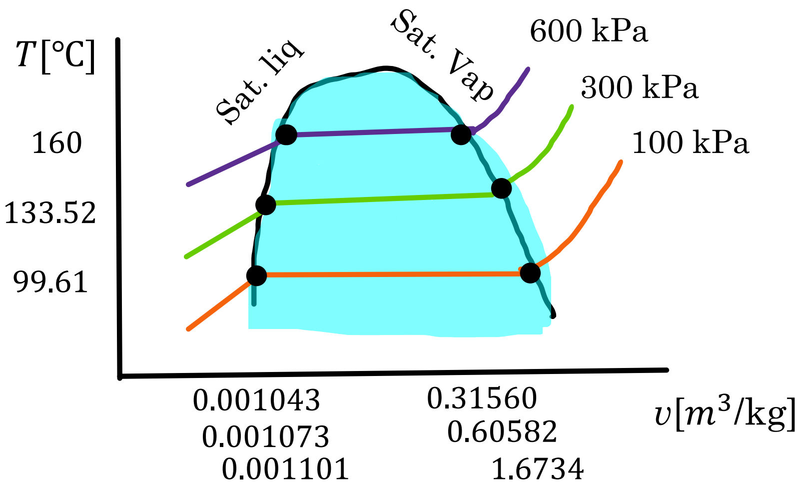
Specific Enthalpy: 2400 $\frac{kJ}{kg}$

Cont…

❖ Example: if you have 3 pressure situations for water at $P_1 = 100\ kPa, P_2 = 300\ kPa\ and\ P_3 = 600$, find the properties for the 3 situations and draw the T-S and T-V diagram for all situations.

Sol:

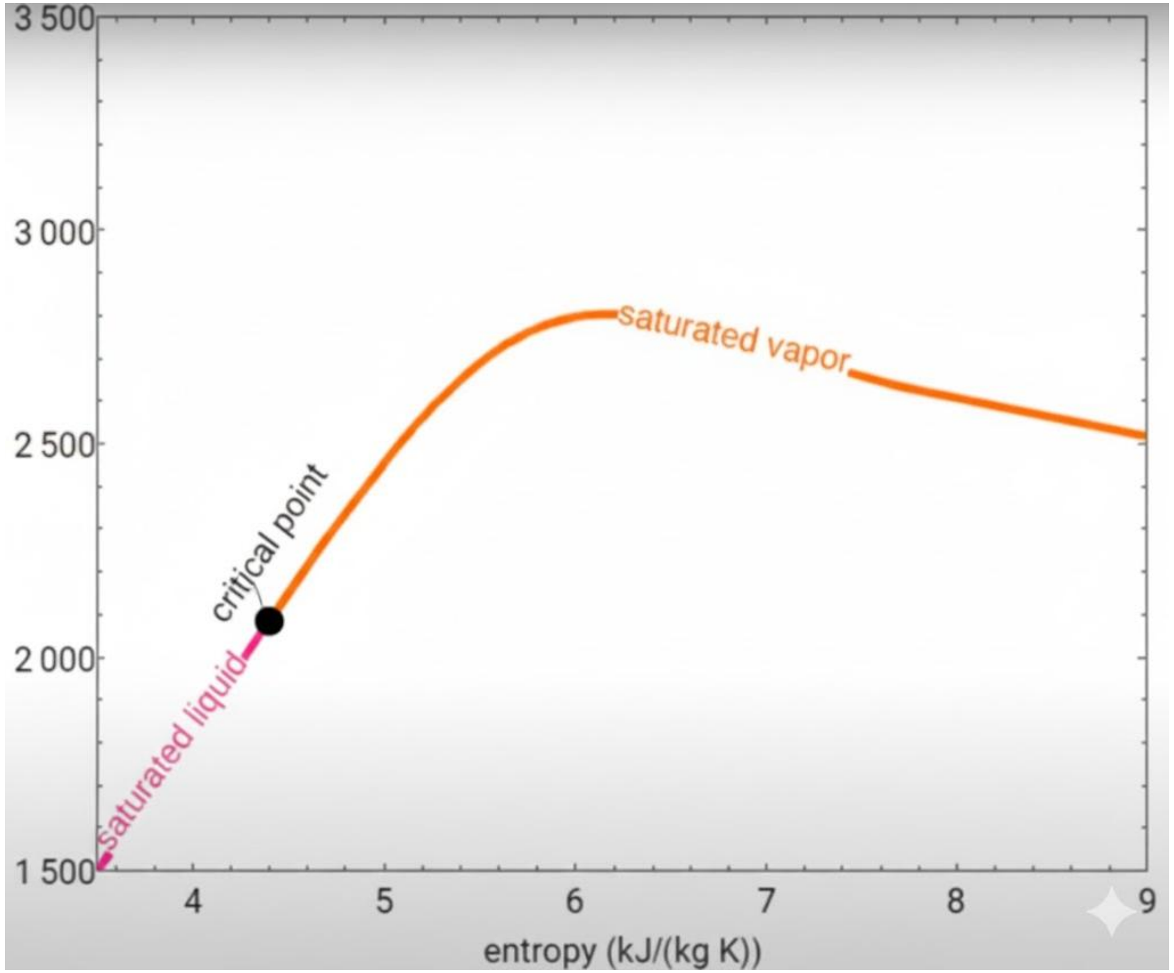




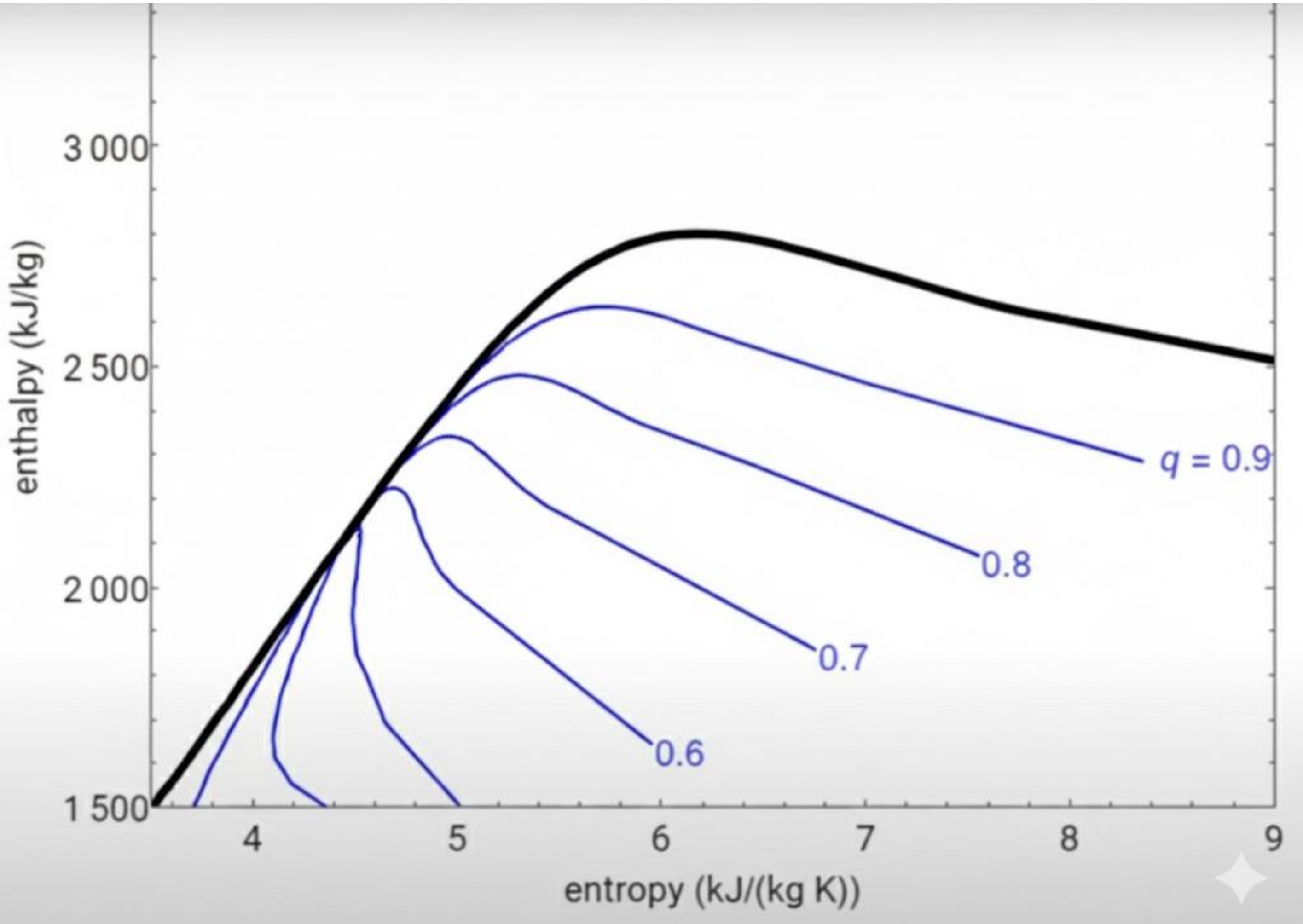
Cont...

H-S diagram

An H-S diagram, or Enthalpy-Entropy diagram, is a graphical representation used in thermodynamics to illustrate the relationship between enthalpy (H) and entropy (S) for a substance during various thermodynamic processes.

