ANNAMACHARYA INSTITUTE OF TECHNOLOGY & SCIENCES
(AUTONOMOUS)
UTUKUR (P), C. K. DINNE (V&M), KADAPA, YSR DIST.
Approved by AICTE, New Delhi & Affiliated to JNTUA, Anantapuramu.
Approved by S.B.T.E.T. Andhra Pradesh.
Accredited by NAAC with 'A' Grade, Bangalore & NBA (EEE, ECE & CSE).

LECTURE NOTES

On

THERMODYNAMICS

(23HES0303)

II B. Tech I Semester (HM23)

DEPARTMENT OF MECHANICAL ENGINEERING

ANNAMACHARYA INSTITUTE OF TECHNOLOGY AND SCIENCES::KADAPA

VISION

To emerge into excellence and premier institute, transforming individuals into highly enlightened professionals enriched with innovative skills entwined with intellectual, ethical and human values.

MISSION

- **M1:** Impart quality technical education to enhance knowledge and skills towards employability, higher education and research.
- **M2:** Promote upgradation of teaching and research skills through quality infrastructure and resources.
- **M3:** Enrich and elevate the rural education seekers, endow them with ethics, innovation thinking and leadership qualities enabling them to utilize their technical skills and competencies for the sustainable development of the Nation and mankind.

DEPARTMENT OF MECHANICAL ENGINEERING

VISION

The Department of Mechanical Engineering excels in Engineering Education and building enterprising professionals commendable with creativity, research and employability, meeting the requirements of potential recruiters.

MISSION

The Mission is to provide quality engineering education that equips the students with adequate knowledge in mechanical engineering to become successful professionals for serving the needs of the society. The department strives to prepare the students to adorn themselves with effective communication, intellectual abilities, teamwork and professional ethics for valuable contribution in their career.

B.Tech. – Mechanical Engineering **HM23 Regulations**

II B. Tech I Semester

COURSE OBJECTIVES

- Familiarize concepts of heat, work, energy and governing rules for conversion of one form to other.
- Explain relationships between properties of matter and basic laws of thermodynamics.
- Teach the concept of entropy for identifying the disorder and feasibility of a thermodynamic process.
- Introduce the concept of available energy for maximum work conversion.
- Provide fundamental concepts of Refrigeration and Psychrometry.

COURSE OUTCOMES (COs)

COs	Statements	Blooms Level
CO1	Explain the importance of thermodynamic properties related to conversion of heat energy into work.	**L3**
CO2	Apply the Zeroth and First Law of Thermodynamics.	**L3**
CO3	Understand Second Law of Thermodynamics.	**L2**
CO4	Analyze the Mollier charts, T-S and h-s diagrams, Steam calorimetry, Phase Transformations.	**L4**
CO5	Evaluate the COP of refrigerating systems and properties, processes of psychrometry and sensible and latent heat loads.	**L5**

PROGRAMME OUTCOMES (Pos)

PO1	**Engineering knowledge:** Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
PO2	**Problem analysis:** Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.
PO3	**Design/development of solutions:** Design solutions for complex engineering problems and design system components of processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
PO4	**Conduct investigations of complex problems:** Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.
PO5	**Modern tool usage:** Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.
PO6	**The engineer and society:** Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
PO7	**Environment and sustainability:** Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.
PO8	**Ethics:** Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.
PO9	**Individual and team work:** Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.
PO10	**Communication:** Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.
PO11	**Project management and finance:** Demonstrate knowledge and understanding of the engineering and management principles and apply these to one’s own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.
PO12	**Life-long learning:** Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change

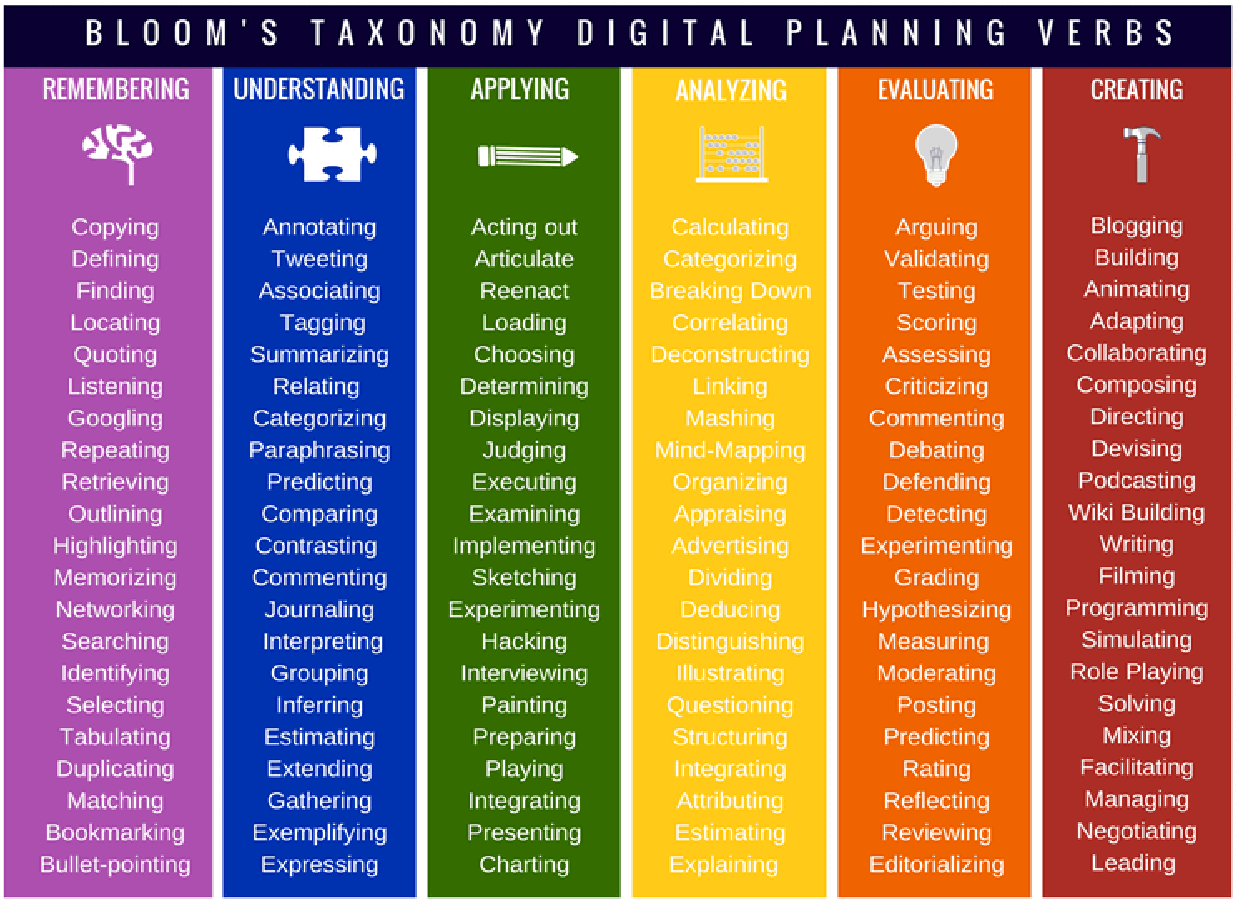
PROGRAMME SPECIFIC OUTCOMES (PSOs)

PSO1	Ability to analyze, design and develop Mechanical systems to solve the Engineering problems by integrating thermal, design and manufacturing domains.
PSO2	Ability to succeed in competitive examinations or to pursue higher studies or research.
PSO3	Ability to apply the learned Mechanical Engineering knowledge for the development of society and self.

PROGRAMME EDUCATIONAL OBJECTIVES (PEOs)

PEO1	Work productively as Mechanical engineers, including supportive and leadership roles on multi-disciplinary teams.
PEO2	Meet the needs of Indian and Multinational companies to synthesize data and technical concepts for application in new product design.
PEO3	Communicate effectively, recognize, and incorporate societal needs and constraints in their professional endeavors along with professional ethics in their professional practice.
PEO4	Engage in continuous learning, such as graduate study to remain current in their profession and be leaders in the technological society.

BLOOMS TAXONOMY



BLOOM'S TAXONOMY DIGITAL PLANNING VERBS

REMEMBERING	UNDERSTANDING	APPLYING	ANALYZING	EVALUATING	CREATING
Copying	Annotating	Acting out	Calculating	Arguing	Blogging
Defining	Tweeting	Articulate	Categorizing	Validating	Building
Finding	Associating	Reenact	Breaking Down	Testing	Animating
Locating	Tagging	Loading	Correlating	Scoring	Adapting
Quoting	Summarizing	Choosing	Deconstructing	Assessing	Collaborating
Listening	Relating	Determining	Linking	Criticizing	Composing
Googling	Categorizing	Displaying	Mashing	Commenting	Directing
Repeating	Paraphrasing	Judging	Mind-Mapping	Debating	Devising
Retrieving	Predicting	Executing	Organizing	Defending	Podcasting
Outlining	Comparing	Examining	Appraising	Detecting	Wiki Building
Highlighting	Contrasting	Implementing	Advertising	Experimenting	Writing
Memorizing	Commenting	Sketching	Dividing	Grading	Filming
Networking	Journaling	Experimenting	Deducing	Hypothesizing	Programming
Searching	Interpreting	Hacking	Distinguishing	Measuring	Simulating
Identifying	Grouping	Interviewing	Illustrating	Moderating	Role Playing
Selecting	Inferring	Painting	Questioning	Posting	Solving
Tabulating	Estimating	Preparing	Structuring	Predicting	Mixing
Duplicating	Extending	Playing	Integrating	Rating	Facilitating
Matching	Gathering	Integrating	Attributing	Reflecting	Managing
Bookmarking	Exemplifying	Presenting	Estimating	Reviewing	Negotiating
Bullet-pointing	Expressing	Charting	Explaining	Editorializing	Leading

UNIT - I

Introduction: Basic Concepts: System, boundary, Surrounding, control volume, Universe, Types of Systems, Macroscopic and Microscopic viewpoints, Concept of Continuum, Thermodynamic Equilibrium, State, Property, Process, Cycle – Reversibility – Quasi static Process, Irreversible Process, Causes of Irreversibility.

UNIT -II

Energy in State and in Transition, Types, Work and Heat, Point and Path function. Zeroth Law of Thermodynamics – PMM-I, Joule's Experiment – First law of Thermodynamics and applications. Limitations of the First Law – Enthalpy, Thermal Reservoir, Heat Engine, Heat pump, Parameters of performance.

UNIT - III

Second Law of Thermodynamics, Kelvin-Planck and Clausius Statements and their Equivalence / Corollaries, PMM-II, Carnot's principle, Carnot cycle and its specialties, Thermodynamic scale of Temperature, Clausius Inequality, Entropy, Principle of Entropy Increase – Energy Equation, Availability and Irreversibility – Thermodynamic Potentials, Gibbs and Helmholtz Functions, Maxwell Relations – Elementary Treatment of the Third Law of Thermodynamics.

UNIT - IV

Pure Substances, P-V-T- surfaces, T-S and h-s diagrams, Mollier Charts, Phase Transformations – Triple point at critical state properties during change of phase, Dryness Fraction – Clausius – Clapeyron Equation Property tables. Mollier charts – Various Thermodynamic processes and energy Transfer – Steam Calorimetry.

UNIT – V

Introduction to Refrigeration: working of Air, Vapour compression, VCR system Components, COP Refrigerants. Introduction to Air Conditioning: Psychrometric properties & processes – characterization of sensible and latent heat loads – load concepts of SHF. Requirements of human comfort and concept of effective temperature- comfort chart – comfort air conditioning, and load calculations.

Textbooks:

1. P. K. Nag, Engineering Thermodynamics, 5/e, Tata McGraw Hill, 2013.
2. Claus Borgnakke Richard E. Sonntag, Fundamentals of Thermodynamics, 7/e, Wiley,2009.

Reference Books

1. J.B. Jones, and R.E. Dugan, Engineering Thermodynamics, 1/e, Prentice Hall, 1995.
2. Y. A. Cengel & M.A. Boles, Thermodynamics – An Engineering Approach,7/e, McGraw Hill, 2010.
3. P. Chattopadhyay, Engineering Thermodynamics, 1/e, Oxford University Press, 2011.

4. CP Arora, Refrigeration and Air-conditioning, 4/e, McGraw Hill, 2021.

Online Learning Resources:

- https://www.edx.org/learn/thermodynamics.
- https://archive.nptel.ac.in/courses/112/106/112106310.
- https://www.youtube.com/watch?v=7NI5P4KqrAs&t=1s
- https://kp.kiit.ac.in/pdf_files/02/Study-Material_3rdSemester_Winter_2021_Mechanical-Engg.-_Thermal-Engineering-1_AbhijitSamant.pdf
- https://www.coursera.org/learn/thermodynamics-intro

UNIT - I

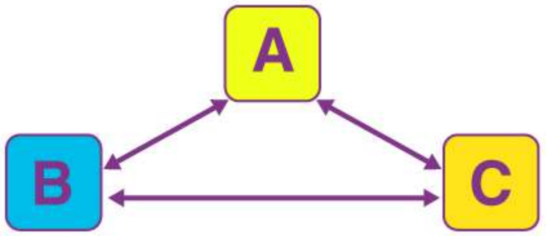
Introduction: Basic Concepts: System, boundary, Surrounding, control volume, Universe, Types of Systems, Macroscopic and Microscopic viewpoints, Concept of Continuum, Thermodynamic Equilibrium, State, Property, Process, Cycle – Reversibility – Quasi static Process, Irreversible Process, Causes of Irreversibility.

Introduction: Basic Concepts:

Thermodynamics is the study of energy, heat, and work and how they interact with each other and with matter. It deals with the principles that govern the transformation and transfer of energy in physical and chemical processes. Thermodynamics is fundamental to understanding how engines, refrigerators, and even the human body work.

There are four main laws of thermodynamics:

1. **Zeroth Law**: If two systems are in thermal equilibrium with a third system, they are in thermal equilibrium with each other. This helps define the concept of temperature.



The zeroth law of thermodynamics states that if two thermodynamic systems are each in thermal equilibrium with a third one, then they are in thermal equilibrium with each other.

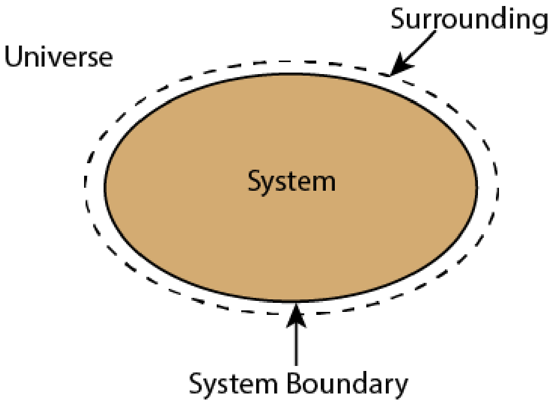
2. **First Law**: Energy cannot be created or destroyed; it can only be transferred or transformed. This is also known as the law of energy conservation.
3. **Second Law**: In any energy transfer or transformation, the total entropy (a measure of disorder) of an isolated system always increases. This means that natural processes tend to move towards a state of greater disorder or randomness.

4. **Third Law**: As the temperature of a system approaches absolute zero, the entropy of the system approaches a minimum value.

Thermodynamics is a branch of physics that deals with the study of energy, heat, and work, and how they interact with matter. At its core, thermodynamics is concerned with understanding the fundamental laws that govern energy transformations and transfers in physical systems.

An Introduction to the key concepts in thermodynamics:

1. **Systems and Surroundings**: In thermodynamics, we define a "system" as the part of the universe we are studying, while the "surroundings" are everything outside the system. Systems can be open (exchange energy and matter with surroundings), closed (exchange only energy), or isolated (exchange neither).

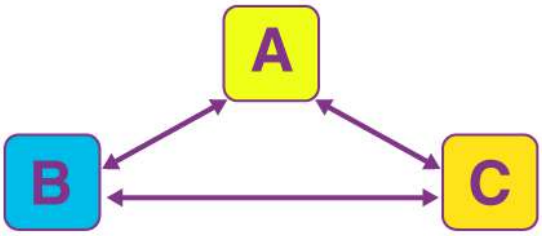


2. **State Functions**: These are properties that describe the state of a system, such as temperature, pressure, volume, and internal energy. State functions depend only on the current state of the system, not on how it got there.

3. **Processes**: Thermodynamic processes describe how systems change from one state to another. These processes can be isothermal (constant temperature), adiabatic (no heat exchange), isobaric (constant pressure), or isochoric (constant volume).