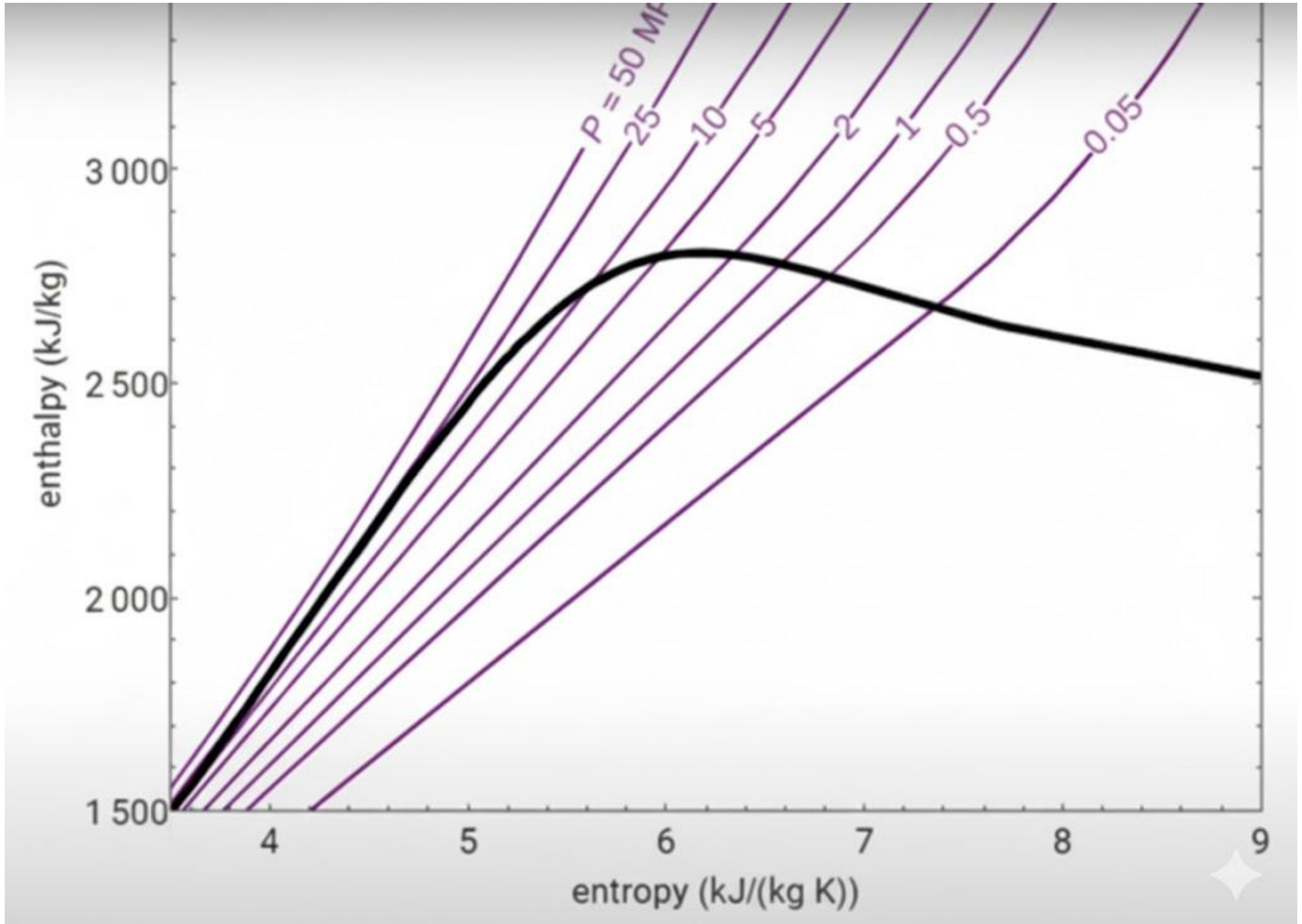


Cont…



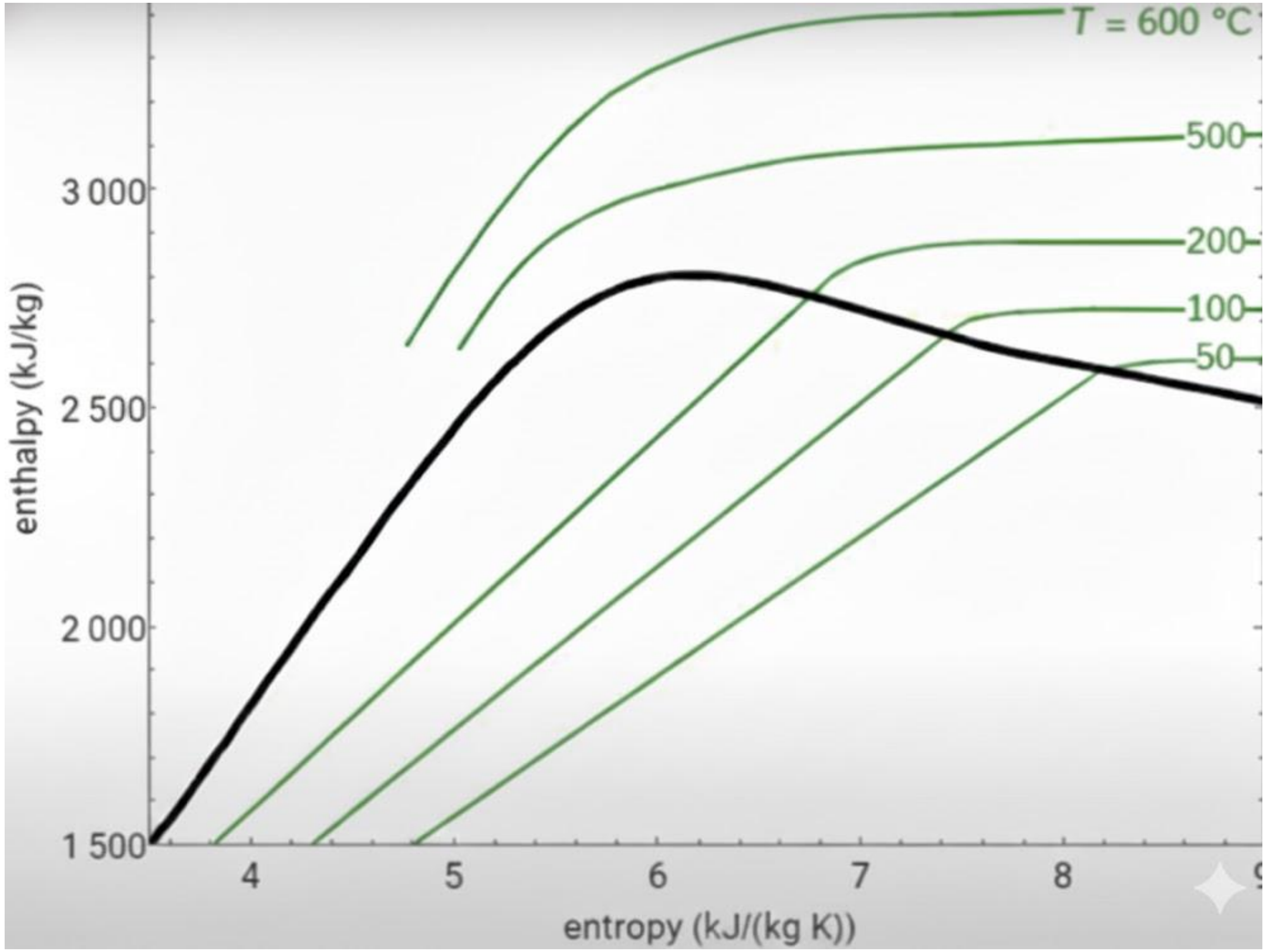
3 000
2 500
2 000
1 500
enthalpy (kJ/kg)
4
5
6
7
8
9
entropy (kJ/(kg K))
q = 0.9
0.8
0.7
0.6

Cont…



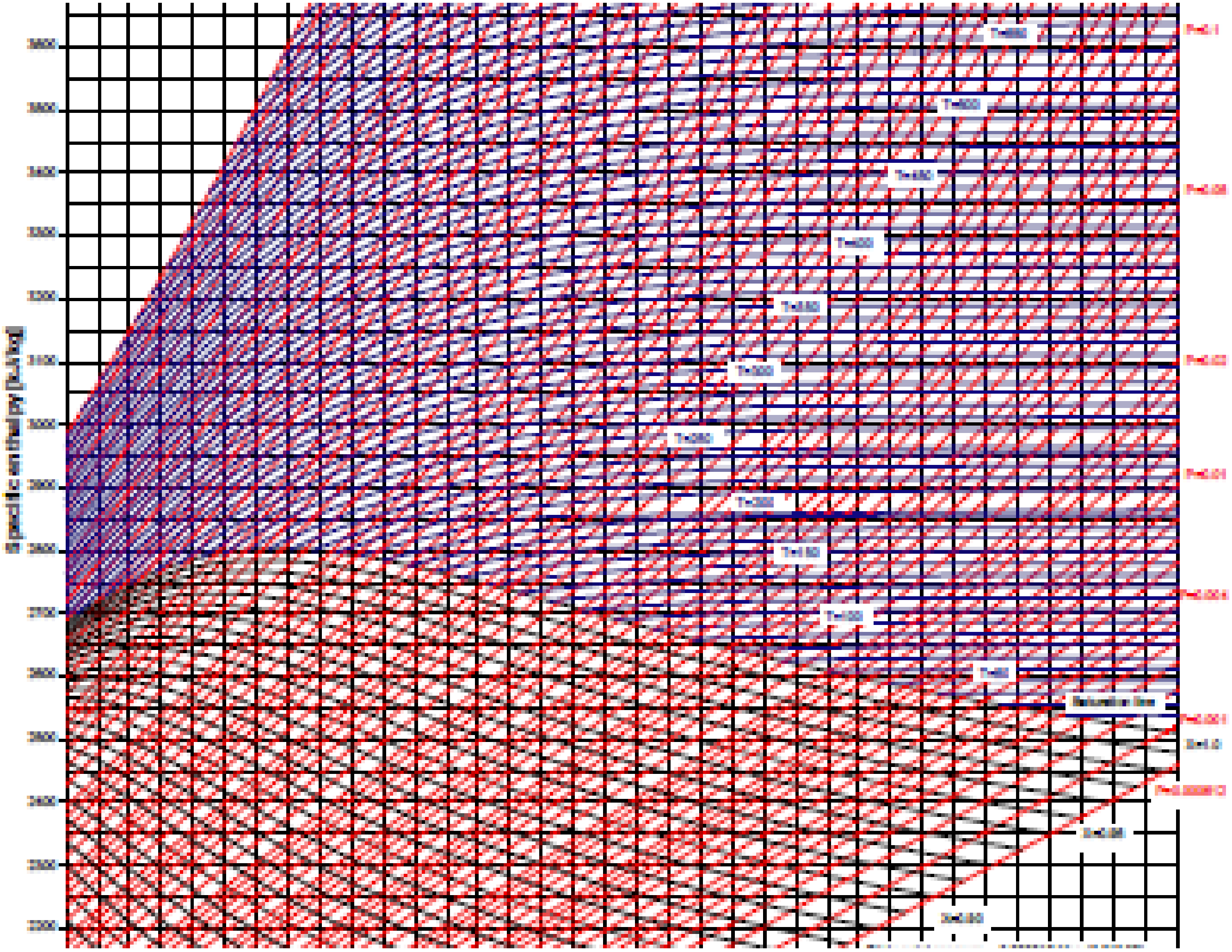
P = 50 MP
25
10
5
2
1
0.5
0.05
3 000
2 500
2 000
1 500
enthalpy (kJ/kg)
4
5
6
7
8
9
entropy (kJ/(kg K))

Cont...



T = 600 °C
500
200
100
50
3 000
2 500
2 000
1 500
enthalpy (kJ/kg)
4
5
6
7
8
entropy (kJ/(kg K))

Cont…



Cont…

- Example: you have a superheated steam at $P = 80\,Bar$ with $T = 400℃$, Using steam Charts Find each of:
  - Specific Enthalpy
  - Specific Entropy

Sol:

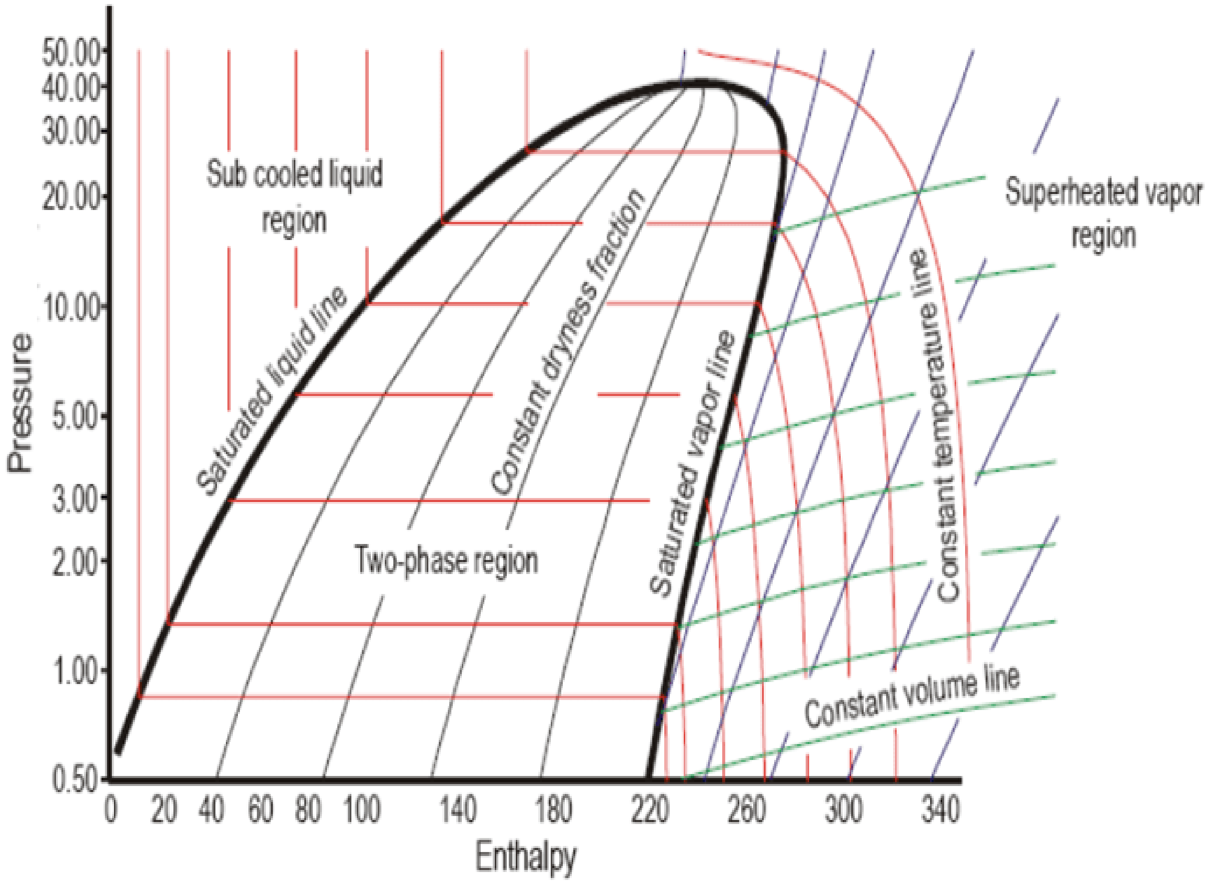
Specific Enthalpy: 3140 $\frac{kJ}{kg}$

Specific Entropy: 6.35 $\frac{kJ}{kg \cdot K}$

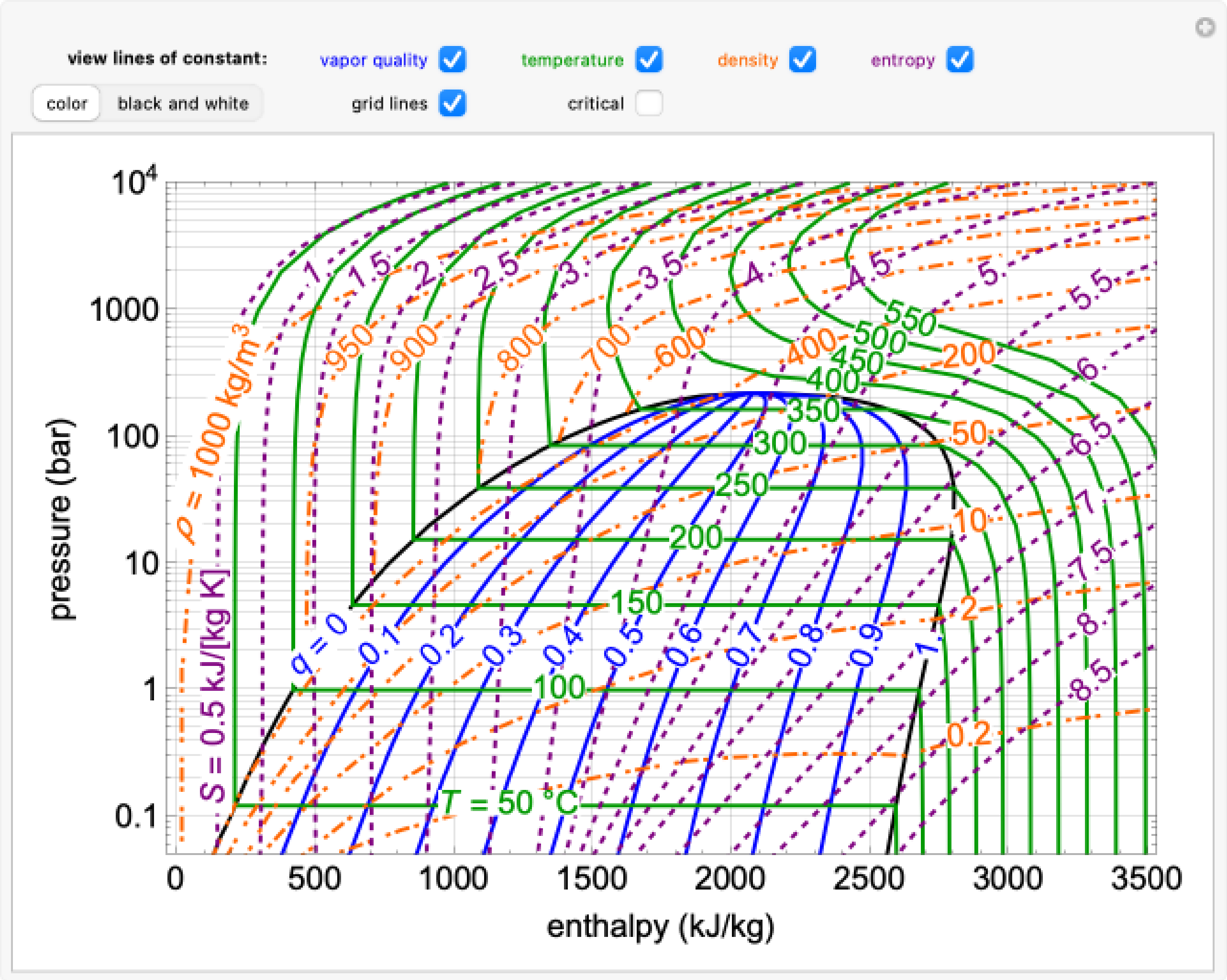
Cont…

P-H diagram

A P-H diagram, or Pressure-Enthalpy diagram, is a graphical representation used in thermodynamics to illustrate the relationships between pressure (P) and enthalpy (H) for a substance, often a refrigerant or steam. It is particularly useful for understanding phase changes and the thermodynamic processes that occur in engines, refrigerators, and heat pumps.

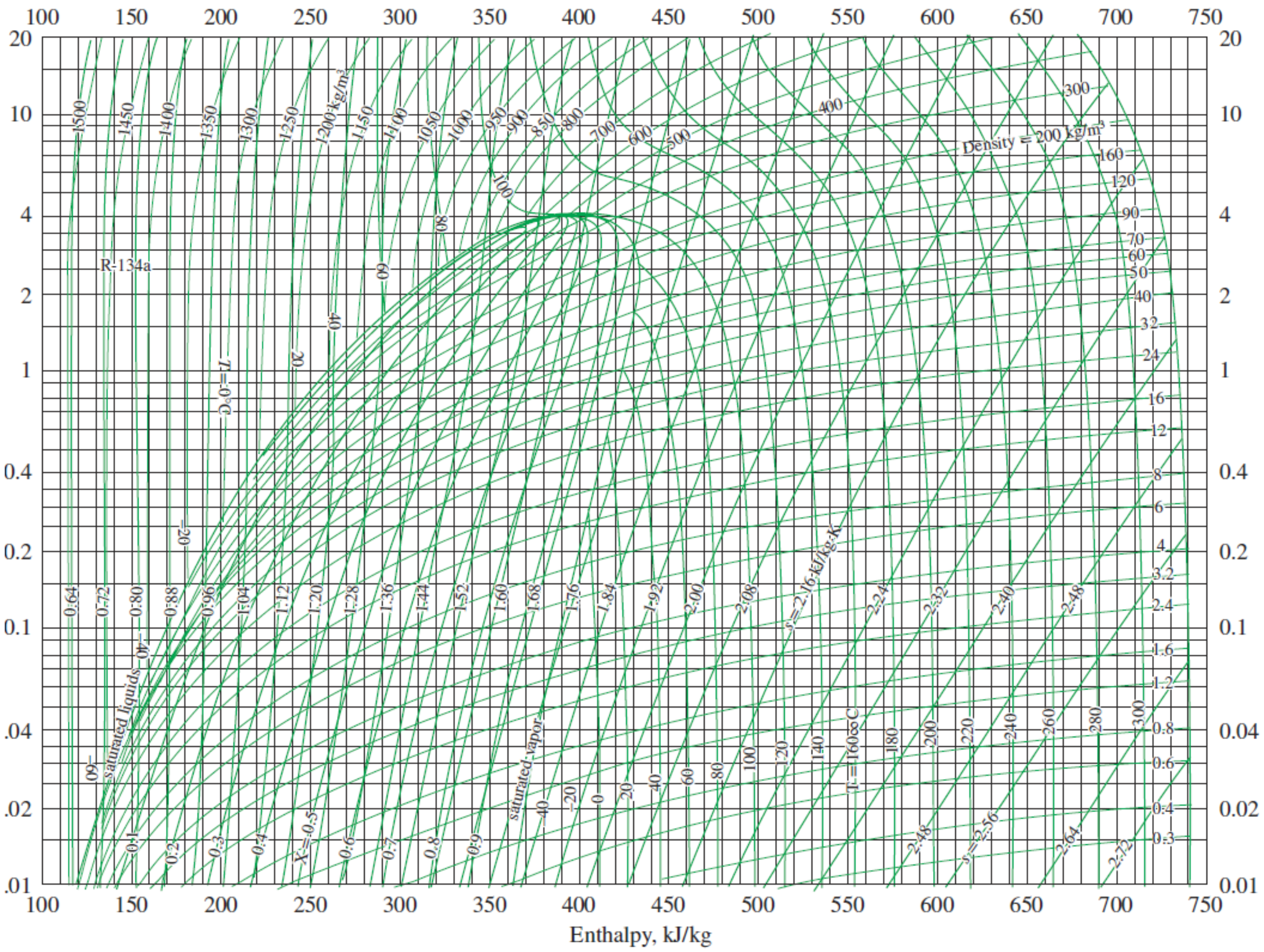


Cont…



view lines of constant:
vapor quality
temperature
density
entropy
color
black and white
grid lines
critical
pressure (bar)
enthalpy (kJ/kg)
ρ = 1000 kg/m^3
S = 0.5 kJ/[kg K]
q = 0
T = 50 °C

Cont...



R-134a
Enthalpy, kJ/kg
Density = 200 kg/m³
saturated liquids
saturated vapor

Cont…

- Example: determine the region for refrigerant-134a at $P = 100\ kPa\ and\ T = -10°C$.

Sol:

By Using Tables, The region for refrigerant-134a is superheated.

- Example: if you have 3 points A,B and C, for Point A the pressure and temperature is $P = 100\ kPa\ and\ T = -26.37°C$. For Point B the pressure and temperature is $P = 320\ kPa\ and\ T = 3°C$ and for point C the pressure and Specific volume is $P = 320\ kPa\ and\ v = 1\ m^3/kg$. determine the region for refrigerant-134a at each Point.