4. **Laws of Thermodynamics**:

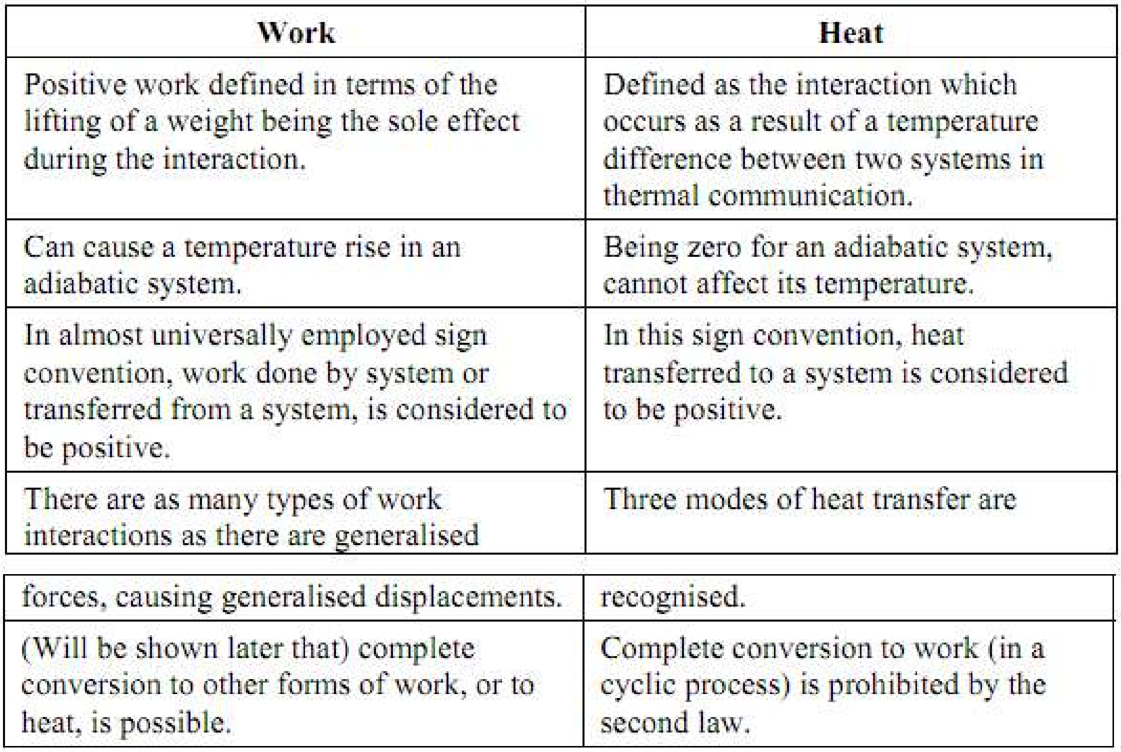
    - **Zeroth Law**: Establishes the concept of temperature. If two systems are in thermal equilibrium with a third system, they are in thermal equilibrium with each other.



The zeroth law of thermodynamics states that if two thermodynamic systems are each in thermal equilibrium with a third one, then they are in thermal equilibrium with each other.

   - **First Law**: Also known as the law of energy conservation. It states that energy cannot be created or destroyed, only transferred or transformed. Mathematically, it is expressed as $\Delta U = Q - W$, where ΔU is the change in internal energy, Q is heat added to the system, and W is work done by the system.
   - **Second Law**: Introduces the concept of entropy, a measure of disorder or randomness. It states that in any energy transfer or transformation, the total entropy of an isolated system always increases.
   - **Third Law**: States that as the temperature of a system approaches absolute zero, the entropy of the system approaches a minimum value.

5. **Heat and Work**: Heat is the transfer of thermal energy between systems due to a temperature difference, while work is the transfer of energy due to mechanical actions.



Work	Heat
Positive work defined in terms of the lifting of a weight being the sole effect during the interaction.	Defined as the interaction which occurs as a result of a temperature difference between two systems in thermal communication.
Can cause a temperature rise in an adiabatic system.	Being zero for an adiabatic system, cannot affect its temperature.
In almost universally employed sign convention, work done by system or transferred from a system, is considered to be positive.	In this sign convention, heat transferred to a system is considered to be positive.
There are as many types of work interactions as there are generalised forces, causing generalised displacements.	Three modes of heat transfer are recognised.
(Will be shown later that) complete conversion to other forms of work, or to heat, is possible.	Complete conversion to work (in a cyclic process) is prohibited by the second law.

6. **Thermodynamic Cycles**: These are sequences of processes that return a system to its initial state. Examples include the Carnot cycle, which is an idealized cycle that provides the maximum efficiency a heat engine can achieve.

System: - In thermodynamics, a system refers to a specific part of the universe that is being studied or analysed. It can be anything from a single gas molecule to an entire power plant.

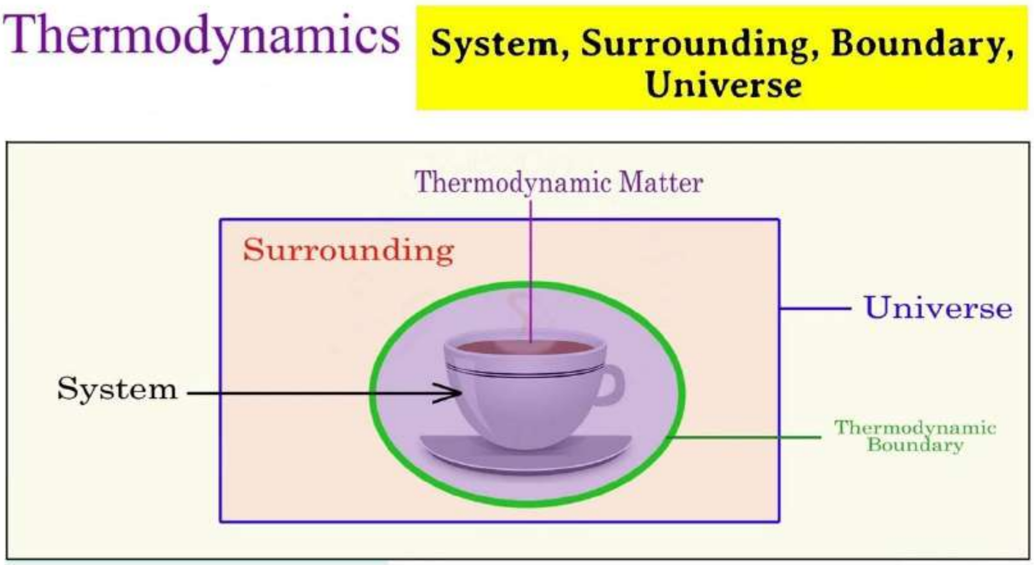
Examples:

- A gas inside a container
- A chemical reaction in a test tube
- A human body

Boundary: - The boundary is the surface that separates the system from its surroundings. It can be real or imaginary and can be fixed or movable. The nature of the boundary determines how the system interacts with its surroundings.

Characteristics:

- Can be fixed or movable.
- Can be permeable (allowing exchange of matter or energy) or impermeable.



Surroundings: - The surroundings, also known as the environment, consist of everything outside the system boundary. The surroundings can exchange energy and matter with the system through the boundary.

Control Volume: -A control volume is a specified region in space where mass and energy transfers are studied. It's commonly used in fluid mechanics and thermodynamics to analyse systems like turbines, compressors, and nozzles. A control volume can have inlets and outlets through which mass and energy can flow.

Universe: - In thermodynamics, the universe is considered to be the system plus its surroundings. It encompasses everything that exists, but for practical purposes, we often focus on a specific system and its immediate surroundings.

Difference between system and control volume

The concepts of **system** and **control volume** are fundamental in thermodynamics and fluid mechanics, but they differ in their definitions and applications.

1. System: -

- A **system** is a **fixed mass** in space that is separated from its surroundings by a boundary.
- The system boundary may be **real or imaginary** and can change in shape or size.
- No **mass crosses** the system boundary, but **energy (heat, work)** can transfer.
- Example: A closed piston-cylinder device containing gas. The gas inside is the system, and no mass enters or leaves, but heat and work can cross the boundary.

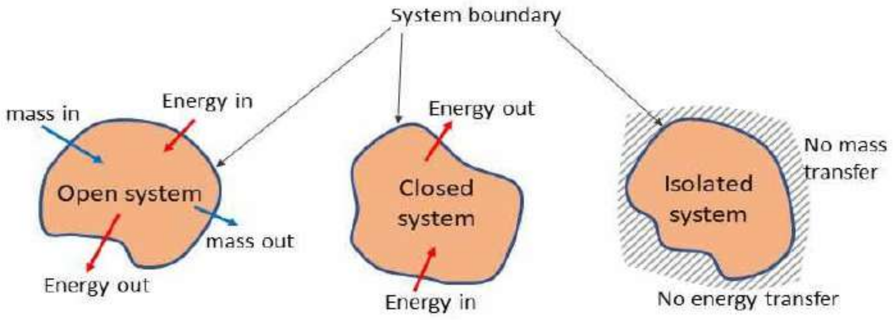
2. Control Volume: -

- A **control volume** is a **region in space** chosen to analyse mass and energy flow.
- Mass **can cross** the control volume boundary (known as the **control surface**).
- It is used for **open systems**, such as turbines, compressors, nozzles, and pumps.
- Example: A jet engine where air enters, fuel burns, and exhaust exits. The control volume encloses the engine, and mass flows in and out.

Differences: -

Feature	System (Closed System)	Control Volume (Open System)
Mass Transfer	No mass crosses the boundary	Mass can enter and leave
Energy Transfer	Heat and work can cross	Heat, work, and mass can cross
Boundary Type	Fixed or movable	Fixed in space, usually enclosing a device
Example	Gas in a piston-cylinder	Steam turbine, nozzle, or compressor

Types of Systems: -



Open, Closed and Isolated system illustration

- **Open System**: An open system can exchange both energy and matter with its surroundings.

  Examples include a boiling pot of water (heat and steam escape) and a car engine (fuel and exhaust gases enter and exit).

- **Closed System**: A closed system can exchange energy but not matter with its surroundings.

  Example is a sealed piston-cylinder assembly, where heat can be transferred in or out, but the gas inside remains.

- **Isolated System**: An isolated system cannot exchange either energy or matter with its surroundings. It is completely insulated.

  Example A perfect thermos flask approximates an isolated system, where neither heat nor matter can enter or leave.

Homogeneous & Heterogeneous System

Homogeneous System: -

- **Definition**: A homogeneous system is one that has a uniform composition and properties throughout. This means that any small sample taken from different parts of the system will have the same composition and properties.
- **Examples**: A solution of salt in water, a mixture of gases like air, and pure substances like a single-phase solid, liquid, or gas are all examples of homogeneous systems.
- **Phases**: A homogeneous system consists of only one phase. For instance, a glass of pure water is a single-phase system where the composition and properties are uniform throughout.

Heterogeneous System: -

- **Definition**: A heterogeneous system is one that has a non-uniform composition and properties throughout. This means that different samples taken from various parts of the system may have different compositions and properties.
- **Examples**: A mixture of oil and water, a container with ice and liquid water, and a bowl of salad are all examples of heterogeneous systems.
- **Phases**: A heterogeneous system consists of two or more distinct phases. For instance, in a container with ice and liquid water, the ice represents one phase (solid) and the liquid water represents another phase (liquid).

Homogeneous & Heterogeneous System Differences: -

Feature	Homogeneous System	Heterogeneous System
Phases	Single phase	Multiple phases
Uniformity	Uniform composition & properties	Different composition & properties in different regions
Phase Boundaries	Not present	Present
Example	Salt solution, air, pure metals	Ice-water mixture, oil-water, steam-liquid water

Differentiate between Microscopic viewpoints Macroscopic viewpoints from Thermodynamics

Sr. No.	Macroscopic Approach	Microscopic Approach
1	In this approach a certain quantity of matter is considered without taking into account the events occurring at molecular level.	The matter is considered to be comprised of a large number of tiny particles known as molecules, which moves randomly in chaotic fashion. The effect of molecular motion is considered.
2	Analysis is concerned with overall behavior of the system.	The Knowledge of the structure of matter is essential in analyzing the behavior of the system.
3	This approach is used in the study of classical thermodynamics.	This approach is used in the study of statistical thermodynamics.
4	A few properties are required to describe the system.	Large numbers of variables are required to describe the system.
5	The properties like pressure, temperature, etc. needed to describe the system, can be easily measured.	The properties like velocity, momentum, kinetic energy, etc. needed to describe the system, cannot be measured easily.
6	The properties of the system are their average values.	The properties are defined for each molecule individually.
7	This approach requires simple mathematical formulas for analyzing the system.	No. of molecules are very large so it requires advanced statistical and mathematical method to explain any change in the system.

Concept of Continuum: -

- The concept of continuum is a kind of idealization of the continuous description of matter where the properties of the matter are considered as continuous functions of space variables. Although any matter is composed of several molecules, the concept of continuum assumes a continuous distribution of mass within the matter or system with no empty space, instead of the actual conglomeration of separate molecules.

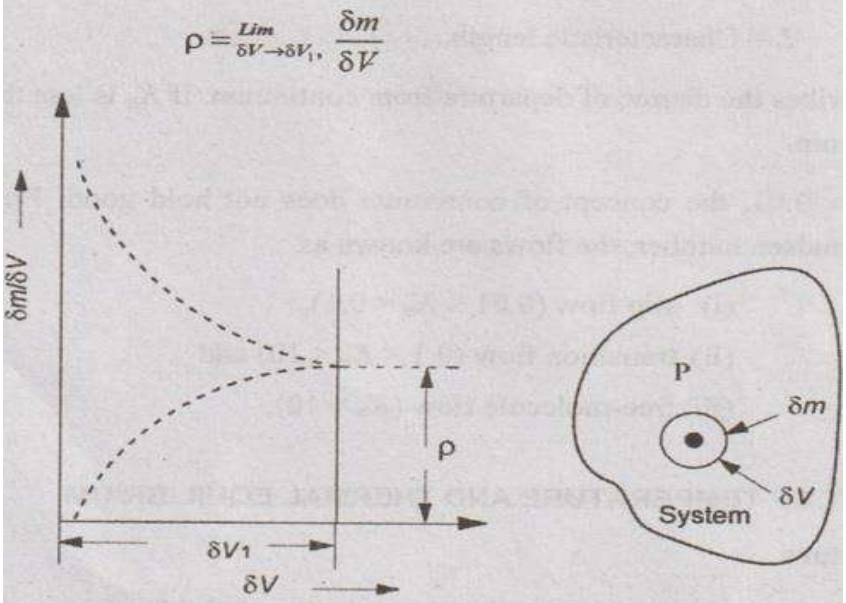


Figure 1.8 Concept of continuum

- Describing a fluid flow quantitatively makes it necessary to assume that flow variables (pressure, velocity etc.) and fluid properties vary continuously from one point to another. Mathematical description of flow on this basis have proved to be reliable and treatment of fluid medium as a continuum has firmly become established. For example, density at a point is normally defined as

$$\rho = \lim_{\Delta\forall \to 0}\left(\frac{m}{\Delta\forall}\right)$$

Here $\Delta\forall$ is the volume of the fluid element and m is the mass

- If $\Delta\forall$ is very large ρ is affected by the inhomogeneities in the fluid medium. Considering another extreme if $\Delta\forall$ is very small, random movement of atoms (or molecules) would change their number at different times. In the continuum approximation point density is defined at the smallest magnitude of $\Delta\forall$, before statistical fluctuations become significant. This is called continuum limit and is denoted by $\Delta\forall_c$.

$$\rho = \lim_{\Delta\forall \to \Delta\forall_C} \left(\frac{m}{\Delta\forall} \right)$$

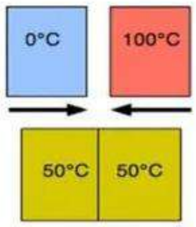
THERMODYNAMIC EQUILIBRIUM

Thermodynamic equilibrium is a state where a system is in balance thermally, mechanically, and chemically. It is a state where the system does not spontaneously change its state.

Types of thermodynamic equilibrium: -

1. Thermal Equilibrium: -

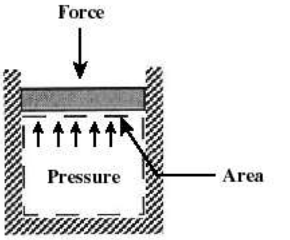
- **Definition**: A system is in thermal equilibrium when there is no temperature gradient within the system or between the system and its surroundings. This means that the temperature is uniform throughout the system.



- **Example**: Two objects at different temperatures placed in contact will eventually reach the same temperature and be in thermal equilibrium.

2. Mechanical Equilibrium: -

- **Definition**: A system is in mechanical equilibrium when there are no unbalanced forces within the system or between the system and its surroundings. This means that the pressure is uniform throughout the system.

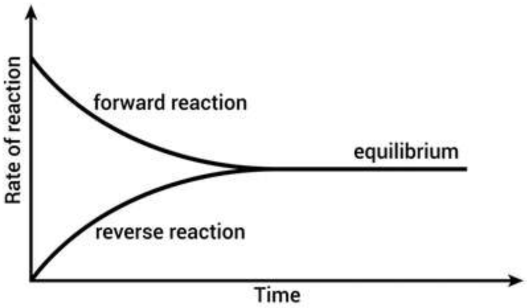


Mechanical equilibrium
(force balance pressure times area)

- **Example**: A gas in a sealed container with a movable piston will be in mechanical equilibrium when the pressure of the gas equals the external pressure acting on the piston.