Sol:

First of all, we have to go for saturated water – Pressure table:

for Point A at $P = 100\ kPa$:

$$T = -26.37°C, and\ T_{sat} = -26.37°C\ so\ T = T_{sat}, \quad Thats\ mean\ Saturated\ refrigerant\ table$$

for Point B at $P = 320\ kPa$:

$$T = 3°C, and\ T_{sat} = 2.46, \quad so\ T > T_{sat}, \quad Thats\ mean\ Superheatedref\ rigerant\ table$$

for Point C at $P = 320\ kPa$:

$$v = 1m^3/kg, and\ v_g = 0.063681, \quad so\ v > v_g, \quad Thats\ mean\ Superheatedref\ rigerant\ table$$

Cont…

- Example: you have a superheated refrigerant-134a at $P = 6\, Bar$ with $T = 140°C$, Using steam Charts Find each of:
  - Specific Enthalpy
  - Specific Entropy

Sol:

Specific Enthalpy: $540\ \frac{kJ}{kg}$

Specific Entropy: $2.06\ \frac{kJ}{kg \cdot K}$

The Second Law in Thermodynamics

- The **Second Law of Thermodynamics** states that the total entropy of an isolated system can never decrease over time. In simpler terms, natural processes tend to move toward a state of greater disorder or randomness. This law has several important implications and relationships:

  1. Entropy Change (ΔS): The change in entropy for a reversible Process can be calculated using the equation:

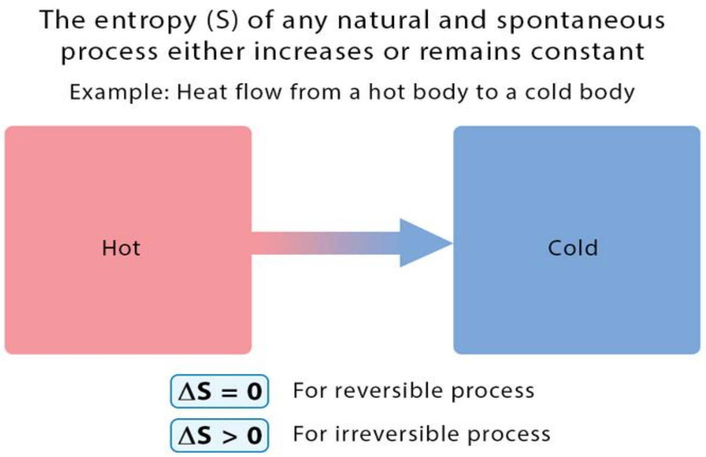
  $$\Delta S = \frac{Q_{rev}}{T}$$

  2. Carnot's Formula: relates to the efficiency of ideal heat engines and is foundational in the study of thermodynamics. It represents the maximum efficiency of any heat engine operating between two thermal reservoirs.

  $$n = \frac{W}{Q_H}, where\ n = 1 - \frac{T_C}{T_H}, \qquad W = Q_H - Q_C$$

  3. Clausius Inequality: For irreversible processes, the change in entropy is given by:

  $$\Delta S \geq \frac{Q}{T}$$



Cont…

4. Thomson's coefficient with Clausius: The Thomson coefficient (μ) is defined as the change in temperature per unit change in entropy for a system at a constant pressure. It can be mathematically represented as:

$$\mu = T\left(\frac{\partial S}{\partial T}\right)_P$$

5. Ostwald's formula: is an important concept in thermodynamics that defines the relationship between changes in free energy, heat, and entropy within a given system. It is primarily used in the analysis of chemical reactions and thermal processes. Ostwald's formula expresses the relationship between the change in Gibbs free energy $\Delta G = \Delta H - T\Delta S$, changes in enthalpy ΔH, and entropy ΔS. It can be formulated as follows:

$$\Delta G = \Delta H - T\Delta S$$

So, in order for part of the temperature to be converted into work, it must meet the following:

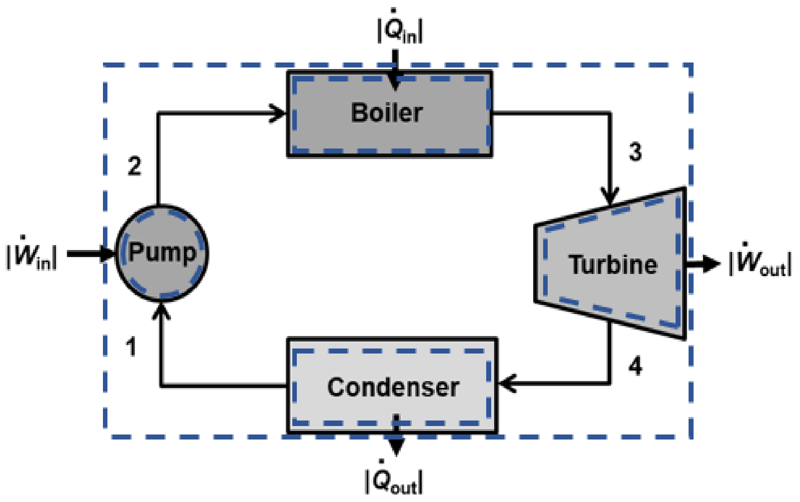
1. Hot Source
2. Working Body
3. Cold Source

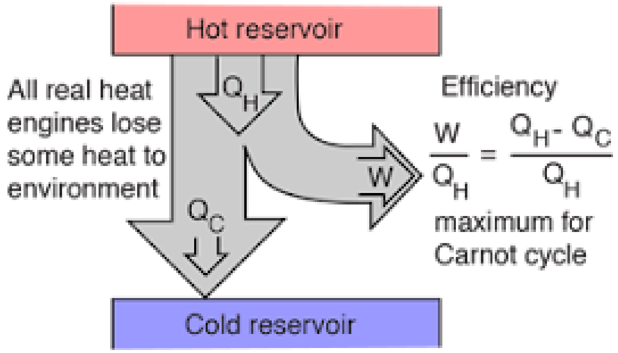
Cont…

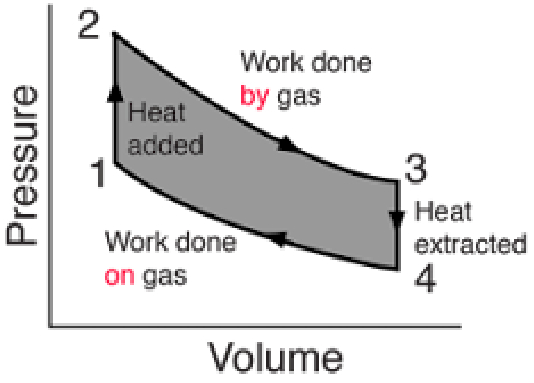
- Thermodynamics cycles

Thermodynamic cycles are a sequence of processes that involve the conversion of heat into work (or vice versa) in a closed system. These cycles are fundamental in understanding how engines, refrigerators, and heat pumps operate. Here are some key thermodynamic cycles:

1. Carnot cycle
2. Otto cycle
3. Diesel cycle
4. Rankine cycle
5. Brayton cycle
6. Stirling cycle
7. Heat Pump cycle







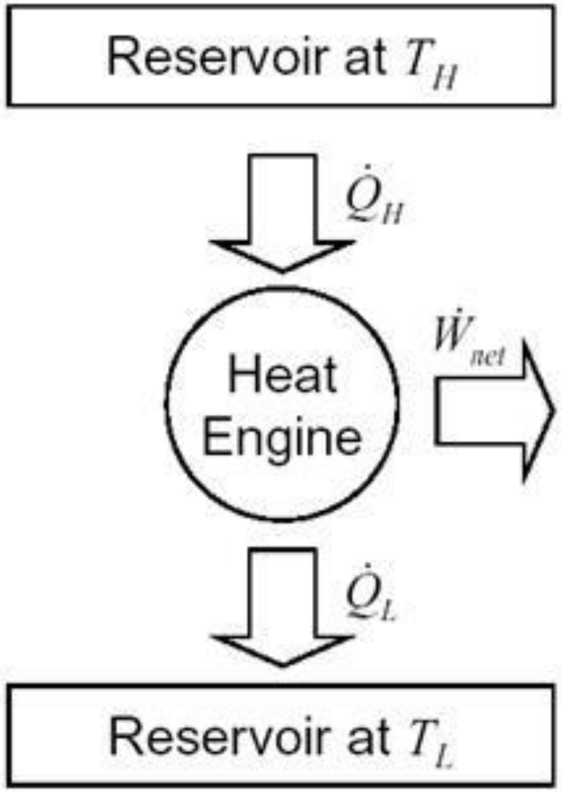
Cont…

- Thermodynamics cycles

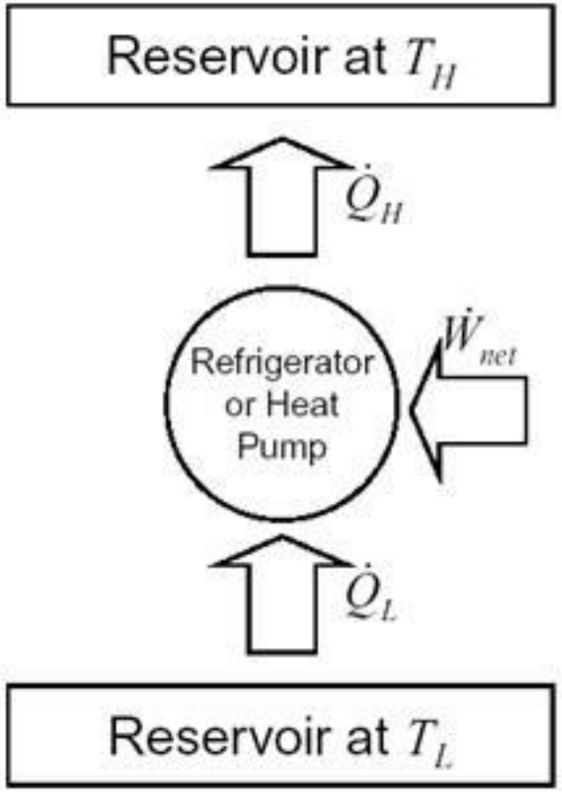
Thermodynamic cycles can be classified into four main categories: reversible cycles, irreversible cycles, direct cycles, and indirect cycles. Here's a brief definition of each:

1. **Reversible Cycles:** These cycles consist of processes that can be reversed without leaving any change in the system or surroundings. They operate in a state of equilibrium, ensuring that no energy is dissipated as waste. The Carnot cycle is a theoretical example of a reversible cycle.
2. **Irreversible Cycles:** These cycles include processes that cannot be reversed without causing changes in the system or the surroundings. They involve dissipative effects such as friction, turbulence, and heat loss. Most real-world thermodynamic cycles, like the Otto or Diesel cycles, are irreversible.
3. **Direct Cycles:** In direct cycles, the working fluid directly absorbs heat from the heat source and converts it into work. The heat addition and work extraction occur in a straightforward manner. The Rankine cycle can be considered a direct cycle since it uses steam directly to generate work.
4. **Indirect Cycles:** Indirect cycles involve a heat exchanger or another intermediary process where the working fluid absorbs heat indirectly. This setup can improve efficiency and reduce the risk of contamination. Refrigeration systems often use indirect cycles where the refrigerant absorbs heat from the space being cooled through an evaporator.

Cont…



Direct Cycle



Indirect Cycle

Cont…

❑ Carnot cycle

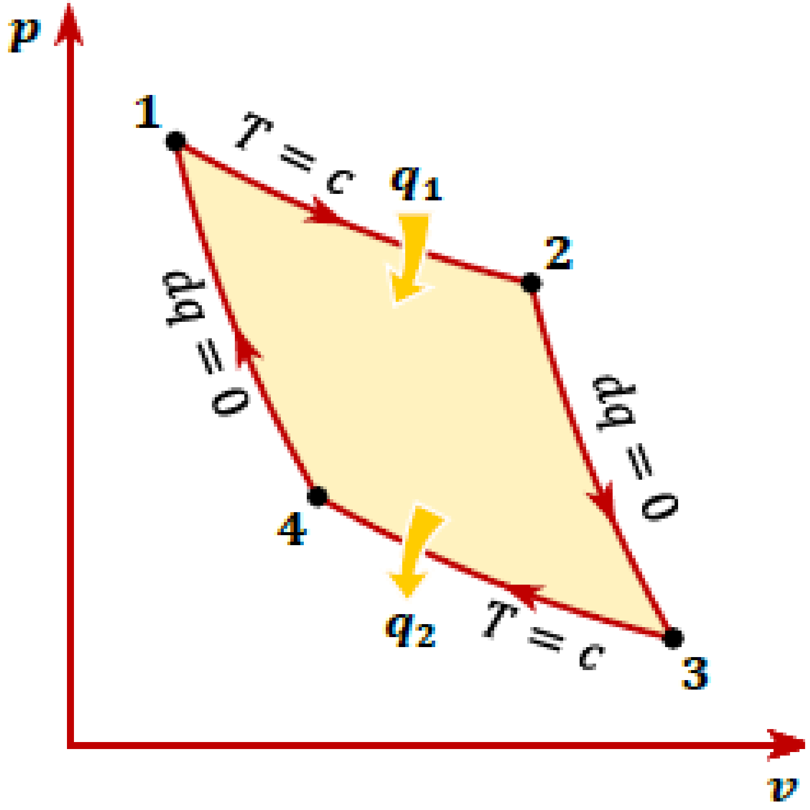
The Carnot cycle is an idealized thermodynamic cycle that serves as a standard for the efficiency of heat engines. It was formulated by the French physicist Sadi Carnot in 1824. It can be divided into two types:

A. Direct Carnot Cycle

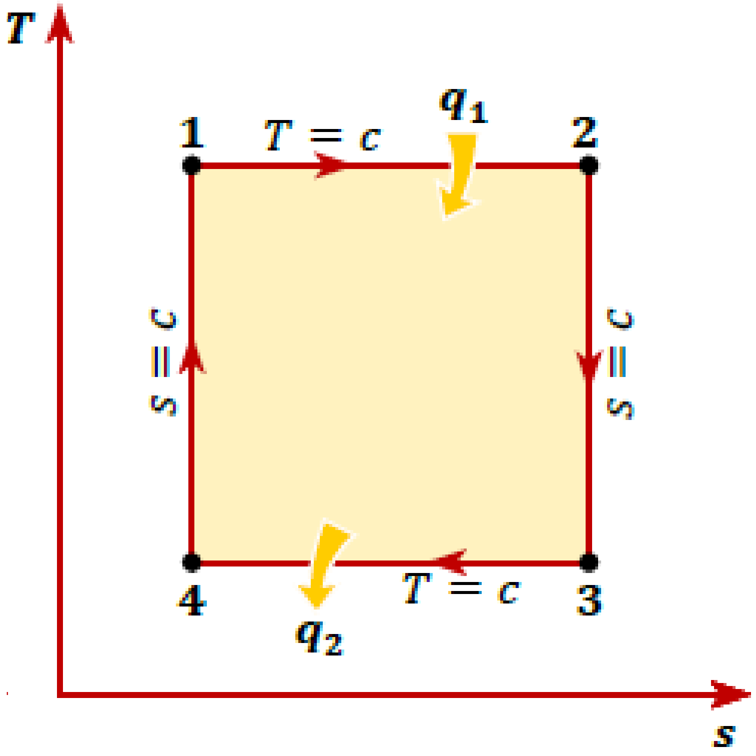
The direct Carnot cycle consists of four processes:

1. **Isothermal Expansion:** The gas absorbs heat Q_h from a hot reservoir at a constant temperature T_h and expands, doing work on the surroundings.
2. **Adiabatic Expansion:** The gas continues to expand without exchanging heat, causing its temperature to drop from T_h to T_c (the temperature of the cold reservoir).
3. **Isothermal Compression**: The gas is compressed at a constant temperature T_c, releasing heat Q_c to the cold reservoir while work is done on the gas.
4. **Adiabatic Compression:** The gas is compressed further without heat exchange, raising its temperature back to T_h.

Cont...



P-V Direct Carnot Cycle



T-S Direct Carnot Cycle

Cont…

The direct Carnot cycle calculations:

1. **Isothermal Expansion:**

$$Q_h = nR_\mu T_h \ln\left(\frac{V_2}{V_1}\right)$$

2. **Adiabatic Expansion:**

$$T_h V_1^{k-1} = T_c V_2^{k-1}$$

3. **Isothermal Compression**:

$$Q_c = nR_\mu T_c \ln\left(\frac{V_2}{V_1}\right)$$

4. **Adiabatic Compression:**

$$T_c V_1^{k-1} = T_H V_2^{k-1}$$

Efficiency:

$$n = 1 - \frac{T_c}{T_h}$$

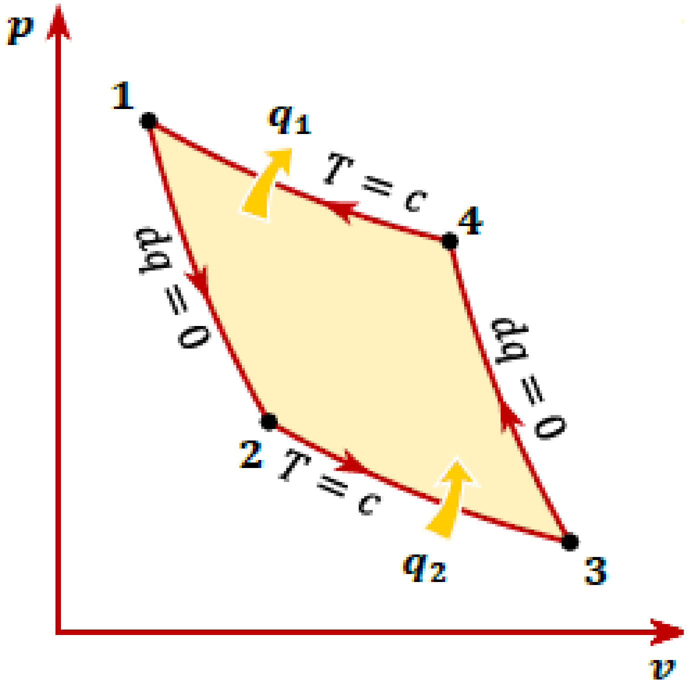
Cont…

B. Reversed Carnot Cycle

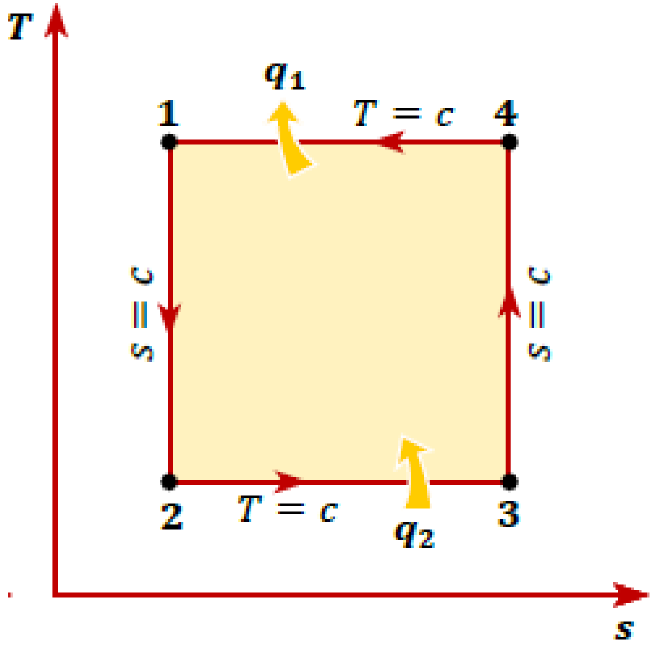
The Reversed Carnot cycle consists of four processes:

1. **Adiabatic Expansion:** The gas continues to expand without exchanging heat, causing its temperature to drop from T_h to T_c (the temperature of the cold reservoir).
2. **Isothermal Expansion:** The gas absorbs heat Q_h from a hot reservoir at a constant temperature T_h and expands, doing work on the surroundings.
3. **Adiabatic Compression:** The gas is compressed further without heat exchange, raising its temperature back to T_h.
4. **Isothermal Compression**: The gas is compressed at a constant temperature T_c, releasing heat Q_c to the cold reservoir while work is done on the gas.

Cont…



P-V Reversed Carnot Cycle



T-S Reversed Carnot Cycle

Cont…

The Reversed Carnot cycle calculations:

1. **Adiabatic Expansion:**

$$T_h V_1^{k-1} = T_c V_2^{k-1}$$

2. **Isothermal Expansion**:

$$Q_c = nR_\mu T_c \ln\left(\frac{V_2}{V_1}\right)$$

3. **Adiabatic Compression:**

$$T_c V_1^{k-1} = T_h V_2^{k-1}$$

4. **Isothermal Compression**:

$$Q_h = nR_\mu T_h \ln\left(\frac{V_2}{V_1}\right)$$

Efficiency:

$$n = 1 - \frac{T_h}{T_c}, n = \frac{Q_h}{W}$$

Cont…

❖ Example

Calculate the maximum efficiency of a heat engine with operating temperatures of 300℃ and 500℃.

Sol:

$$T_h = 500℃ \Longrightarrow T_h = 773\ K$$

$$T_c = 300℃ \Longrightarrow T_c = 573\ K$$

$$n_{carnot} = 1 - \frac{T_c}{T_h} = 1 - \frac{573}{773} = 0.26 \Longrightarrow 26\%$$

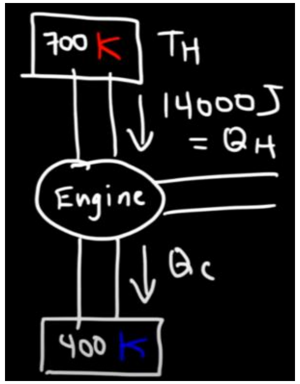
❖ Example

A carnot engine is operating at temperatures of 400K and 700K. Find the following:

a. If 14,000J of heat energy is absorbed by the engine, how much heat energy is discarded into the cold reservoir ?

b. How much mechanical work is performed by this engine?

c. Calculate the efficiency of this carnot engine.



Sol:

a.

$$\frac{T_h}{T_c} = \frac{|Q_h|}{|Q_c|} \Longrightarrow \frac{700\ K}{400\ K} = \frac{1400\ J}{|Q_c|} \Longrightarrow |Q_c| = 8000\ J \Longrightarrow Q_c = -8000\ J$$

Cont…

b.

$$W = Q_h - Q_c = 14{,}000\,J - 8{,}000\,J = 6{,}000\,J$$

c.

$$n_{carnot} = 1 - \frac{T_c}{T_h} = 1 - \frac{400\,K}{700\,K} = 0.43 \Longrightarrow n_{carnot} = 43\%$$

❖ Example

A heat engine releases heat into the cold reservoir at 500K with a carnot efficiency of 25%. What exhaust temperature will increase the carnot efficiency to 60%?