3. Chemical Equilibrium: -

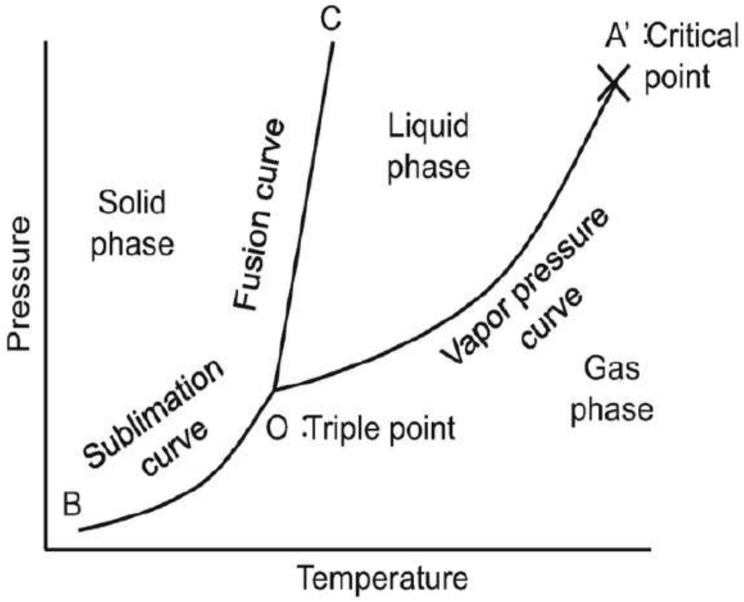
- **Definition**: A system is in chemical equilibrium when the chemical composition of the system does not change over time. This occurs when the rates of forward and reverse chemical reactions are equal, resulting in no net change in the concentrations of reactants and products.



- **Example:** A balloon filled with air is in mechanical equilibrium when the outward force of the air pressure inside equals the inward force of the atmospheric pressure and the balloon's elasticity.

4. Phase Equilibrium: -

- **Definition**: A system is in phase equilibrium when multiple phases (solid, liquid, gas) coexist without any net transfer of matter between them. The conditions (temperature, pressure) are such that the phases are in balance.



- **Example**: Water in a closed container with liquid water, ice, and water vapor all in coexistence is in phase equilibrium.

State: -

- **Definition**: The state of a system is defined by its properties at a specific point in time. When a system is in a given state, all its properties have fixed values.

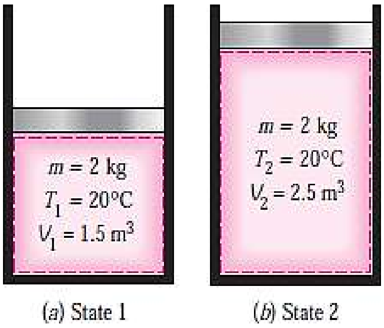


Fig. A system at twodifferent states

- **Example**: The state of water in a container can be described by its temperature, pressure, and volume.

Property: -

- **Definition**: Properties are measurable characteristics of a system that help define its state. They can be intensive or extensive.
    - **Intensive Properties**: These do not depend on the size or mass of the system (e.g., temperature, pressure, density).

  - **Extensive Properties**: These depend on the size or mass of the system (e.g., volume, mass, total energy).

- **Example**: Temperature, pressure, volume, and internal energy are properties of a system.

Process: -

- **Definition**: A process is a transformation that occurs when a system changes from one state to another. During a process, one or more properties of the system change.

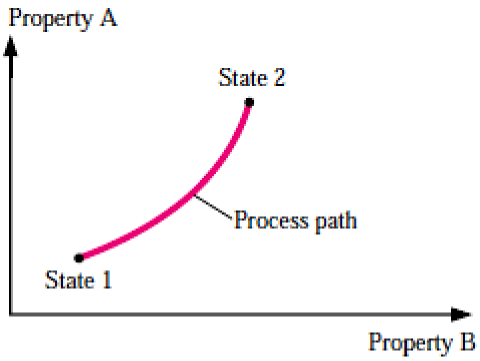


Fig. A process between states1 and 2 and a process path

- **Example**: Heating water from 25°C to 100°C is a process that changes the temperature and possibly the pressure of the water.

Cycle: -

- **Definition**: A cycle is a series of processes that return a system to its initial state. In a cycle, the final state is identical to the initial state, and the system undergoes various transformations in between.

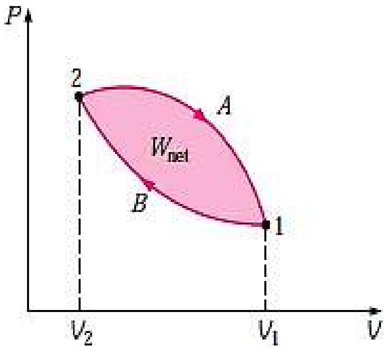


Fig. Cycle of operations

- **Example**: The Carnot cycle, which is an idealized thermodynamic cycle that provides the maximum efficiency for a heat engine, is an example of a thermodynamic cycle.

Reversibility: -

- **Definition**: A reversible process is an idealized process that occurs infinitely slowly and without any dissipative effects (like friction or unrestrained expansion), allowing the system to be returned to its initial state without any net change in the surroundings. In practice, perfectly reversible processes do not exist, but they provide a useful idealization for analysis.
- **Example**: An infinitesimally slow compression or expansion of a gas in a perfectly insulated piston-cylinder assembly can be considered a reversible process.

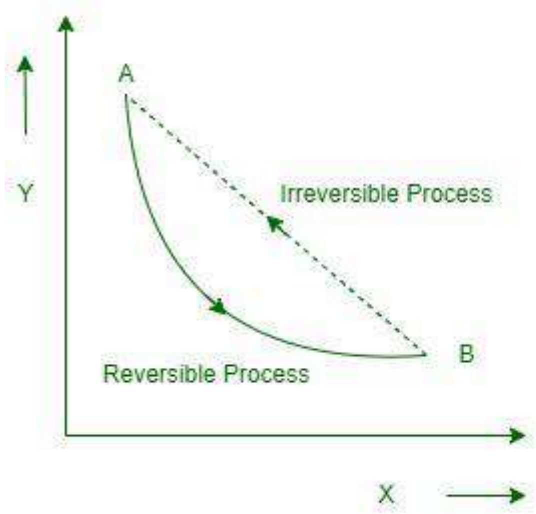


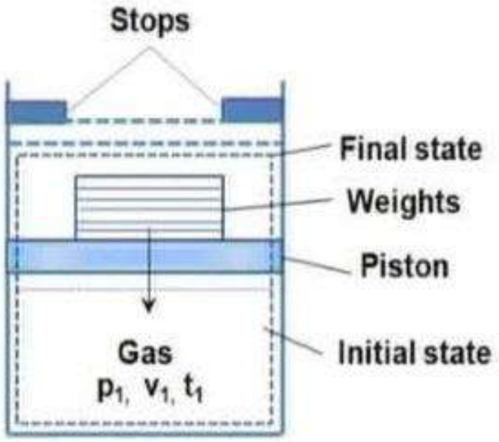
Fig. Reversible & Irreversible Process

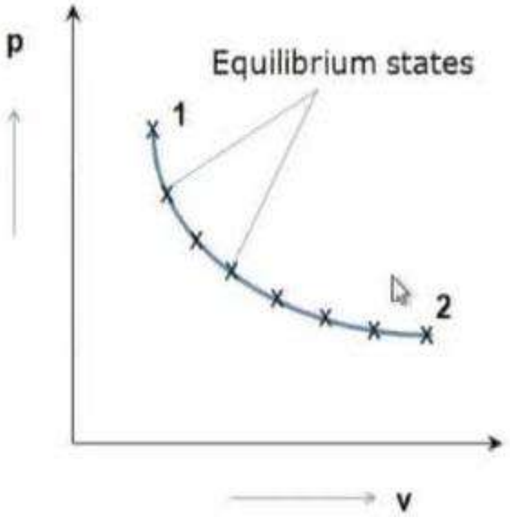
Irreversibility: -

- **Definition**: An irreversible process is a real process that occurs at a finite rate with dissipative effects, meaning it cannot be reversed without leaving a net change in the system and its surroundings.
- **Example**: The rapid mixing of two gases, heat transfer through a finite temperature difference, and frictional effects are examples of irreversible processes.

S.No.	Reversible process	Irreversible process
1.	Driving force is infinitesimally small.	Driving force is large and finite.
2.	PV work is done across pressure difference dp	PV work is done across pressure difference ΔP
3.	A reversible heat transfer take place across temperature difference dT	Irrerversible heat transfer take place across difference ΔT
4.	It is an ideal process.	It is a real process
5.	It takes infinite time for completion of process.	It takes finite time for completion of process.
6.	It is an imaginary process and can not be realised in actual practice.	It is a natural process and occurs in particular direction under given set of conditions.
7.	Throughout the process, the system remain infinetesimelly closer to state of equilibrium and exact path of process can be drawn	The system is far away from state of equilibrium and exact path of process can not be defined as different part of the system are under different conditions

Quasi-static processes





A quasi-static process in thermodynamics is a process that happens so slowly that the system remains in equilibrium at all times. This process is also known as a quasi-equilibrium process.

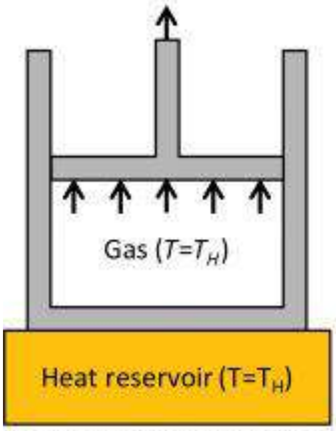
- “Quasi” means Almost slow or infinitely slow.
- Consider a system of gas contained in a cylinder fitted with a piston upon which many very small pieces of weights are placed.
- The upward force exerted by the gas just balances the weights on the piston and the system is initially in equilibrium state identified by pressure temperature.
- When these weights are removed slowly, one at a time, the unbalanced potential is infinitesimally small.
- The piston will slowly move upwards and at any particular instant of piston travel, the system would be almost close to state of equilibrium.
- Every state passed by the system will be an equilibrium state.
- The locus of a series of such equilibrium states is called a “Quasi-Static or Quasi Equilibrium process.”
- It should be pointed out that a quasi-equilibrium process is an idealized process and is not a true representation of an actual process.
- But many actual processes closely approximate it, and they can be modelled as quasi-equilibrium with negligible error.
- Engineers are interested in quasi-equilibrium processes for two reasons. First, they are easy to analyse; second, work-producing devices deliver the most work when they operate on quasi-equilibrium processes.
- Therefore, quasi-equilibrium processes serve as standards to which actual processes can be compared. The p-v diagram of a compression process of a gas.

- A quasi-static process is also called a reversible process. This process is a succession of equilibrium states and infinite slowness is its characteristic feature.

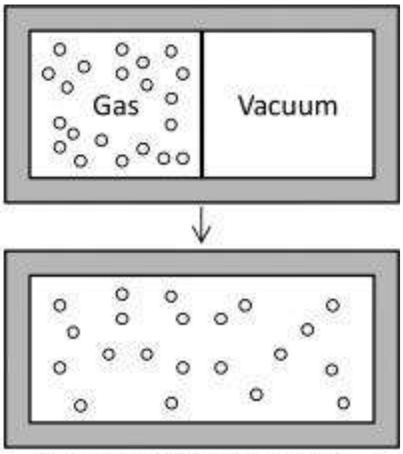
In thermodynamics, an irreversible process is a real-world process that cannot be reversed without leaving a net change in the system and its surroundings. In other words, once an irreversible process has occurred, the system cannot be returned to its initial state without some form of external intervention. Irreversible processes are characterized by the presence of dissipative effects, such as friction, unrestrained expansion, heat transfer through a finite temperature difference, and mixing of different substances.

Irreversible Process: -

- **Definition**: An irreversible process is one that cannot be reversed without leaving a net change in the system and the surroundings. Such processes are non-ideal and occur naturally due to the inherent inefficiencies in real systems.

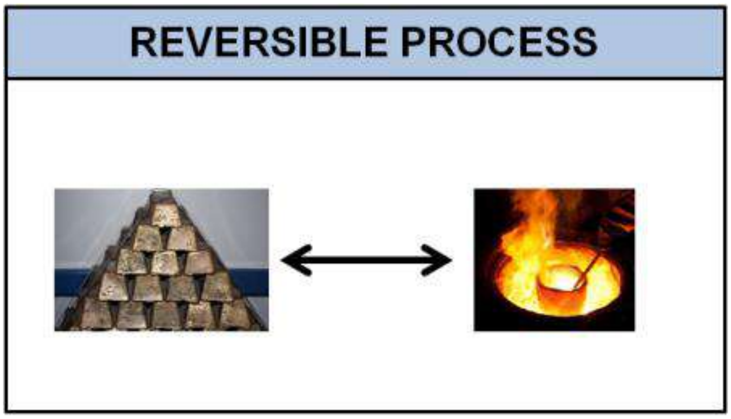


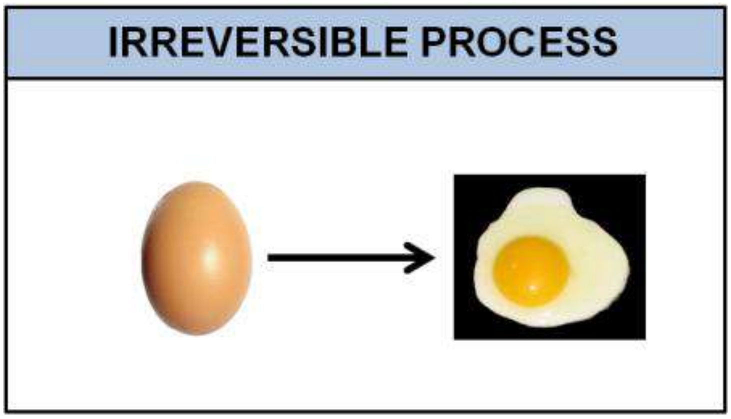
(a) Reversible expansion



(b) Irreversible expansion

- **Examples**: Common examples of irreversible processes include the rapid expansion of a gas, heat transfer from a hot object to a cold one, natural mixing of two gases, and the frictional dissipation of mechanical energy.





Causes of Irreversibility: -

Several factors contribute to the irreversibility of a process. These factors introduce inefficiencies and prevent the process from being perfectly reversible:

1. **Friction**: - Mechanical friction between moving parts converts useful mechanical energy into heat, which is dissipated into the surroundings. This results in a loss of energy that cannot be fully recovered.
2. **Unrestrained Expansion**: - When a gas expands freely into a vacuum without any resistance, it undergoes an unrestrained expansion. This process is highly irreversible because it results in a significant increase in entropy and no work is done.
3. **Heat Transfer Through a Finite Temperature Difference**: - When heat is transferred between two objects with a significant temperature difference, the process is irreversible. The greater the temperature difference, the more irreversible the process. Heat transfer through finite temperature differences leads to an increase in entropy.
4. **Mixing of Different Substances**: - When two different substances mix spontaneously, the process is irreversible. This is because the mixing

increases the entropy of the system, and separating the substances back into their original pure forms would require an input of energy.

5. **Inelastic Deformation**: - When a material undergoes inelastic deformation (e.g., plastic deformation of a metal), the process is irreversible. The energy expended in deforming the material cannot be fully recovered.
6. **Chemical Reactions**: - Many chemical reactions are irreversible because they proceed in a specific direction and result in the formation of new products. Reversing the reaction would require significant external intervention and energy input.

UNIT -II

Energy in State and in Transition, Types, Work and Heat, Point and Path function. Zeroth Law of Thermodynamics – PMM-I, Joule's Experiment – First law of Thermodynamics and applications. Limitations of the First Law – Enthalpy, Thermal Reservoir, Heat Engine, Heat pump, Parameters of performance.

ENERGY IN STATE AND IN TRANSITION

In **thermodynamics**, energy can be classified based on whether it is associated with a particular **state** or **transition** of a system.

1. Energy in State (State Function): -

This refers to properties that depend only on the current state of the system, not on the path taken to reach that state. These include:

- **Internal Energy (U)**: The total energy contained within a system, including kinetic and potential energy at the molecular level.
- **Enthalpy (H)**: The total heat content of a system, defined as **$H=U+PV$.**
- **Entropy (S)**: A measure of disorder or randomness in a system.
- **Gibbs Free Energy (G)**: Determines the spontaneity of a process, defined as **$G=H-TS$**.
- **Helmholtz Free Energy (A)**: Defined as **$A=U-TS$**, used in constant volume systems.

Characteristics of State Energy

- Depends only on the initial and final states.
- Independent of the path taken.
- Represented as exact differentials in calculus.

2. Energy in Transition (Path Function): -

This refers to energy that is transferred between a system and its surroundings. Unlike state functions, these depend on the process or path taken. Examples include:

- **Heat (Q)**: Energy transfer due to a temperature difference.
- **Work (W)**: Energy transfer due to mechanical, electrical, or other means.

Characteristics of Transition Energy

- Not a property of the system itself.
- Depends on the path taken between states.
- Represented as inexact differentials (δQ, δW).

State Vs Transition Energy

Feature	**State Energy (State Function)**	**Transition Energy (Path Function)**
Examples	U, H, S, G, A	Q, W
Depends on	Initial and final state	Path taken
Mathematical Form	Exact differentials	Inexact differentials
Additive?	Yes	No

POINT FUNCTION & PATH FUNCTION

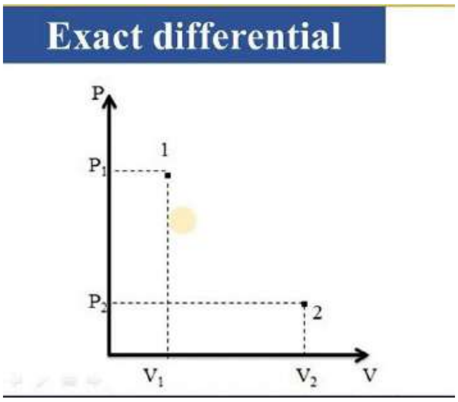
Point Function: -

A point function, also known as a state function, is a property that depends only on the current state of the system, not on the path taken to reach that state. The value of a point function is determined by the system's current conditions, such as pressure, volume, temperature, and internal energy.

Definition: A point function (or state function) is a property that depends only on the state of the system and not on how the system reached that state. In other words, it is independent of the path taken to reach that particular state.

Examples of Point Functions: -

- **Pressure (P)**: The pressure of a gas in a container depends only on the current state of the gas.
- **Temperature (T)**: The temperature of a system depends only on its current state.
- **Volume (V)**: The volume of a system depends only on its current state.
- **Internal Energy (U)**: The internal energy of a system depends only on its current state.



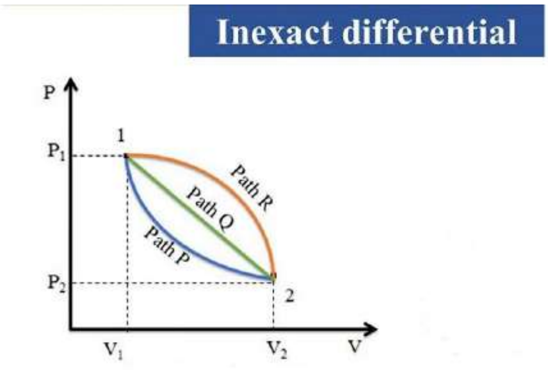
Characteristics of Point Functions: -

- Point functions are properties of the system that have definite values for each state.
- They are independent of the path taken to reach the state.
- Changes in point functions are given by the difference between their values at the initial and final states.

Path Function: -

A path function is a property that depends on the specific path taken to transition from one state to another. Unlike point functions, path functions are not determined solely by the initial and final states but also by the process that occurred.

Definition: A path function is a property that depends on the specific path taken to transition from one state to another. Path functions are not determined solely by the state of the system.



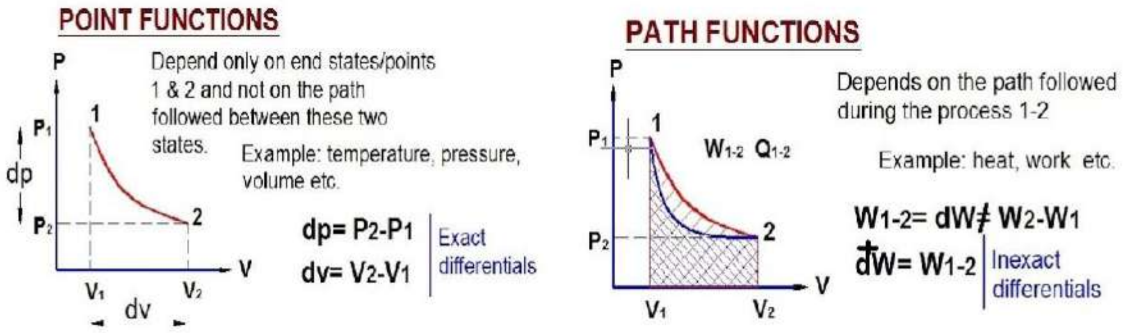
Examples of Path Functions: -

- **Work (W)**: The amount of work done by or on a system depends on the specific path taken during the process.
- **Heat (Q)**: The amount of heat transferred to or from a system depends on the specific path taken during the process.

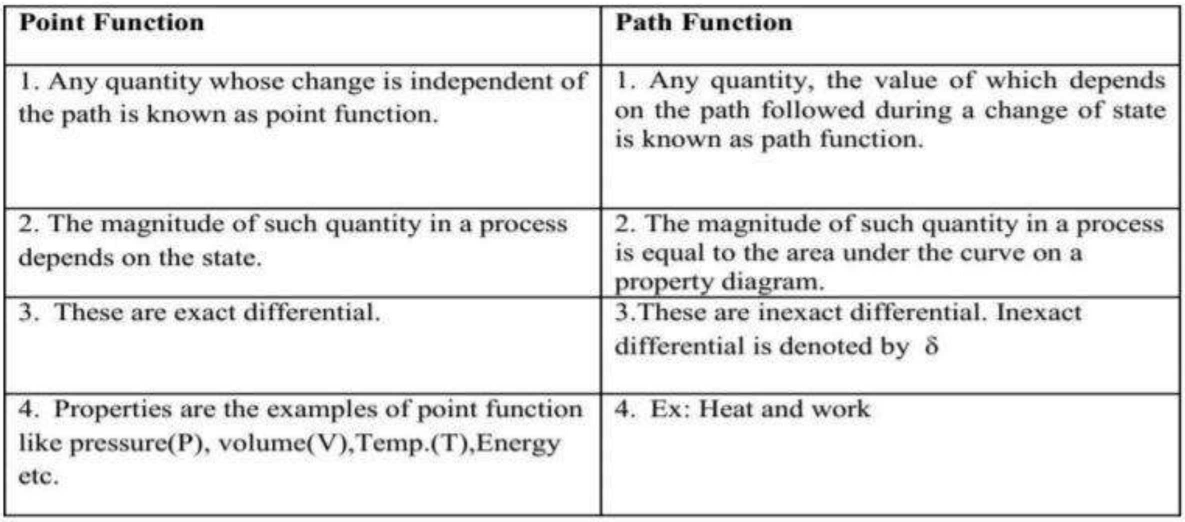
Characteristics of Path Functions: -

- Path functions are not properties of the system and do not have definite values for each state.

- They depend on the process or path taken to transition between states.
- Path functions are represented as inexact differentials, meaning their values cannot be determined solely by the endpoints.

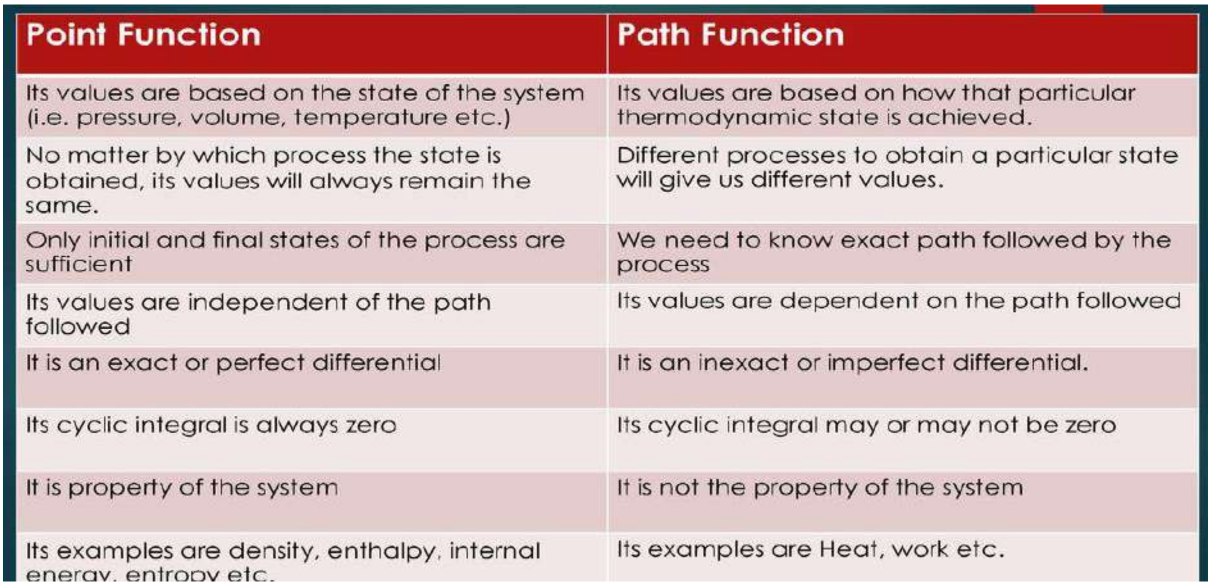


POINT FUNCTION & PATH FUNCTION



Point Function	**Path Function**
1. Any quantity whose change is independent of the path is known as point function.	1. Any quantity, the value of which depends on the path followed during a change of state is known as path function.
2. The magnitude of such quantity in a process depends on the state.	2. The magnitude of such quantity in a process is equal to the area under the curve on a property diagram.
3. These are exact differential.	3.These are inexact differential. Inexact differential is denoted by δ
4. Properties are the examples of point function like pressure(P), volume(V),Temp.(T),Energy etc.	4. Ex: Heat and work

DIFFERENCES POINT FUNCTION & PATH FUNCTION



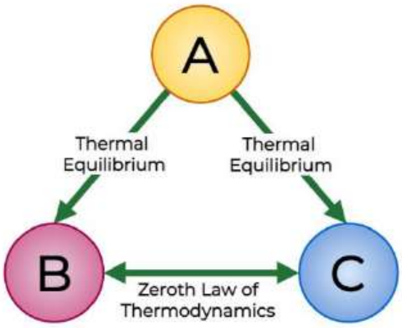
Point Function	Path Function
Its values are based on the state of the system (i.e. pressure, volume, temperature etc.)	Its values are based on how that particular thermodynamic state is achieved.
No matter by which process the state is obtained, its values will always remain the same.	Different processes to obtain a particular state will give us different values.
Only initial and final states of the process are sufficient	We need to know exact path followed by the process
Its values are independent of the path followed	Its values are dependent on the path followed
It is an exact or perfect differential	It is an inexact or imperfect differential.
Its cyclic integral is always zero	Its cyclic integral may or may not be zero
It is property of the system	It is not the property of the system
Its examples are density, enthalpy, internal energy, entropy etc.	Its examples are Heat, work etc.

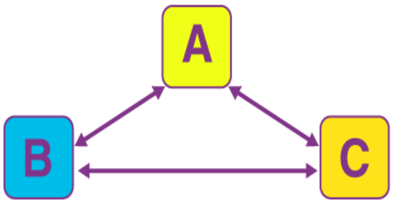
ZEROTH LAW OF THERMODYNAMICS: -

The Zeroth Law of Thermodynamics is a fundamental principle that forms the basis for the concept of temperature in thermodynamics.

Zeroth Law of Thermodynamics: If two systems are each in thermal equilibrium with a third system, then they are in thermal equilibrium with each other.

Example: -Consider three systems: A, B, and C.



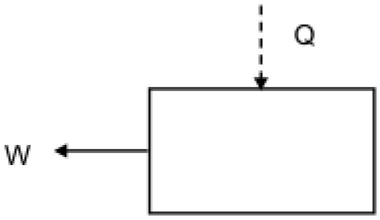


The zeroth law of thermodynamics states that if two thermodynamic systems are each in thermal equilibrium with a third one, then they are in thermal equilibrium with each other.

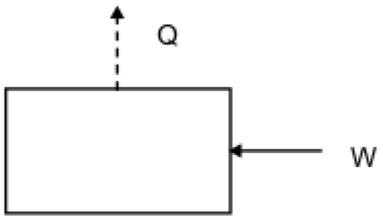
- System A is in thermal equilibrium with system C (same temperature).
- System B is in thermal equilibrium with system C (same temperature).

According to the Zeroth Law, system A must be in thermal equilibrium with system B, meaning system A and system B are at the same temperature.

PMM-I



PMMFK



Converse of PMMFK

Perpetual motion machine of the first kind (PMM1)

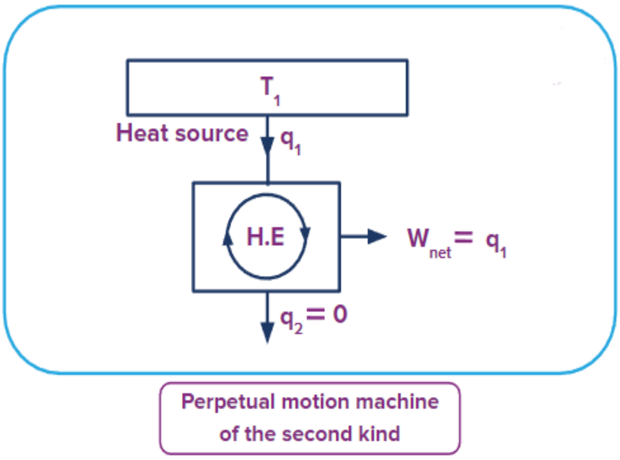
“A machine that produces work without consuming energy from its surroundings.”

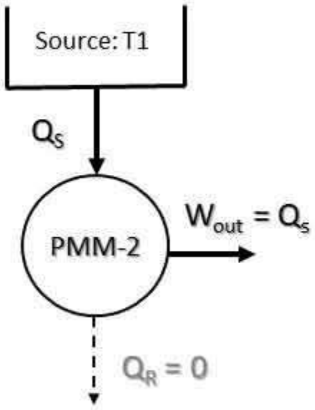
This violates the first law of thermodynamics, which states that energy cannot be created or destroyed.

PMM-II

Perpetual motion machine of the second kind (PMM2)

“A machine that produces work by exchanging heat with a single reservoir.” This violates the second law of thermodynamics.



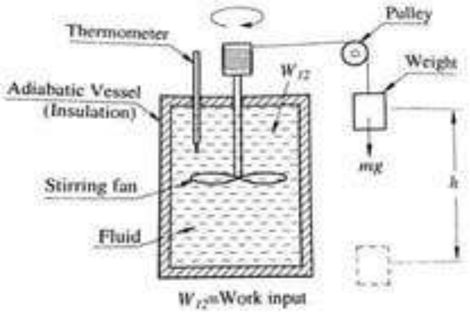


A perpetual motion machine of the second kind (PMM-II) is a hypothetical machine that produces work from a single heat source.
It violates the second law of thermodynamics, which states that heat cannot be transferred from a colder to a hotter body.

Explanation: -

- A PMM-II is a heat engine that uses heat energy to create work.
- It has a single heat reservoir that cools spontaneously, creating work without transferring heat to a cooler reservoir.
- The Kelvin-Planck statement of the second law of thermodynamics states that it's difficult to construct a heat engine that only takes in heat energy and creates an equivalent amount of work.
- Some heat must always be rejected in order to sink.

JOULE’S EXPERIMENT



Process 1-2 Work entering the system

Fig. 2.3(a) Joule’s experiment.

Joule's experiment was conducted by **James Prescott Joule** in the 1840s to establish the relationship between **mechanical work** and **heat energy**, leading to the concept of the **first law of thermodynamics**.

Experimental Setup: - Joule's apparatus consisted of:

1. **A thermally insulated container** filled with **water**.
2. **A rotating paddle wheel** inside the container.
3. **A falling mass connected to the paddle wheel** through a pulley system.
4. **A thermometer** to measure temperature changes in the water.

Working of Joule’s Experiment: -

1. **Potential Energy to Mechanical Work:**
   - A **known mass** is lifted to a certain height and then allowed to fall.
   - As it falls, it rotates the **paddle wheel** inside the water.
2. **Mechanical Work to Internal Energy:**
   - The rotating **paddle wheel agitates the water molecules**, causing **friction**.
   - This increases the **internal energy** of water, leading to a **rise in temperature**.
3. **Measuring Temperature Change:**
   - A **thermometer** records the temperature before and after the experiment.
   - The **increase in temperature** is proportional to the **mechanical work** done by the falling mass.

Observations & Conclusion: -

Joule found that **mechanical work can be completely converted into heat energy**.
He established the **mechanical equivalent of heat**, showing that:

$$\mathbf{W=Q}$$

Where:

- W = **Work done by the falling weight** (measured in Joules)
- Q = **Heat energy gained by water** (measured in calories or Joules)

Joule's Mechanical Equivalent of Heat: -

Through multiple experiments, Joule determined that:

$$\mathbf{1\ calorie=4.186\ Joules}$$

This means that **4.186 Joules of mechanical work** is needed to **raise the temperature of 1 gram of water by 1°C**.