Sol:

At $n_{carnot} = 0.25$:

$$n_{carnot} = 1 - \frac{T_c}{T_h} \Longrightarrow 0.25 = 1 - \frac{500k}{T_h} \Longrightarrow T_h = \frac{500}{0.75} = 666.7K$$

At $n_{carnot} = 0.60$:

$$n_{carnot} = 1 - \frac{T_c}{T_h} \Longrightarrow 0.60 = 1 - \frac{T_c}{666.7K} \Longrightarrow T_c = 666.7 \cdot 0.40 = 266.7K$$

Cont…

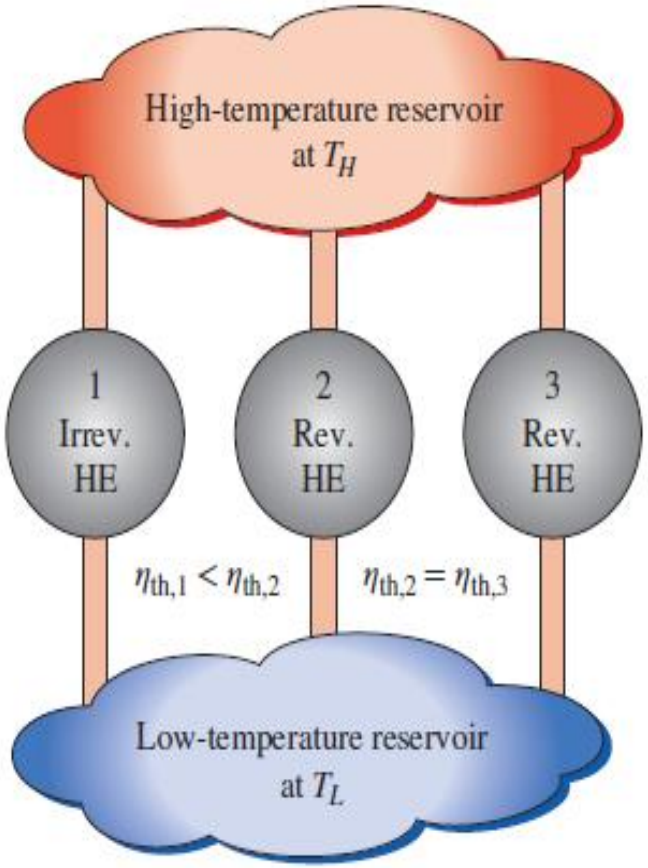
- The Carnot Principles

Two conclusions pertain to the thermal efficiency of reversible and irreversible (i.e., actual) heat engines, and they are known as the Carnot principles shown in the figure, expressed as follows:

1. The efficiency of an irreversible heat engine is always less than the Efficiency of a reversible one operating between the same two reservoirs.
2. The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.

The thermal efficiencies of actual and reversible heat engines operating between the same temperature limits compare as follows:

$$n_{th} \begin{cases} < n_{th,rev} & \textit{irreversible heat engine} \\ = n_{th,rev} & \textit{reversible heat engine} \\ > n_{th,rev} & \textit{impossible heat engine} \end{cases}$$



Cont...

❖ Example

Consider a heat engine operating between a hot reservoir at 500℃ and a cold reservoir at 30℃, find the following:

1- Calculate the maximum efficiency (carnot efficiency) of this engine.

2- If the actual efficiency of the engine is measured to be 45%, determine whether the engine is reversible or irreversible based on the efficiency comparison.

Sol:

1-

$$T_h = 500 + 273.15 = 773.15K$$

$$T_c = 303.15K$$

$$n_{carnot} = 1 - \frac{T_c}{T_h} \Longrightarrow n_{carnot} = 1 - \frac{303.15K}{773.15K} \Longrightarrow n_{carnot} = 0.60 \Longrightarrow n_{carnot} = 60\%$$

2-

$$n_{carnot} = 60\%, \qquad n = 45\%$$

$$n = 45\% < n_{carnot} = 60\%$$

So, the engine is irreversible.

Cont…

- Example

A heat engine operates between a hot reservoir and a cold reservoir. The heat absorbed from the hot reservoir Q_h is 800 J, and the heat rejected to the cold reservoir Q_c is 500 J, find the following:

1- Calculate the efficiency of the engine.

2- Determine whether the engine is reversible or irreversible based on its efficiency compared to the Carnot efficiency. Assume the temperatures of the hot and cold reservoirs are 600 K and 300 K, respectively.

Sol:

1-

$$n = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = \frac{800 - 500}{800} = 0.375 = 37.5\%$$

2-

$$n_{carnot} = 1 - \frac{T_c}{T_h} \Longrightarrow n_{carnot} = 1 - \frac{300K}{600K} \Longrightarrow n_{carnot} = 0.50 \Longrightarrow n_{carnot} = 50\%$$

So,

$$n = 37.5\%, \qquad n_{carnot} = 50\%, \qquad n < n_{carnot}, \qquad \textit{the engine is irreversible}$$

Cont…

❖ Example

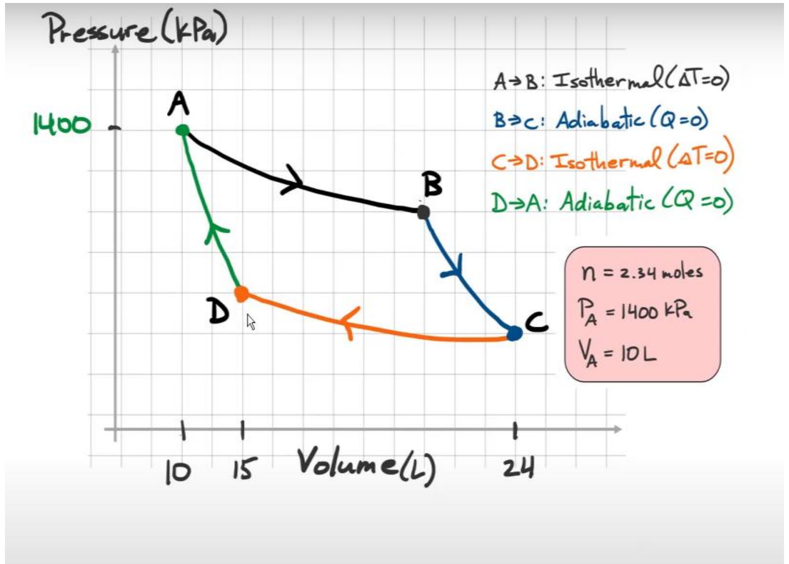
Using the chart, Calculate the following parameters:

Heat, Work, Internal energy and efficiency. (k=5/3)

Sol:

First step, we have to find the pressure, volume and temperature for each point.

	P(kPa)	V(L)	T(K)
A	1400	10	720
B			
C		24	
D		15	



A: From Ideal Gas Law

$$T_A = \frac{P_A V_A}{nR_\mu} = \frac{1400 \cdot 10}{2.34 \cdot 8.314} = 720K,$$

$$T_A = T_B, \qquad isothermal$$

Cont…

For Isothermal:

$$P_A V_A = P_B V_B$$
$$P_C V_C = P_D V_D$$

For Adiabatic:

$$P_B V_B^k = P_C V_C^k$$
$$P_D V_D^k = P_A V_A^k$$

From D-A:

$$P_D = P_A \cdot \left(\frac{V_A^k}{V_D^k}\right) = 1400 \cdot \left(\frac{10}{15}\right)^{\frac{5}{3}} = 712\ kPa$$

$$T_D = \frac{P_D V_D}{nR_\mu} = \frac{712 \cdot 15}{2.34 \cdot 8.314} = 549K$$

$$T_D = T_C, \qquad isothermal$$

For P_C:

$$P_C = \frac{nR_\mu T_C}{V_C} = \frac{2.34 \cdot 8.314 \cdot 549}{24} = 445\ kPa$$

Cont…

For Adiabatic:

$$T_B V_B^{k-1} = T_C V_C^{k-1}$$
$$T_D V_D^{k-1} = T_A V_A^{k-1}$$

For V_B:

$$V_B^{k-1} = \frac{T_C}{T_B} V_C^{k-1} \Longrightarrow V_B^{\frac{5}{3}-1} = \frac{549}{720} \cdot 24^{\frac{5}{3}-1} = 16\ L$$

For P_B:

$$P_B = \frac{n R_\mu T_B}{V_B} = 875\ kPa$$

	P(kPa)	V(L)	T(K)
A	1400	10	720
B	875	16	720
C	445	24	549
D	712	15	549

Cont…

Now, for heat, work and internal energy:

	Q	W	ΔU
A→B			
B→C			
C→D			
D→A			
ABCD			

For Process A→B: Isothermal Process ($Q = -W$)

$$W = -nR_\mu T ln\left(\frac{V_B}{V_A}\right) = -2.34 \cdot 8.314 \cdot ln\left(\frac{16}{10}\right) = -6580\,J$$

For Process C→D: Isothermal Process ($Q = -W$)

$$W = -nR_\mu T ln\left(\frac{V_D}{V_C}\right) = -2.34 \cdot 8.314 \cdot ln\left(\frac{15}{24}\right) = 5020\,J$$

Cont…

For Adiabatic:

$$Q = 0, \qquad For\ adiabatic$$

$$\Delta U = nc_v\Delta T \Longrightarrow \Delta U = \frac{3}{2}nR_\mu\Delta T$$

$$\Delta U = \frac{3}{2}nR_\mu\Delta T$$

For Process B→C: Adiabatic Process ($Q = 0$)

$$\Delta U = \frac{3}{2}nR_\mu(T_C - T_B) = \frac{3}{2}\cdot 2.34\cdot 8.314\cdot(549 - 720) = -4980\,J$$

For Process D→A: Adiabatic Process ($Q = 0$)

$$\Delta U = \frac{3}{2}nR_\mu(T_A - T_D) = \frac{3}{2}\cdot 2.34\cdot 8.314\cdot(720 - 549) = 4980\,J$$

Calculate the efficiency

$$n = \frac{W}{Q_h} = \frac{1560}{6580} = 0.237 = 23.7\%$$

$$n_{carnot} = 1 - \frac{T_c}{T_h} = 1 - \frac{549}{720} = 0.237 = 23.7\%$$

	Q	W	ΔU
A→B	6580	-6580	0
B→C	0	-4980	-4980
C→D	-5020	5020	0
D→A	0	4980	4980
ABCD	1560	-1560	0

Cont…

Otto cycle

The Otto cycle is a thermodynamic cycle that describes the operation of a spark-ignition internal combustion engine. It is the thermodynamic cycle most commonly found in automobile engines.

- **The relation between otto cycle and internal combustion engine**

The Otto cycle provides a theoretical framework that describes the thermodynamic processes occurring within a spark-ignition internal combustion engine. It outlines the steps of expansion, compression, combustion and exhaust.

Most gasoline engines operate on a four-stroke cycle, which corresponds directly to the four processes of the Otto cycle:

- **Intake** (filling the cylinder with an air-fuel mixture).
- **Compression** (compressing the mixture).
- **Power Stroke** (combustion and expansion).
- **Exhaust** (removing spent gases).

Cont…

Some gasoline engines operate on a two-stroke cycle, which corresponds directly to the two combined processes of the Otto cycle:

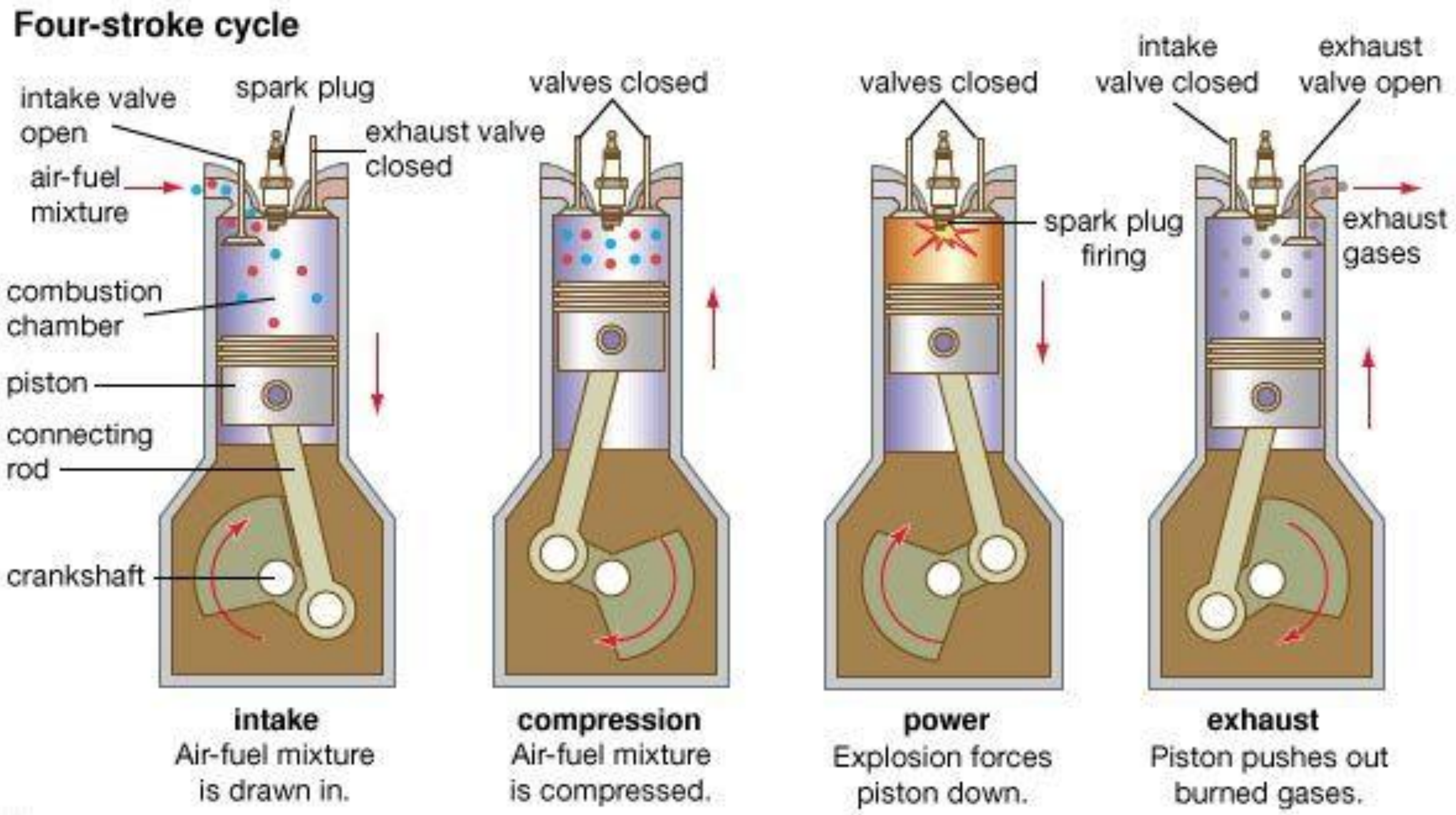
First Stroke (Compression and Combustion):

- As the piston moves upward, it compresses the air-fuel mixture inside the cylinder.
- At the end of this stroke, the spark plug ignites the mixture, causing combustion and resulting in a rapid increase in pressure.

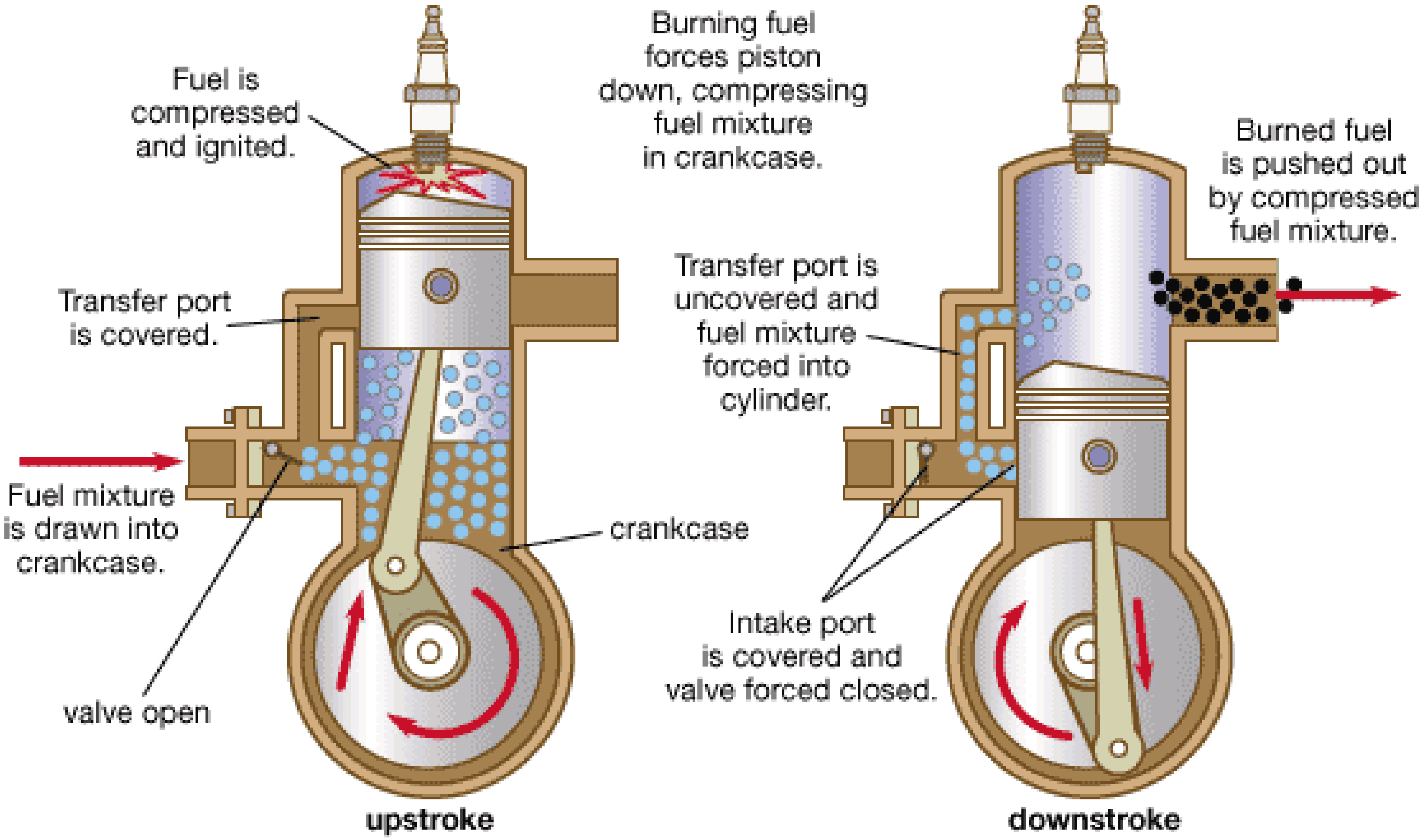
Second Stroke (Power and Exhaust):

- The high-pressure gases from combustion push the piston downward.
- As the piston moves down, it opens the exhaust ports, expelling the burnt gases while simultaneously drawing in a new air-fuel mixture into the cylinder.

Cont…


Four-stroke cycle
intake valve open
spark plug
exhaust valve closed
air-fuel mixture
combustion chamber
piston
connecting rod
crankshaft
valves closed
valves closed
spark plug firing
intake valve closed
exhaust valve open
exhaust gases
intake
Air-fuel mixture is drawn in.
compression
Air-fuel mixture is compressed.
power
Explosion forces piston down.
exhaust
Piston pushes out burned gases.

Cont…



Fuel is compressed and ignited.
Burning fuel forces piston down, compressing fuel mixture in crankcase.
Burned fuel is pushed out by compressed fuel mixture.
Transfer port is covered.
Transfer port is uncovered and fuel mixture forced into cylinder.
Fuel mixture is drawn into crankcase.
crankcase
Intake port is covered and valve forced closed.
valve open
upstroke
downstroke

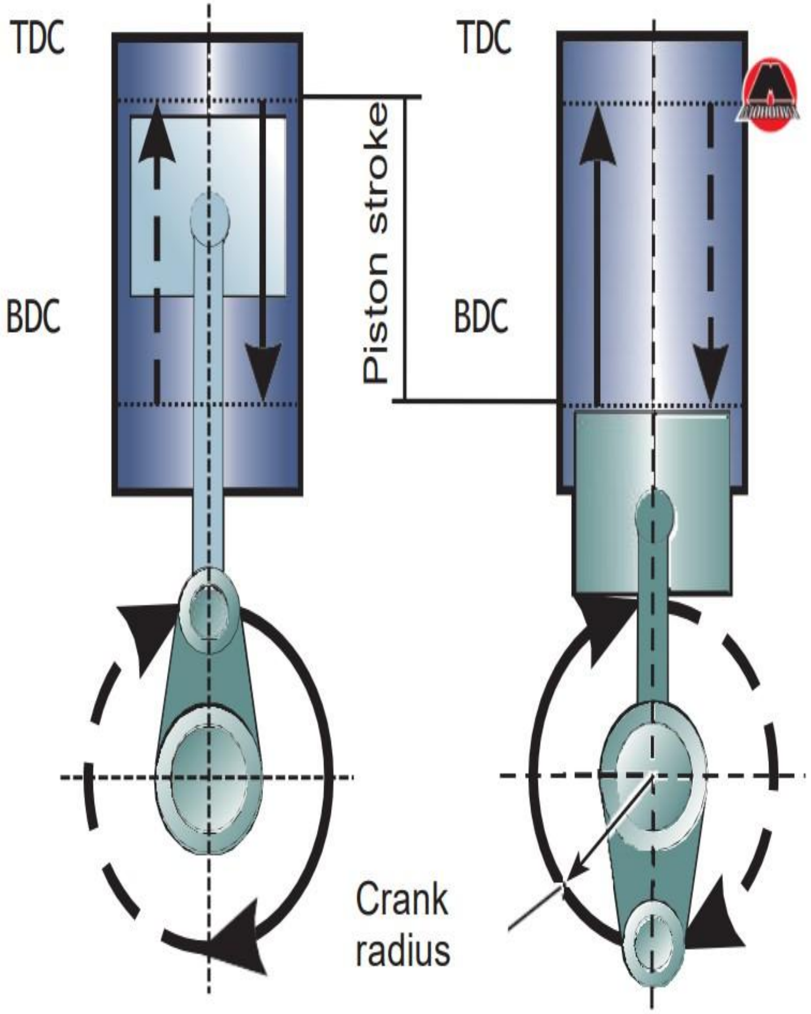
Cont…

❖ **Top Dead Center (TDC) and Bottom Dead Center (BDC)**

- Top Dead Center (TDC): TDC is the position of the piston when it is at its highest point within the cylinder. This is the point where the volume of the combustion chamber is at its minimum.
- Bottom Dead Center (BDC): BDC is the position of the piston when it is at its lowest point within the cylinder. This is the point where the volume of the combustion chamber is at its maximum.
- Stroke: a **stroke** refers to the movement of the piston within the cylinder during one complete motion from one dead center to the other.

❖ Air-Fuel Ratio (AFR)

The air-fuel ratio (AFR) is a critical parameter in internal combustion engines that indicates the proportion of air to fuel in the combustion mixture. It plays a significant role in engine performance, efficiency, and emissions.



Cont...

The air-fuel ratio is defined as the mass of air divided by the mass of fuel in the combustion mixture:

$$AFR = \frac{m_{air}}{m_{fuel}}$$

- Stoichiometric Ratio:

The stoichiometric air-fuel ratio is the ideal ratio at which all fuel is burned completely with no excess air. For gasoline, this is typically around 14.7:1 (14.7 parts air to 1 part fuel by mass).

- Effects of AFR on Engine Performance:

– Rich Mixture (AFR < Stoichiometric): More fuel than necessary is present, which can lead to incomplete combustion. Results in increased power output but may cause higher emissions of unburned hydrocarbons and carbon monoxide.

– Lean Mixture (AFR > Stoichiometric): More air than necessary is present, which can lead to higher combustion temperatures. Improves fuel economy and reduces emissions of hydrocarbons but may cause knocking or detonation.