Significance of Joule's Experiment: -

1. **Proved the First Law of Thermodynamics** – Energy is **conserved** and can be **converted** from one form to another.
2. **Disproved Caloric Theory** – Heat is **not a fluid** but a form of energy.
3. **Led to the Joule Unit** – The SI unit of energy, **Joule (J)**, is named after him.
4. **Foundation for Energy Conservation** – Helped establish the law of **conservation of energy**.

First law of Thermodynamics: -

The First Law of Thermodynamics, also known as the Law of Energy Conservation, is a fundamental principle that states that "energy cannot be created or destroyed; it can only be transferred or transformed from one form to another." Mathematically, it can be expressed as:

The first law of thermodynamics states that "energy can't be created or destroyed, but it can change forms." It's also known as the **law of conservation of energy.**

$$\mathbf{\Delta U=Q-W}$$

where:

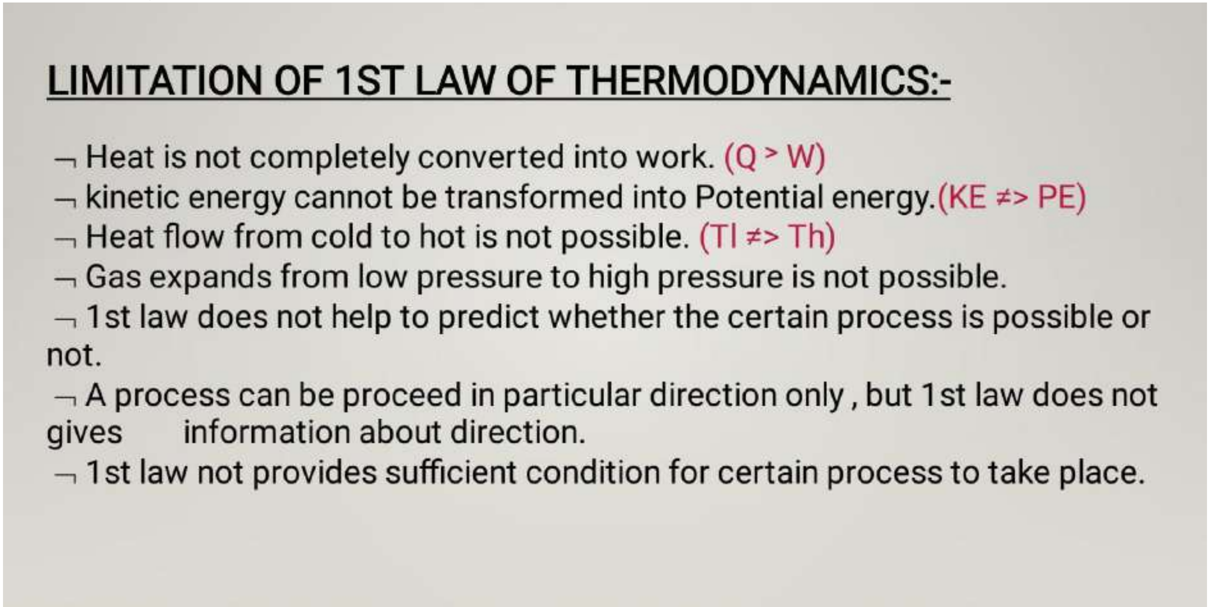
- ΔU is the change in internal energy of a system,
- Q is the heat added to the system, and
- W is the work done by the system.

Applications of the First Law of Thermodynamics: -

1. **Heat Engines**:
    - In heat engines, the First Law of Thermodynamics is used to analyse the conversion of heat into work. For example, in an internal combustion engine, the chemical energy in fuel is converted into thermal energy through combustion, which is then converted into mechanical work.
2. **Refrigerators and Heat Pumps**:
    - The First Law is applied to analyse the performance of refrigerators and heat pumps. These devices transfer heat from a cold reservoir to a hot reservoir by doing external work. The work input and heat transfer are analysed using the First Law.
3. **Power Plants**:
    - In power plants, whether thermal or nuclear, the First Law is used to analyse the conversion of energy from fuel or nuclear reactions into electrical energy. The efficiency of the plant and energy losses can be calculated using the First Law.
4. **Calorimetry**:
    - Calorimetry is the science of measuring the heat of chemical reactions or physical changes. The First Law is applied to determine the heat absorbed or released in a reaction by measuring the temperature change in a calorimeter.
5. **Compressors and Expanders**:
    - The First Law is used to analyse the work done by compressors and expanders. In a compressor, work is done on a gas to increase its pressure, while in an expander, a gas does work as it expands and decreases in pressure.
6. **Heat Exchangers**:
    - The First Law is applied to analyse the energy transfer in heat exchangers. These devices transfer heat between two or more fluids without mixing them. The heat transferred and energy balance are determined using the First Law.
7. **Biological Systems**:
    - In biological systems, the First Law is used to analyse metabolic processes. The energy intake from food, energy expenditure, and energy storage in the body are all analysed using the principles of the First Law.

Limitations of the First Law: -

1. Direction of heat flow: It doesn't specify the direction in which heat flows. **For example**, it doesn't explain why heat can't flow from a cold object to a hot object.
2. Feasibility of a process: It doesn't indicate whether a process is possible or not.
For example, it doesn't explain why you can melt ice with heat but not extract heat from ice with cold.
3. Efficiency of conversion: In real-world scenarios, heat doesn't convert completely into work.
For example, when you apply brakes to a car, the work done against friction is converted into heat, but that heat can't be converted back into kinetic energy.
4. Entropy: It doesn't discuss the entropy of a system.
5. Final temperature: It doesn't explain the final temperature of two objects when they come into contact.

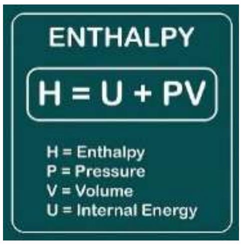


LIMITATION OF 1ST LAW OF THERMODYNAMICS:-

¬ Heat is not completely converted into work. (Q > W)
¬ kinetic energy cannot be transformed into Potential energy.(KE ≠> PE)
¬ Heat flow from cold to hot is not possible. (Tl ≠> Th)
¬ Gas expands from low pressure to high pressure is not possible.
¬ 1st law does not help to predict whether the certain process is possible or not.
¬ A process can be proceed in particular direction only , but 1st law does not gives information about direction.
¬ 1st law not provides sufficient condition for certain process to take place.

ENTHALPY

Definition: - The enthalpy H of a thermodynamic system is defined as “the sum of its internal energy and the product of its pressure and volume.”



ENTHALPY

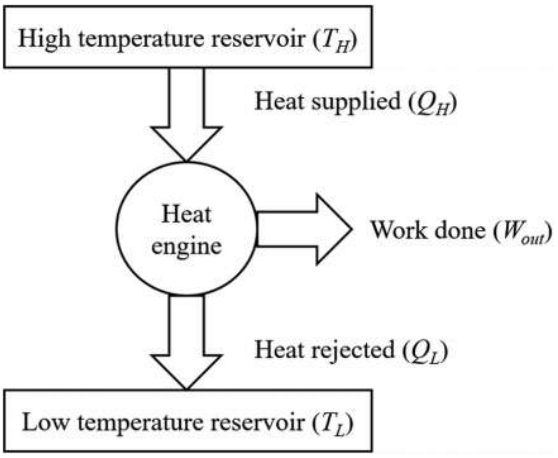
$$H = U + PV$$

H = Enthalpy
P = Pressure
V = Volume
U = Internal Energy

where U is the internal energy, p is pressure, and V is the volume of the system.

Thermal Reservoir: -

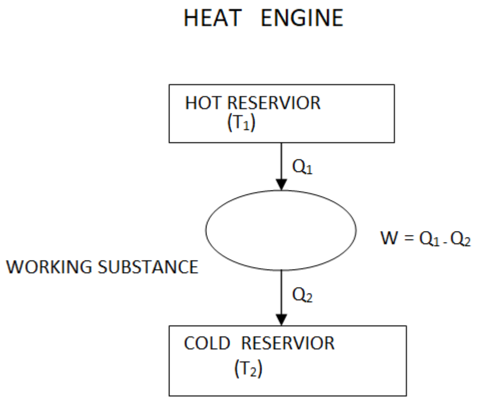
A thermal reservoir is a hypothetical body with a relatively large thermal energy capacity that can absorb or supply finite amounts of heat without undergoing any change in temperature. Examples include oceans, lakes, and large atmospheric bodies.

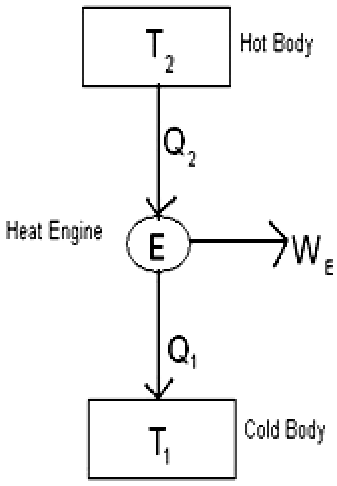


- **Hot Reservoir**: Supplies heat to the system (heat source).
- **Cold Reservoir**: Absorbs heat from the system (heat sink).

Heat Engine: -

A heat engine is a device that converts heat energy into mechanical work by exploiting the temperature difference between a hot reservoir and a cold reservoir. The basic components of a heat engine include:





- **Heat Source**: Provides heat to the engine.
- **Working Substance**: The medium that undergoes the thermodynamic cycle (e.g., steam in a steam engine).
- **Heat Sink**: Absorbs the waste heat from the engine.

Working Principle:

1. Heat is absorbed from the hot reservoir.
2. The working substance converts part of the heat into work.
3. The remaining heat is rejected to the cold reservoir.

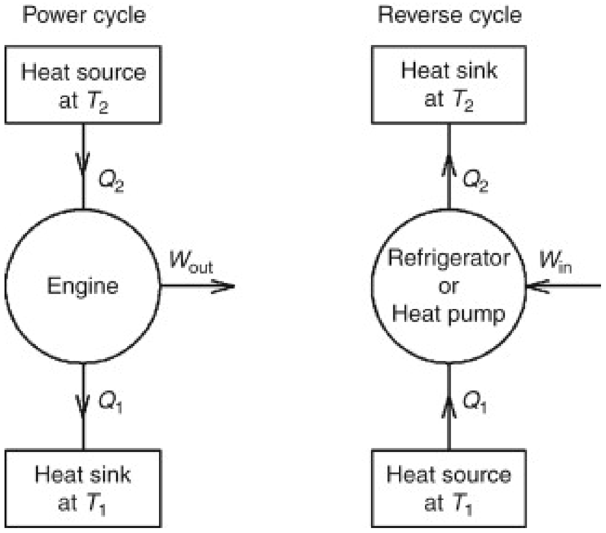
Efficiency (η): The efficiency of a heat engine is the ratio of the work output to the heat input.

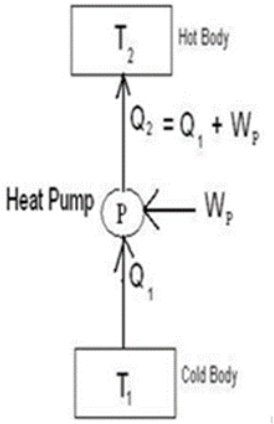
$$\eta = W / Q_H = 1 - Q_C / Q_H$$

Where,
Q_H is the heat absorbed from the hot reservoir,
Q_C is the heat rejected to the cold reservoir, and
W is the work done by the engine.

Heat Pump: -

A heat pump is a device that transfers heat from a cold reservoir to a hot reservoir by doing external work. It operates on the same principles as a refrigerator but with the purpose of heating rather than cooling.





Working Principle:

1. Absorbs heat from the cold reservoir.
2. External work is done on the working substance.
3. Rejects heat to the hot reservoir.

Coefficient of Performance (COP): The performance of a heat pump is measured by its coefficient of performance, defined as the ratio of the heat delivered to the hot reservoir to the work input.

$$COP_{HP} = Q_H / W$$

where QH is the heat delivered to the hot reservoir, and WW is the work input.

Heat Engine vs. Heat Pump

Feature	**Heat Engine**	**Heat Pump**
Function	Converts heat into work	Transfers heat from cold to hot
Heat Flow	Absorbs Q_H, rejects Q_C	Absorbs Q_C, delivers Q_HQ
Efficiency	$\eta=1-Q_C/Q_H$	$COP=Q_H/W_C$
Examples	Car engines, steam turbines	Air conditioners, refrigerators

Parameters of Performance: -

- **Efficiency (η)**: Measures the effectiveness of a heat engine. Higher efficiency means better performance.
- **Coefficient of Performance (COP)**: For heat pumps and refrigerators, COP is a measure of performance. Higher COP indicates better performance.
    - For Refrigerators: $COP_R = Q_C/W$
    - For Heat Pumps: $COP_{HP} = Q_H/W$

Note: COP_{HP} is always greater than 1, as the heat pump delivers more heat than the work input.

UNIT - III

Second Law of Thermodynamics, Kelvin-Planck and Clausius Statements and their Equivalence / Corollaries, PMM-II, Carnot's principle, Carnot cycle and its specialties, Thermodynamic scale of Temperature, Clausius Inequality, Entropy, Principle of Entropy Increase – Energy Equation, Availability and Irreversibility – Thermodynamic Potentials, Gibbs and Helmholtz Functions, Maxwell Relations – Elementary Treatment of the Third Law of Thermodynamics.

Second Law of Thermodynamics

The Second Law of Thermodynamics is a fundamental principle that deals with the direction of natural processes. It can be understood through two primary statements:

Kelvin-Planck Statement: -

- **Statement:** It is impossible to construct a heat engine that, operating in a cycle, produces no effect other than the absorption of heat from a single thermal reservoir and the performance of an equivalent amount of work.
- **Implication:** No heat engine can be 100% efficient; some energy is always lost as waste heat to the surroundings.

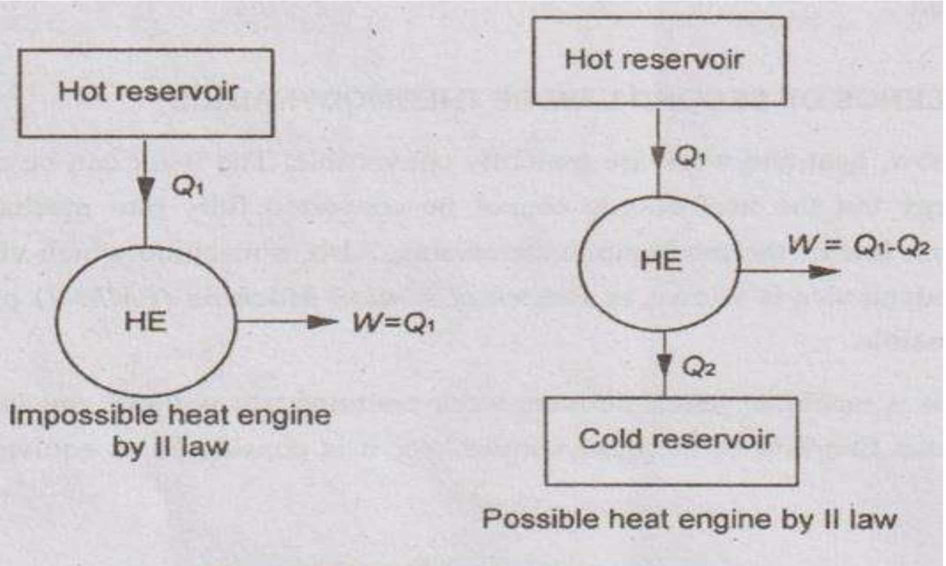


Figure 2.5 Kelvin-Planck statement

Examples and Applications

1. **Heat Engines:** Any practical heat engine, such as those in cars and power plants, cannot achieve 100% efficiency due to the Kelvin-Planck statement.

Clausius Statement: -

- **Statement:** It is impossible to construct a device that, operating in a cycle, has no effect other than the transfer of heat from a colder body to a hotter body.
- **Implication:** Heat cannot spontaneously flow from a colder body to a hotter body without external work being performed on the system.