- Calculating AFR:

$$AFR = \frac{\rho_{air} \cdot \dot{V}_{air}}{\rho_{fuel} \cdot \dot{V}_{fuel}}$$

Cont…

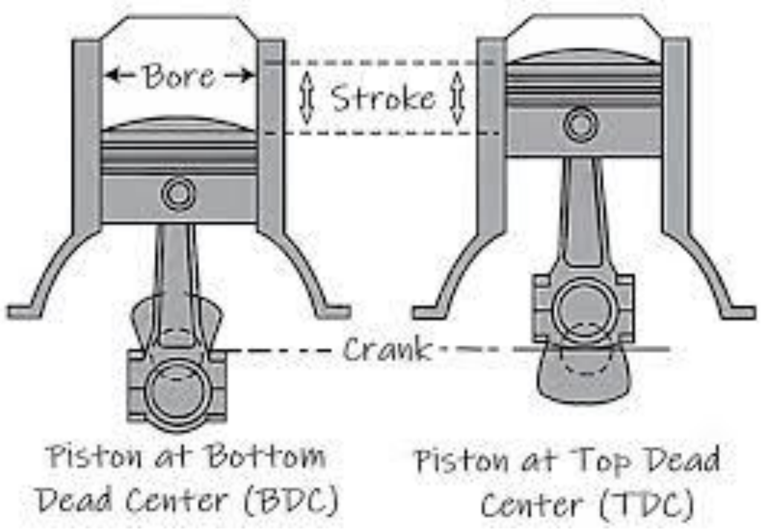
❖Engine Displacement (Volume)

The engine displacement can be calculated using the formula:

$$V_d = \frac{\pi}{4} \cdot D^2.S.N$$

Where:

- $V_d = Engine\ Displacement\ (cm^3 or\ liters)$
- $D = Bore\ diameter\ (cylinder\ diameter)\ in\ centimeters$
- $S = Stroke\ length\ (cm)$
- $N = number\ of\ cylnder$



❖Compression Ratio (CR)

The compression ratio is the ratio of the maximum cylinder volume to the minimum cylinder volume:

$$CR = \frac{V_{max}}{V_{min}} = \frac{V_d + V_c}{V_c}$$

Where, V_c is the combustion chamber volume.

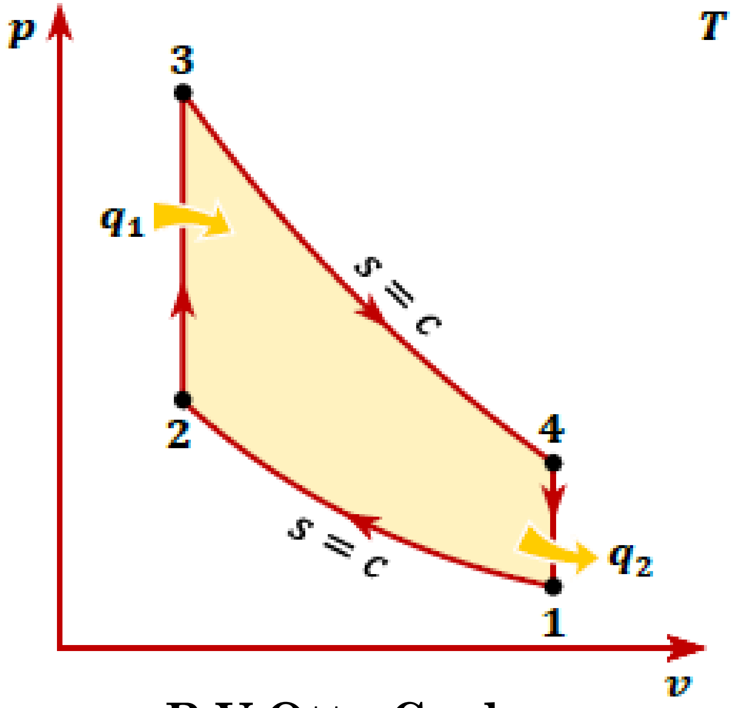
Cont…

- The thermal process for otto cycle

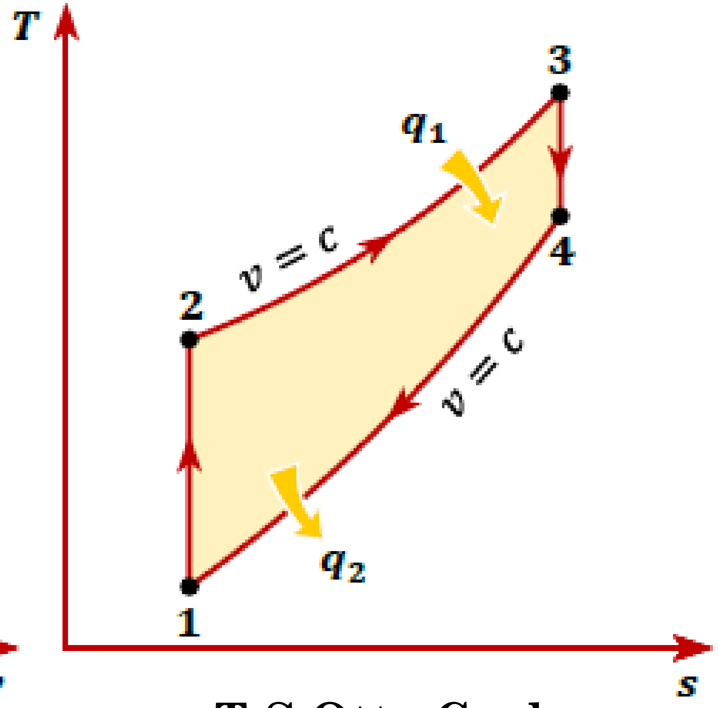
The otto cycle consists of four processes:

1. **Adiabatic Compression:** The piston moves upward in the cylinder, compressing the air-fuel mixture. This process is adiabatic, meaning no heat is exchanged with the surroundings. As the volume decreases, both pressure and temperature increase.
2. **Isochoric Expansion:** At the end of the compression stroke, the spark plug ignites the compressed air-fuel mixture. The combustion occurs at constant volume, causing a rapid increase in pressure and temperature.
3. **Adiabatic Expansion**: The high-pressure gases expand adiabatically, pushing the piston down during the power stroke. This process also follows the adiabatic relations, leading to a decrease in pressure and temperature.
4. **Isochoric Compression:** After the expansion, the exhaust valves open, and the spent gases are expelled. Heat is rejected at constant volume, returning the system to its initial state.

Cont…



P-V Otto Cycle



T-S Otto Cycle

Cont…

The otto cycle calculations:

1. **Adiabatic Compression:**

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1}$$

2. **Isochoric Expansion:**

$$Q_h = m \cdot c_v \cdot (T_3 - T_2)$$

3. **Adiabatic Expansion:**

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{k-1}$$

4. **Isochoric Compression:**

$$Q_C = m \cdot c_v \cdot (T_4 - T_1)$$

Efficiency:

$$n = 1 - \frac{1}{CR^{k-1}}$$

Cont…

- Example

An otto cycle of an internal combustion engine has a compression ratio of 8 and a gamma ratio of 1.4. calculate the efficiency of this engine?

Sol:

$$n_{otto} = 1 - \frac{1}{CR^{k-1}} = 1 - \frac{1}{8^{1.4-1}} = 0.564 = 56.4\%$$

- Example

The efficiency of a combustion engine is 45%. Using a gamma ratio of 1.4. calculate the compression ratio of the engine?

Sol:

$$n_{otto} = 1 - \frac{1}{CR^{k-1}} = 1 - \frac{1}{CR^{1.4-1}} = 0.45 \Longrightarrow \frac{1}{CR^{1.4-1}} = 1 - 0.45 \Longrightarrow CR^{1.4-1} = \frac{1}{0.55} \Longrightarrow CR^{0.4} = 1.8181 \Longrightarrow CR = \sqrt[0.4]{1.8181} = 4.45$$

Cont...

- Example

The efficiency of an internal combustion engine is 52% and the compression ratio is 9.2. (a) what is the gamma ratio of the working substance? (b) If the substance has a molar heat capacity of 21.47 J/mol.K at constant volume, what is the molar heat capacity of the substance at constant pressure?

Sol:

$n_{otto} = 0.52,\ CR = 9.2$

a) $\mathrm{n_{otto}} = 1 - \frac{1}{\mathrm{CR^{k-1}}} \Longrightarrow 0.52 = 1 - \frac{1}{9.2^{\mathrm{k}-1}} \Longrightarrow \frac{1}{9.2^{\mathrm{k}-1}} = 0.48 \Longrightarrow 9.2^{\mathrm{k}-1} = 2.0833 \Longrightarrow (\mathrm{k}-1)\ln 9.2 = \ln 2.0833 \Longrightarrow (\mathrm{k}-1) = \frac{\ln 2.0833}{\ln 9.2} \Longrightarrow (\mathrm{k}-1) = 0.330 \Longrightarrow \mathrm{k} = 1.33$

b) $\mathrm{k} = \frac{c_{P\mu}}{c_{V\mu}} \Longrightarrow \mathrm{c_p} = \mathrm{k} \cdot \mathrm{c}_{V\mu} \Longrightarrow \mathrm{c}_{P\mu} = 1.33 \cdot 21.47 = 28.5551\ \mathrm{J/mol.K}$

Cont…

❖ Example

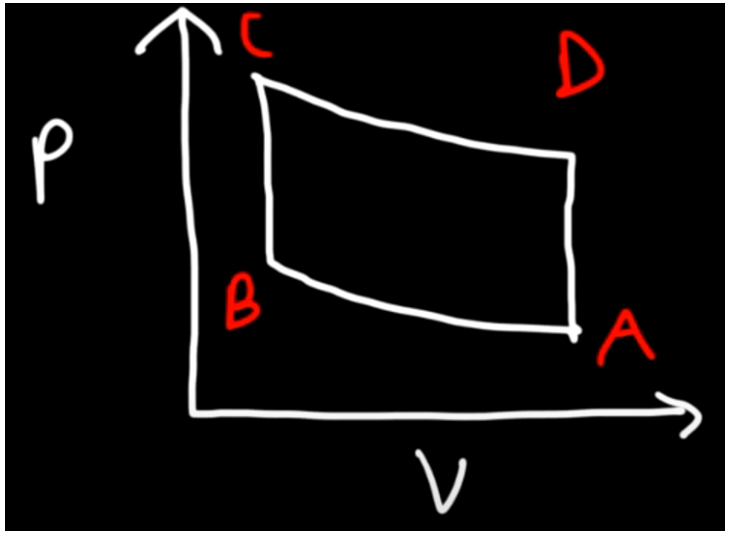
The temperature of a gasoline-air mixture is 300K when it enters the cylinder at point A. The gamma ratio is 1.4 and the compression ratio for the combustion engine is 8.7. (a) calculate the temperature at the end of the adiabatic compression at point B. (b) if the pressure of the gasoline-air mixture is 0.92 atm at point A, what is the pressure at point B?

Sol:

a) For adiabatic compression:

$$\frac{T_B}{T_A} = \left(\frac{V_A}{V_B}\right)^{k-1} \Longrightarrow \frac{T_B}{T_A} = CR^{k-1} \Longrightarrow T_B = T_A \cdot CR^{k-1} \Longrightarrow T_B = 300 \cdot 8.7^{1.4-1}$$

$$T_B = 712.7K$$



b) $\frac{P_A V_A}{T_A} = \frac{P_B V_B}{T_B} \Longrightarrow P_B = P_A \cdot \frac{V_A}{V_B} \cdot \frac{T_B}{T_A} \Longrightarrow P_B = P_A \cdot CR \cdot \frac{T_B}{T_A}$

$$\Longrightarrow P_B = 0.92\,atm \cdot 8.7 \cdot \left(\frac{712.7}{300}\right) = 19.01\,atm$$

Thanks for Your Valuable Attention