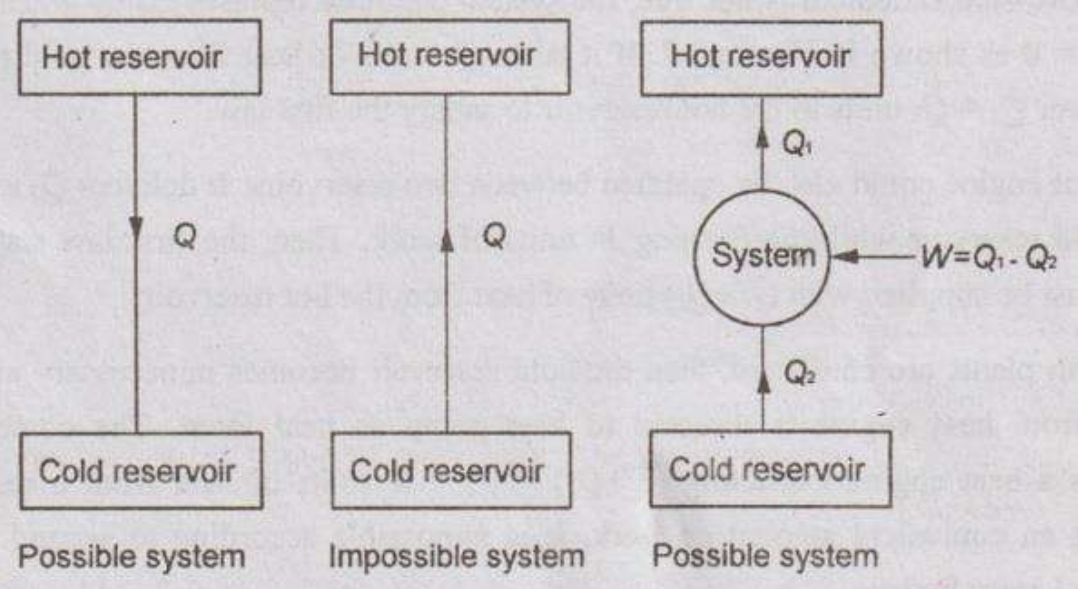


Figure 2.6 Clausius statement

Examples and Applications

1. Refrigerators and Heat Pumps: These devices operate by transferring heat from a colder to a hotter body, but they require external work to do so, aligning with the Clausius statement.

Proof of Equivalence: -

1. **Kelvin-Planck to Clausius:** If a heat engine violates the Kelvin-Planck statement and converts all absorbed heat into work without any heat rejection, we could combine it with a Clausius device (heat pump) to transfer heat from a cold to a hot body without work input, violating the Clausius statement.
2. **Clausius to Kelvin-Planck:** If a heat pump violates the Clausius statement by transferring heat from a cold body to a hot body without work input, we could use this device to create a heat engine that absorbs heat from a single reservoir and converts it entirely into work, violating the Kelvin-Planck statement.

Corollaries and Implications: -

1. **Irreversibility:** Both statements imply that real processes are irreversible. There is always some loss of usable energy in the form of waste heat.
2. **Entropy:** These statements lead to the concept of entropy, which measures the disorder or randomness of a system. The second law implies that the total entropy of a closed system always increases.

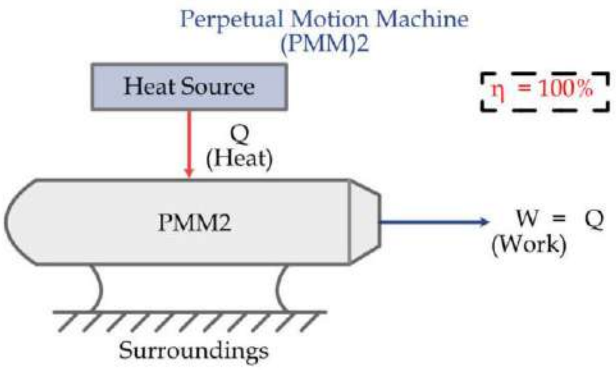
3. **Perpetual Motion Machines:** The second law rules out the possibility of perpetual motion machines of the second kind (PMM-II), which would violate either the Kelvin-Planck or Clausius statement.

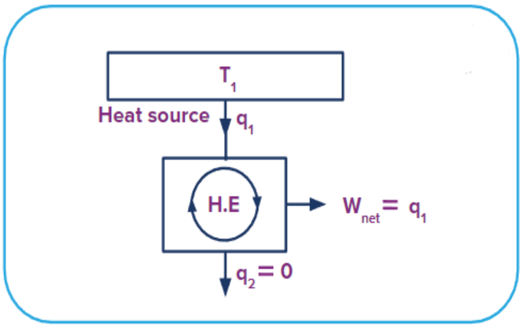
PMM-II

PMM-II, or Perpetual Motion Machine of the Second Kind, refers to a hypothetical machine that violates the Second Law of Thermodynamics.

Perpetual Motion Machine of the Second Kind (PMM-II)

Definition: A PMM-II is a theoretical machine that would continuously convert heat into work without any waste, effectively operating with 100% efficiency.





Perpetual motion machine of the second kind

Violation of the Second Law

Both the Kelvin-Planck and Clausius statements of the Second Law of Thermodynamics imply the impossibility of PMM-II:

- **Kelvin-Planck Statement:** No heat engine can convert all the heat it absorbs into work without rejecting some heat to a cooler reservoir.
- **Clausius Statement:** Heat cannot spontaneously flow from a colder body to a hotter body without external work.

Why PMM-II is Impossible

1. **Irreversibility:** All real processes involve some irreversibility, meaning some energy is always dissipated as waste heat.
2. **Entropy:** According to the Second Law, the total entropy of a closed system always increases. A PMM-II would imply a decrease in entropy, which is impossible.

CARNOT’S PRINCIPLE

Statement: No heat engine operating between two thermal reservoirs can be more efficient than a Carnot engine operating between the same reservoirs.

Carnot's principle is a fundamental concept in thermodynamics, formulated by Sadi Carnot in 1824. It describes the maximum possible efficiency that a heat engine can achieve when operating between two temperature reservoirs.

According to Carnot's principle:

1. **The efficiency of a heat engine depends only on the temperatures of the hot and cold reservoirs.**
   A heat engine that operates between two temperature reservoirs (one hot and one cold) has an upper limit on its efficiency. This limit is defined by the temperatures of the two reservoirs.
2. **No engine can be more efficient than a Carnot engine operating between the same two reservoirs.**
   The Carnot engine is an idealized, reversible heat engine. The principle states that the maximum efficiency that any real engine can achieve is equal to the efficiency of a Carnot engine operating between the same two temperatures. Real engines will always have some form of irreversibility and thus will be less efficient than the Carnot engine.
3. **The Carnot efficiency equation:**
   The efficiency (η) of a Carnot engine is given by the following formula:

$$\eta = 1 - Tc/Th$$

Where:

- η is the efficiency of the Carnot engine.
- T_c is the absolute temperature of the cold reservoir (in Kelvin).
- T_h is the absolute temperature of the hot reservoir (in Kelvin).

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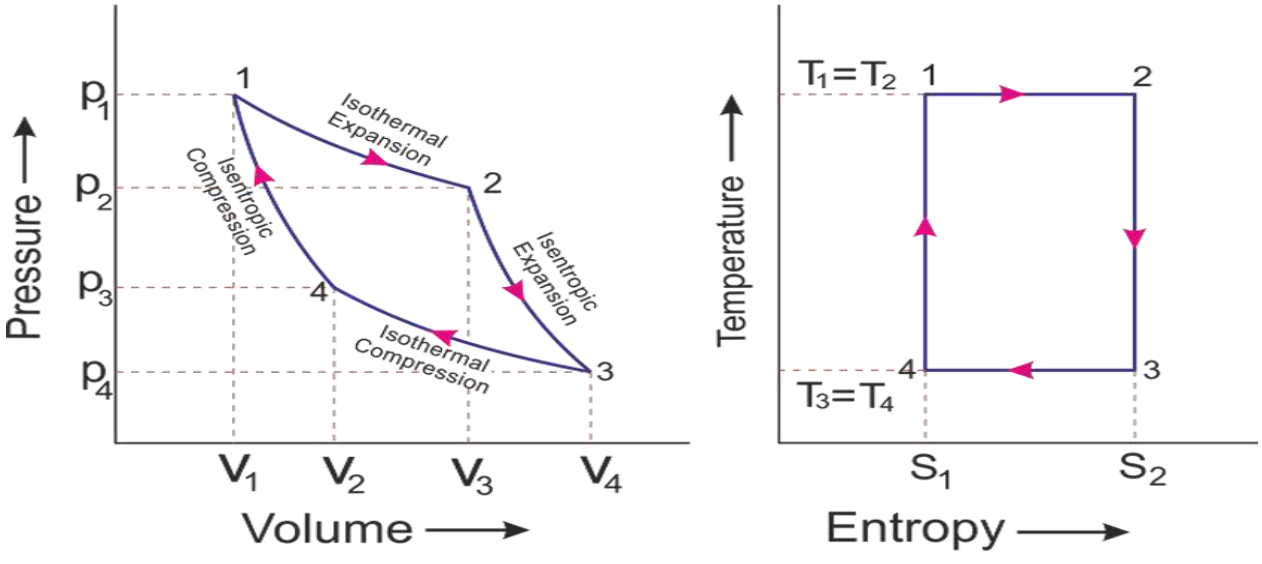
CARNOT CYCLE



(a) p-v diagram (b) T-S diagram

The **Carnot cycle** is an idealized thermodynamic cycle that provides the maximum possible efficiency for a heat engine operating between two temperature reservoirs. It consists of four reversible processes: two isothermal (constant temperature) processes and two adiabatic (no heat exchange) processes. Here's the working and derivation of the Carnot cycle.

The Four Processes of the Carnot Cycle: -

1. **Isothermal Expansion (1 → 2): -**
   - The gas is in contact with a hot reservoir at temperature Th.
   - The gas expands isothermally (at constant temperature), absorbing heat Q_h from the hot reservoir.
   - During expansion, the gas does work on the surroundings, and its internal energy remains unchanged since the temperature is constant.
2. **Adiabatic Expansion (2 → 3): -**
   - The gas is thermally isolated, meaning no heat is exchanged (Q=0).
   - The gas expands adiabatically, doing work on the surroundings.
   - As the gas expands, its temperature and pressure decrease. The work done by the gas causes the temperature to drop from T_h.

3. **Isothermal Compression (3 → 4): -**

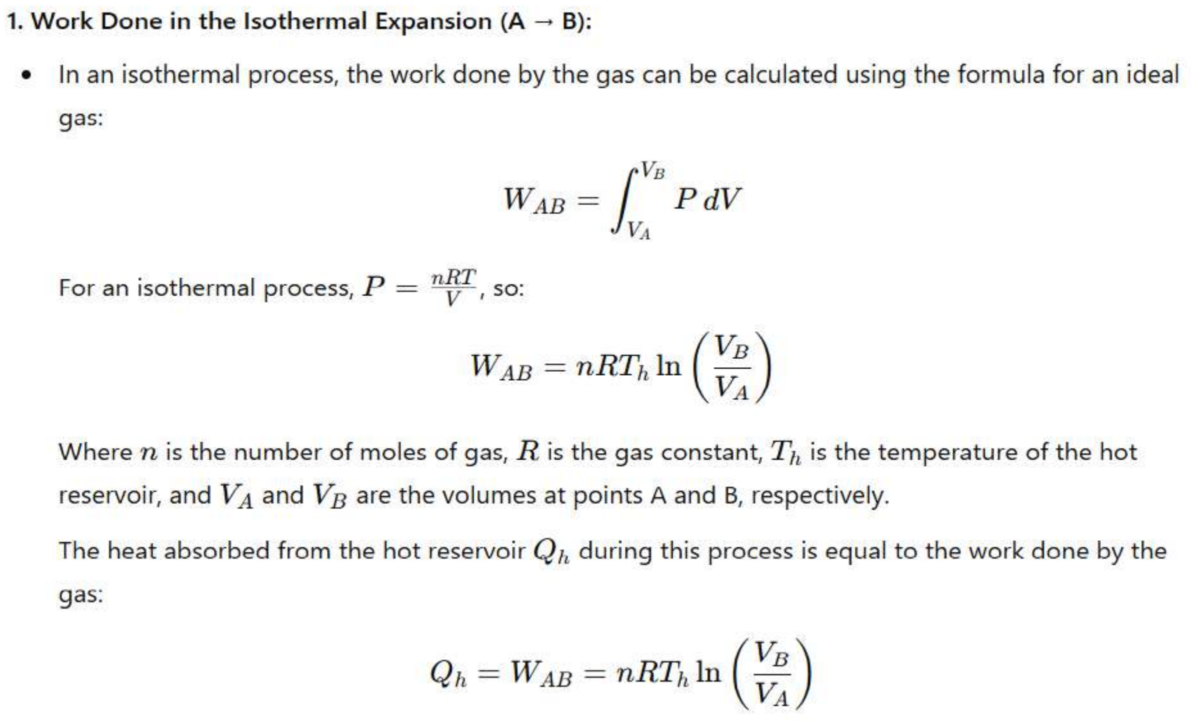
- The gas is now in contact with a cold reservoir at temperature Tc
- The gas is compressed isothermally, releasing heat Q_c to the cold reservoir.
- Since the temperature is constant during compression, the internal energy does not change, and work is done *on* the gas by the surroundings.

4. **Adiabatic Compression (4 → 1): -**

   - The gas is again thermally isolated.
   - The gas is compressed adiabatically, which increases its internal energy, and as a result, the temperature of the gas rises from T_c to T_h.
   - No heat is exchanged during this process.

Derivation of Carnot Efficiency: -

To derive the efficiency of the Carnot cycle, we look at the work done by the gas in each of the four processes and the net heat exchanged.



1. Work Done in the Isothermal Expansion (A → B):

- In an isothermal process, the work done by the gas can be calculated using the formula for an ideal gas:

$$W_{AB} = \int_{V_A}^{V_B} P\,dV$$

For an isothermal process, $P = \frac{nRT}{V}$, so:

$$W_{AB} = nRT_h \ln\left(\frac{V_B}{V_A}\right)$$

Where n is the number of moles of gas, R is the gas constant, T_h is the temperature of the hot reservoir, and V_A and V_B are the volumes at points A and B, respectively.

The heat absorbed from the hot reservoir Q_h during this process is equal to the work done by the gas:

$$Q_h = W_{AB} = nRT_h \ln\left(\frac{V_B}{V_A}\right)$$

2. Work Done in the Isothermal Compression (C → D):

- Similarly, in the isothermal compression process, the work done on the gas is:

  $$W_{CD} = nRT_c \ln\left(\frac{V_C}{V_D}\right)$$

  Here, T_c is the temperature of the cold reservoir, and V_C and V_D are the volumes at points C and D, respectively.

  The heat rejected to the cold reservoir Q_c during this process is:

  $$Q_c = -W_{CD} = nRT_c \ln\left(\frac{V_C}{V_D}\right)$$

3. Net Work Done by the Gas:

The net work done over one full Carnot cycle is the difference between the work done during the expansion (A → B) and the work done during the compression (C → D):

$$W_{\text{net}} = W_{AB} - W_{CD}$$

Substituting the expressions for W_{AB} and W_{CD}:

$$W_{\text{net}} = nR\left(T_h \ln\left(\frac{V_B}{V_A}\right) - T_c \ln\left(\frac{V_C}{V_D}\right)\right)$$

Using the fact that the Carnot cycle is a cyclic process, we can relate the volumes of the states in the two isothermal processes by the temperature ratio:

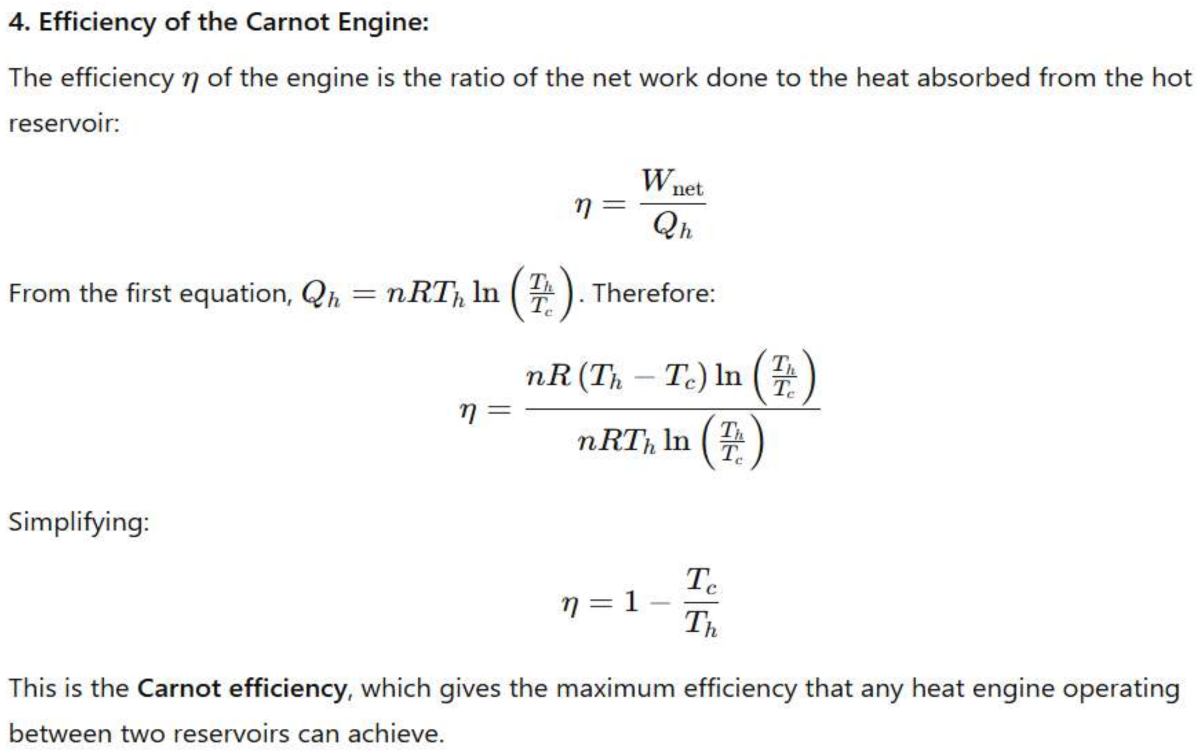
$$\frac{V_B}{V_A} = \frac{V_D}{V_C} = \frac{T_h}{T_c}$$

Thus, the net work simplifies to:

$$W_{\text{net}} = nRT_h \ln\left(\frac{T_h}{T_c}\right) - nRT_c \ln\left(\frac{T_c}{T_h}\right)$$

This simplifies further to:

$$W_{\text{net}} = nR\left(T_h - T_c\right) \ln\left(\frac{T_h}{T_c}\right)$$



4. Efficiency of the Carnot Engine:

The efficiency η of the engine is the ratio of the net work done to the heat absorbed from the hot reservoir:

$$\eta = \frac{W_{\text{net}}}{Q_h}$$

From the first equation, $Q_h = nRT_h \ln\left(\frac{T_h}{T_c}\right)$. Therefore:

$$\eta = \frac{nR\left(T_h - T_c\right)\ln\left(\frac{T_h}{T_c}\right)}{nRT_h \ln\left(\frac{T_h}{T_c}\right)}$$

Simplifying:

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

This is the **Carnot efficiency**, which gives the maximum efficiency that any heat engine operating between two reservoirs can achieve.

Specialties and Features of the Carnot Cycle: -

1. **Maximum Efficiency**:
   - The Carnot cycle provides the **maximum possible efficiency** for any heat engine operating between two temperature reservoirs. This efficiency is determined solely by the temperatures of the hot and cold reservoirs and is given by the formula: $\eta=1-Tc/Th$ where Th is the temperature of the hot reservoir and Tc is the temperature of the cold reservoir (in absolute Kelvin).
2. **Reversibility**:
   - All the processes in the Carnot cycle are **reversible**, meaning that if the direction of the cycle is reversed, the engine can function as a heat pump or refrigerator. Reversibility implies no friction, no dissipation of energy, and no entropy generation, which makes the Carnot cycle the most efficient thermodynamic process possible.
3. **Isothermal and Adiabatic Processes**:
   - The Carnot cycle alternates between isothermal and adiabatic processes:
     - **Isothermal processes** (constant temperature) allow for maximum heat absorption or rejection, since the system is in thermal equilibrium with the reservoirs.

        - **Adiabatic processes** (no heat transfer) allow the gas to expand or compress without exchanging heat with the surroundings, which leads to a change in temperature.

4. **Entropy Change**:
    - During the Carnot cycle, the total **entropy change** of the system and surroundings is zero, since the cycle is entirely reversible. This implies that the entropy lost during the isothermal compression (3 → 4) is exactly equal to the entropy gained during the isothermal expansion (1 → 2). The overall process does not increase the entropy of the universe, as it would in real engines.

5. **Idealized Assumptions**:
    - The Carnot cycle assumes **ideal conditions**, including:
        - The working substance behaves as an ideal gas.
        - There is no friction or any other form of irreversibility in the engine.
        - The heat reservoirs are large enough that their temperatures remain constant during heat exchange with the working substance.

These assumptions are not present in real-world engines, where friction, heat losses, and non-ideal gas behavior reduce efficiency.

6. **Thermodynamic Efficiency Limitation**:
    - The Carnot cycle shows that no engine can be more efficient than a Carnot engine operating between the same two temperatures. This is a direct consequence of the **second law of thermodynamics**, which states that the total entropy of a system must always increase in a real, irreversible process. A real engine will always involve some form of irreversibility, making it less efficient than the ideal Carnot engine.

THERMODYNAMIC SCALE OF TEMPERATURE

The **thermodynamic scale of temperature** is a scientific temperature scale based on the principles of thermodynamics, which defines temperature in terms of the behaviour of matter at a microscopic level. It is independent of the properties of any particular substance and is rooted in the laws of thermodynamics, especially the concept of temperature being a measure of the average kinetic energy of particles in a system.

The most commonly known thermodynamic temperature scale is the **Kelvin scale (K)**.

Points of the Thermodynamic Scale of Temperature:

1. **Kelvin Scale (K)**:

   - The Kelvin scale is the **SI (International System of Units) standard** for temperature.
   - The zero point on the Kelvin scale is **absolute zero (0 K)**, which represents the temperature at which all molecular motion stops, and theoretically, no more heat can be extracted from a system.
   - The Kelvin scale starts at 0 K, and the temperature intervals are the same as those of the Celsius scale.
      - **0 K** = Absolute zero, the lowest possible temperature.
      - **273.15 K** = 0°C (freezing point of water).
      - **373.15 K** = 100°C (boiling point of water).
2. **Absolute Zero (0 K)**:
   - This is the point at which the temperature of a system reaches its lowest possible value.
   - At absolute zero, the entropy of a system reaches its minimum value, and no heat can be transferred.
3. **Relation to Celsius**:
   - The Kelvin and Celsius scales are related by the equation: K=°C+273.15K = °C + 273.15K=°C+273.15
      - For example, **0°C** is **273.15 K**, and **100°C** is **373.15 K**.
4. **Thermodynamic Temperature and Energy**:
   - The thermodynamic temperature scale measures the average kinetic energy of the particles in a system.
   - It is important in thermodynamics because it provides an absolute measure of temperature, unlike scales like Fahrenheit or Celsius, which are based on arbitrary points (like the freezing and boiling points of water).

Concepts Related to the Thermodynamic Temperature Scale:

- **Zeroth Law of Thermodynamics**: This law states that if two systems are each in thermal equilibrium with a third system, then they are in thermal equilibrium with each other. This defines temperature in a way that is independent of the substance used to measure it, allowing the establishment of a universal scale like Kelvin.
- **Thermal Energy**: Temperature is directly related to the thermal energy (or internal energy) of a system. At absolute zero, the thermal energy of the system would theoretically be zero.

Importance of the Thermodynamic Scale:

- The Kelvin scale is crucial in fields like physics, chemistry, and engineering because it provides an absolute reference for temperature.

- Unlike the Celsius and Fahrenheit scales, which are based on relative measures (e.g., freezing and boiling points of water), the Kelvin scale is based on the fundamental physical property of temperature.

Clausius Inequality: -

The **Clausius Inequality** is a fundamental concept in thermodynamics, particularly in the study of **entropy**. It provides a mathematical expression that relates the change in entropy of a system to the heat exchanged and the temperature at which the heat is transferred. The inequality essentially describes the **irreversibility** of real thermodynamic processes.

Statement of the Clausius Inequality:

The Clausius Inequality is given by:

$$\oint dQ/T \leq 0$$

Where:

- dQ is the heat exchanged by the system,
- TTT is the absolute temperature at which the heat is transferred,
- The integral sign ($\oint$) indicates that the process could be cyclic or irreversible, and
- The inequality sign ≤ means that the quantity dQ / T integrated over the entire cycle or process is always less than or equal to zero for real, irreversible processes.

Explanation:

- **Reversible Process**: In the case of a **reversible process**, the Clausius inequality becomes an equality:

$$\oint dQ/T = 0$$

This means that for a reversible process, the total entropy change of the system and surroundings is zero.

- **Irreversible Process**: For an **irreversible process**, the inequality holds:

$$\oint dQ/T < 0$$

This indicates that during irreversible processes, the total entropy of the system and its surroundings increases. In other words, the system has **positive entropy generation** during the process.

Significance of the Clausius Inequality:

1. **Entropy Generation**: The Clausius inequality provides a criterion for determining the direction of spontaneous processes. It implies that in any real, irreversible process, entropy must increase, which is

associated with the generation of irreversibility's (such as friction, unrestrained heat flow, etc.).

2. **Second Law of Thermodynamics**: The Clausius inequality is a mathematical formulation of the **second law of thermodynamics**, which states that the total entropy of an isolated system can never decrease. In practical terms, it says that natural processes tend to move towards a state of higher entropy, or disorder.
3. **Thermodynamic Cycles**: For a cyclic process (like a heat engine), the Clausius inequality suggests that no heat engine can be 100% efficient because some energy is always lost as heat to the surroundings. In a **Carnot engine**, for example, the heat intake and exhaust occur at different temperatures, and some heat is always expelled to the cold reservoir, creating an increase in entropy.

Example: -

In a real thermodynamic cycle:

- If heat Q_1 is absorbed at temperature T_1, and Q_2 is rejected at temperature T_2, the Clausius inequality can be written as:

  $$Q_1/T_1 - Q_2/T_2 \leq 0$$

  This shows that for the system to be efficient, Q_1/T_1 must be less than or equal to Q_2/T_2, and any real heat engine will have losses, meaning some heat will be irreversibly lost in the process.

Entropy in Thermodynamics

Entropy (S) is a fundamental concept in thermodynamics that measures the degree of disorder or randomness in a system. It plays a key role in the **Second Law of Thermodynamics**, which states that the total entropy of an isolated system **always increases** over time for any spontaneous process.

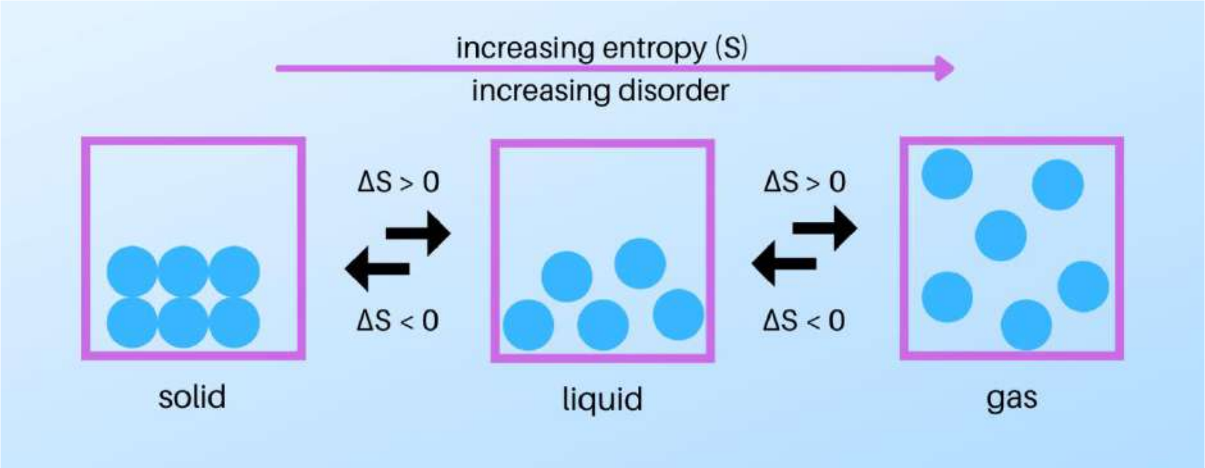
Definition of Entropy: -

Entropy is a **state function**, meaning its value depends only on the current state of the system and not on the path taken to reach that state. It is mathematically defined as:

$$\mathbf{dS = dQrev/T}$$

where:

- dS = change in entropy.
- dQrev = infinitesimal heat transfer in a **reversible** process.
- T = absolute temperature (Kelvin).



Entropy and the Second Law of Thermodynamics

The Second Law states:

☑ In an **isolated system**, entropy **never decreases** and generally increases over time:

$$\Delta \text{Suniverse} \geq 0$$

- If $\Delta S>0$, the process is **irreversible** and **spontaneous.**
- If $\Delta S=0$, the process is **reversible** (ideal case).
- If $\Delta S<0$, the process is **impossible** in an isolated system.

Entropy in Different Processes

- **Isothermal Process ($\Delta T=0$)**

$$\Delta S = Q/T$$

Example: Melting of ice at 0°C

- **Adiabatic Process ($Q=0$)**
  $\Delta S=0$ (reversible), meaning no heat exchange occurs
- **Free Expansion**
  $\Delta S>0$ because gas molecules spread out, increasing disorder

Entropy and the Universe

Entropy is often associated with the "**arrow of time**", meaning natural processes move toward **higher entropy** (disorder).

This explains why:
☑Heat flows from **hot to cold**, never the reverse spontaneously
☑ Natural systems tend to become **more disordered**
☑ The universe is evolving toward a state of **maximum entropy** (heat death theory)

Practical Applications of Entropy: -

- **Heat Engines**: Entropy helps determine **efficiency** (Carnot cycle).
- **Refrigerators & Heat Pumps**: Work is needed to **reduce entropy locally.**
- **Chemical Reactions**: Spontaneity depends on **Gibbs Free Energy.**
- **Information Theory**: Entropy also measures **uncertainty in data.**

Principle of Entropy Increase

The **Principle of Entropy Increase** is a fundamental consequence of the **Second Law of Thermodynamics**, which states that:

In any spontaneous (irreversible) process, the entropy of an isolated system always increases.

Mathematically, for an **isolated system**:

$\Delta Ssystem \geq 0$

where ΔS_{system} is the change in entropy.

- If the process is **reversible**, $\Delta S=0$.
- If the process is **irreversible (spontaneous)**, $\Delta S>0$.

Since the **universe is an isolated system**, its total entropy **never decreases** and will always increase over time:

$$\Delta S\ universe=\Delta Ssystem+\Delta Ssurroundings \geq 0$$

Explanation of the Principle

Entropy is a measure of **disorder** or **randomness** in a system.

The principle of entropy increase tells us that:

☑ Natural processes tend to move from **ordered states to disordered states**.

☑ Energy spontaneously disperses unless work is done to maintain order.

Examples of Entropy Increase: -

Heat Transfer

Heat always flows from a **hot object** to a **cold object**, increasing total entropy:

$$\Delta\ Shot=-Q/T_{hot},\ \Delta\ Scold=Q/T_{cold}$$

Since $T\ cold<ThotT$, $\Delta S\ cold>\Delta S\ hot$, leading to $\Delta S\ total>0$.

Expansion of a Gas into a Vacuum (Free Expansion)

If a gas is allowed to expand into an empty space, its entropy increases because:

☑ The gas molecules spread out, increasing disorder.

☑ No heat or work is involved, but entropy still rises.

Melting of Ice

When ice melts at room temperature:
✅ The structured arrangement of water molecules in ice breaks.
✅ The liquid state is more **disordered** than the solid state.
✅ Entropy increases.

Entropy and Irreversibility

The **Principle of Entropy Increase** explains why some processes are **irreversible** in nature:
🚫 **Heat does not spontaneously flow from cold to hot.**
🚫 **Gases do not spontaneously compress into a small volume.**
🚫 **Broken objects do not reassemble themselves.**

To reverse an increase in entropy, **external energy (work) must be applied**, such as in refrigeration or air conditioning.

Entropy and the Heat Death of the Universe

Since entropy **always increases**, the universe is moving toward a state of **maximum entropy** where all energy is evenly distributed, and no useful work can be done. This is known as the "**heat death**" theory.

Mathematical Formulation for Entropy Change

For a reversible process:

$$dS=dQrev/T$$

For an isolated system in an **irreversible process**:

$$dS>dQirrev/T$$

Since an isolated system **does not exchange heat**, the entropy increase is purely due to internal irreversible changes.

Availability and Irreversibility

In thermodynamics, **availability (exergy)** and **irreversibility** are crucial concepts for analysing the efficiency of energy conversion processes.

Availability (Exergy): -

Availability (or exergy) is the **maximum useful work** that can be extracted from a system as it moves to equilibrium with its surroundings. It represents the **useful energy potential** of a system.

Definition of Availability (Exergy)

The total energy of a system consists of:
✅ **Useful energy** (available for work) = **Exergy**
✅ **Unusable energy** (wasted as entropy increases)

Mathematically, the exergy (X) of a system is given by:

$$X=(U-U_0)+P_0(V-V_0)-T_0(S-S_0)+1/2mV^2+mgz$$

where:

- U = internal energy
- P_0, T_0 = ambient pressure and temperature
- V, S = system volume and entropy
- $V^2/2$ = kinetic energy
- mgz = potential energy

Exergy is destroyed due to irreversibility's like friction, heat transfer, and chemical reactions.

Irreversibility (Energy Loss)

Irreversibility refers to the **loss of useful work** due to entropy generation. It occurs in all real-world processes because of:

☑ **Friction**
☑ **Unrestrained expansion**
☑ **Heat transfer with finite temperature difference**
☑ **Mixing of fluids**

◈ Expression for Irreversibility

The rate of irreversibility (I) is given by:

$$I = T_0 S_{gen}$$

where Sgen is the entropy generated during the process.

For a **control volume**, the irreversibility is:

$$I = (X_{in}-X_{out})+X_{destroyed}$$

where $X_{destroyed}$ is due to entropy generation.

Exergy Balance Equation: -

The **Exergy Balance Equation** is similar to the energy equation but includes exergy destruction:

$$\dot{X}_{in}-\dot{X}_{out}=\dot{X}_{destroyed}+\dot{W}_{useful}$$

For a **closed system**:

$$\Delta X=X_{heat}+X_{work}-X_{destroyed}$$

◈ **Key Insight:**

- **Reversible processes**: No exergy destruction (X destroyed=0).
- **Irreversible processes**: X destroyed>0, meaning useful work is lost.

Second Law Efficiency (η_{II}): -

The **Second Law Efficiency** measures how effectively a process converts available energy into useful work:

η_{II}=Actual Work Output/Maximum Possible Work Output (Exergy Input)

For heat engines:

$$\eta_{II} = W\ actual/W\ reversible$$

◈ **Key Insight:**

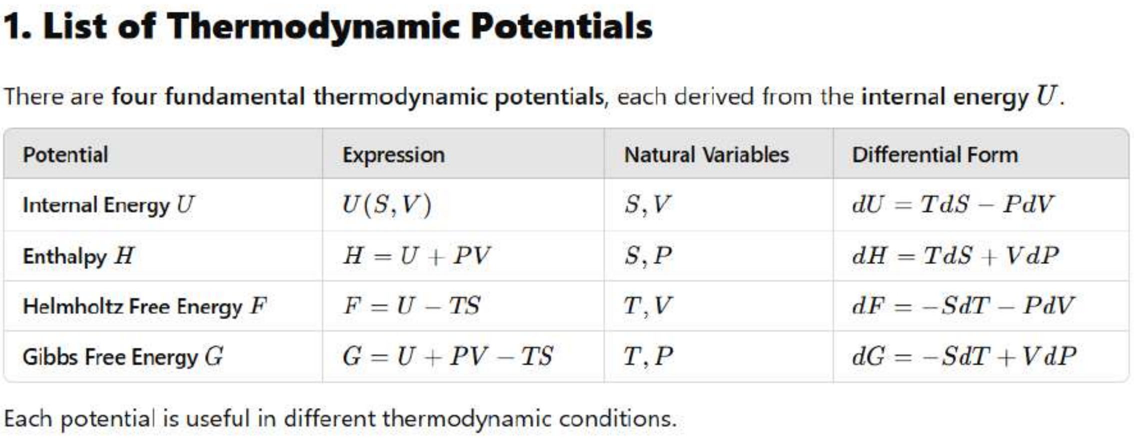
- Ideal (reversible) engines have $\eta_{II}=1$.
- Real engines have $\eta_{II}<1$ due to losses.

Practical Implications of Availability and Irreversibility: -

☑ **Power Plants**: Reducing irreversibility's improves efficiency.
☑ **Engines**: Lower friction, better insulation reduces exergy destruction.
☑ **Refrigeration Systems**: Minimizing heat leaks enhances performance.
☑ **Renewable Energy**: Maximizing exergy conversion boosts sustainability.

Thermodynamic Potentials

Thermodynamic potentials are functions that help describe the state and energy transformations of a system. They provide valuable relationships between measurable properties like temperature, pressure, entropy, and volume.



1. List of Thermodynamic Potentials

There are **four fundamental thermodynamic potentials**, each derived from the **internal energy** U.

Potential	Expression	Natural Variables	Differential Form
Internal Energy U	$U(S,V)$	S,V	$dU = TdS - PdV$
Enthalpy H	$H = U + PV$	S,P	$dH = TdS + VdP$
Helmholtz Free Energy F	$F = U - TS$	T,V	$dF = -SdT - PdV$
Gibbs Free Energy G	$G = U + PV - TS$	T,P	$dG = -SdT + VdP$

Each potential is useful in different thermodynamic conditions.

2. Explanation of Each Potential

(a) Internal Energy (U)

- Represents the total energy (kinetic + potential) of a system.
- Changes due to heat transfer (Q) and work done (W) on or by the system: $\mathbf{dU = \delta Q - \delta W}$
- Useful in systems with **constant volume**.

(b) Enthalpy (H)

$$\mathbf{H = U + PV}$$

- Accounts for **internal energy + work due to expansion**.
- Useful for processes at **constant pressure**, such as phase changes.
- Many chemical reactions occur at constant P, so enthalpy helps calculate **heat changes**.

(c) Helmholtz Free Energy (F)

$$\mathbf{F = U - TS}$$

- Represents **useful work** a system can do at **constant temperature and volume**.
- Used in statistical mechanics and molecular thermodynamics.

(d) Gibbs Free Energy (G)

$$\mathbf{G = H - TS}$$

- Measures the **maximum useful work** at **constant temperature and pressure**.
- Determines **spontaneity** of a process:
  - If $\Delta G<0$, the process is **spontaneous**.
  - If $\Delta G>0$, the process is **non-spontaneous**.
  - If $\Delta G=0$, the system is at **equilibrium**.
- Crucial in **chemical reactions, phase changes, and biological processes**.

3. Thermodynamic Potentials and Their Natural Variables

Each thermodynamic potential is a function of specific **natural variables**:

Potential	**Natural Variables**
U (S, V)	Entropy S and Volume V
H (S, P)	Entropy S and Pressure P
F (T, V)	Temperature T and Volume V
G (T, P)	Temperature T and Pressure P

Since each potential is a function of different variables, they can be used in **Maxwell relations** to derive useful thermodynamic equations.

4. Applications of Thermodynamic Potentials: -

- **Internal Energy (U)**: Used in first law of thermodynamics and energy balance.
- **Enthalpy (H)**: Used in heat transfer, chemical reactions, and phase transitions.
- **Helmholtz Free Energy (F)**: Important in statistical mechanics and molecular physics.
- **Gibbs Free Energy (G)**: Determines spontaneity of reactions, phase equilibrium, and biochemical processes.

Gibbs and Helmholtz Functions

The **Gibbs Free Energy (G)** and **Helmholtz Free Energy (F)** are two important thermodynamic potentials that help in analysing energy transformations in physical and chemical systems.

1. Helmholtz Free Energy (F)

Definition: - The Helmholtz free energy is defined as:

$$F = U - TS$$

where:

- U = Internal energy
- T = Temperature
- S = Entropy

Differential Form

$$dF = -SdT - PdV$$

This shows that at **constant temperature (T) and volume (V)**, the Helmholtz free energy determines the system's ability to do work.

Physical Meaning: -

- F is useful in **closed systems at constant T and V**.
- It tells us whether a process will occur spontaneously in a system with fixed volume.
- A process is **spontaneous** if $\Delta F<0$.

Application: -

- Used in statistical mechanics and molecular thermodynamics.

- Important for studying **systems with fixed volume**, such as gases in a rigid container.

2. Gibbs Free Energy (G)

Definition: - The Gibbs free energy is defined as:

$$G = H - TS$$

where:

- H = Enthalpy (H=U+PV)
- T = Temperature
- S = Entropy

Differential Form: -

$$dG = -SdT + VdP$$

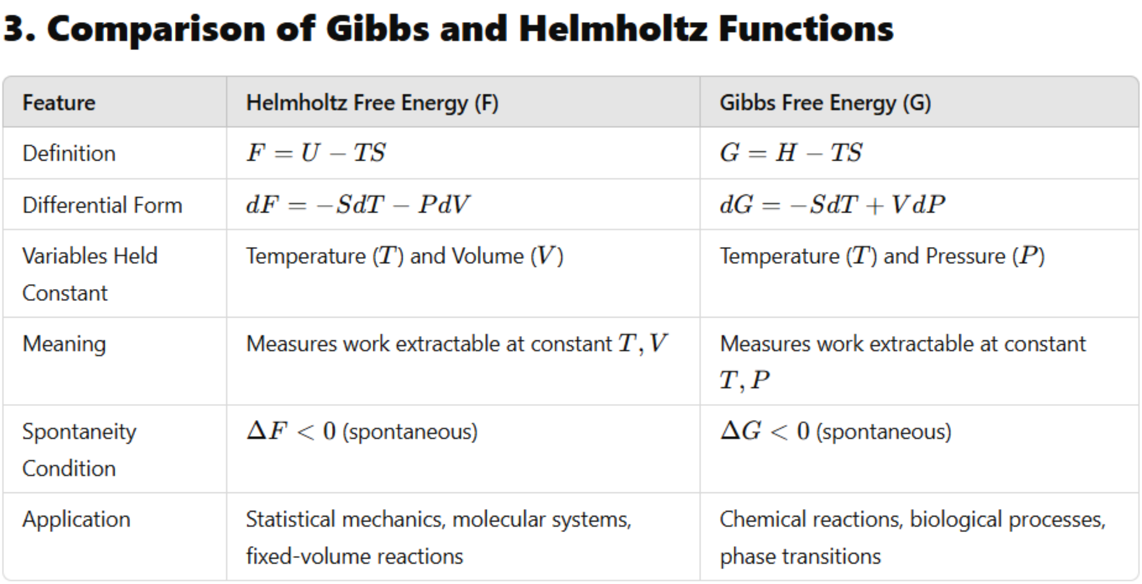
This shows that at **constant temperature (T) and pressure (P)**, the Gibbs free energy determines whether a reaction or process is spontaneous.

Physical Meaning: -

- G is important for **open systems at constant T and P**.
- It tells us whether a chemical reaction will proceed spontaneously.
- A reaction is **spontaneous** if $\Delta G<0$ (exergonic process).
- If $\Delta G>0$, the reaction is **non-spontaneous** (endergonic process).
- If $\Delta G=0$, the system is at **equilibrium**.

Application: -

- Used extensively in **chemical thermodynamics** to determine reaction feasibility.
- Critical in **phase transitions** (e.g., melting, boiling).
- Important in **biochemical reactions**, such as ATP hydrolysis in cells.



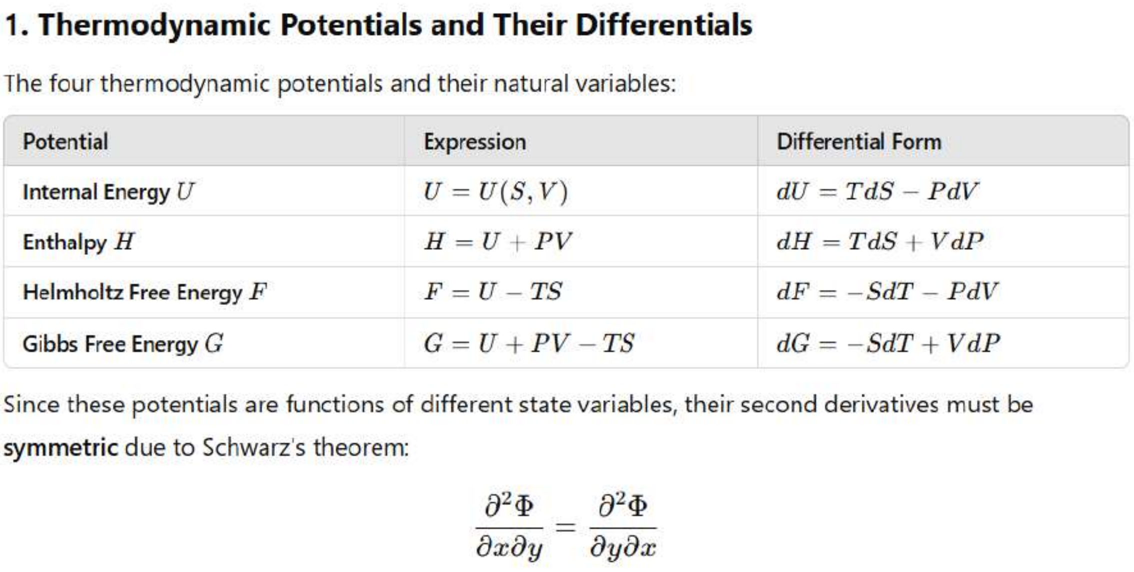
3. Comparison of Gibbs and Helmholtz Functions

Feature	Helmholtz Free Energy (F)	Gibbs Free Energy (G)
Definition	$F = U - TS$	$G = H - TS$
Differential Form	$dF = -SdT - PdV$	$dG = -SdT + VdP$
Variables Held Constant	Temperature (T) and Volume (V)	Temperature (T) and Pressure (P)
Meaning	Measures work extractable at constant T, V	Measures work extractable at constant T, P
Spontaneity Condition	$\Delta F < 0$ (spontaneous)	$\Delta G < 0$ (spontaneous)
Application	Statistical mechanics, molecular systems, fixed-volume reactions	Chemical reactions, biological processes, phase transitions

Maxwell Relations

Maxwell Relations in Thermodynamics

Maxwell relations are a set of four fundamental equations in thermodynamics derived from the **Gibbs equations** and the **symmetry of second derivatives** of thermodynamic potentials. They provide useful relationships between measurable thermodynamic properties like pressure, volume, temperature, and entropy.



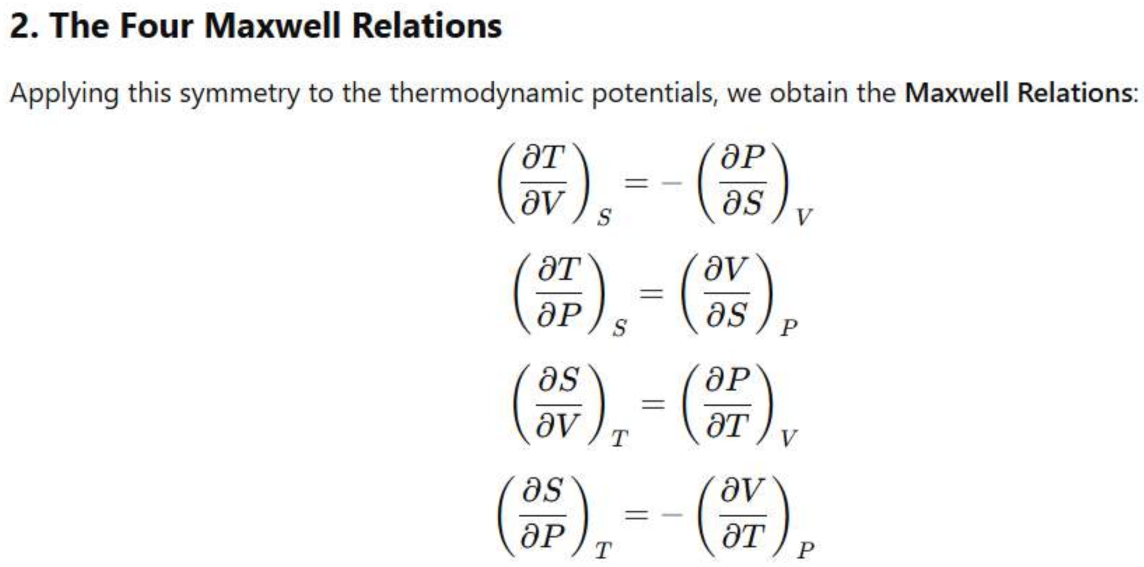
1. Thermodynamic Potentials and Their Differentials

The four thermodynamic potentials and their natural variables:

Potential	Expression	Differential Form
Internal Energy U	$U = U(S, V)$	$dU = TdS - PdV$
Enthalpy H	$H = U + PV$	$dH = TdS + VdP$
Helmholtz Free Energy F	$F = U - TS$	$dF = -SdT - PdV$
Gibbs Free Energy G	$G = U + PV - TS$	$dG = -SdT + VdP$

Since these potentials are functions of different state variables, their second derivatives must be **symmetric** due to Schwarz's theorem:

$$\frac{\partial^2 \Phi}{\partial x \partial y} = \frac{\partial^2 \Phi}{\partial y \partial x}$$



2. The Four Maxwell Relations

Applying this symmetry to the thermodynamic potentials, we obtain the **Maxwell Relations**:

$$\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V$$

$$\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P$$

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V$$

$$\left(\frac{\partial S}{\partial P}\right)_T = -\left(\frac{\partial V}{\partial T}\right)_P$$

Importance of Maxwell Relations

- **They allow indirect measurement of entropy changes**, which is difficult to measure directly.
- **They help in deriving equations of state** (e.g., Clapeyron equation for phase changes).
- **They simplify calculations in thermodynamics** by linking different state variables.

Elementary Treatment of the Third Law of Thermodynamics

The **Third Law of Thermodynamics** states that:
"As the temperature of a system approaches absolute zero (0 K), the entropy of a perfect crystal approaches a constant minimum value, typically taken as zero."

1. Understanding the Law in Simple Terms

Entropy (SSS) is a measure of disorder or randomness in a system. The Third Law implies that at **absolute zero**, a perfectly ordered crystal has only one possible arrangement (its ground state), so its entropy is **zero**.
Mathematically:

$$\lim_{T \to 0} S = S_0$$

where S_0 is a constant, often set to zero for a perfect crystal.

2. Why is the Third Law Important?

- It establishes an **absolute reference point** for entropy.

- It explains why absolute zero **can never be reached** (as cooling slows down infinitely).
- It plays a key role in **low-temperature physics and cryogenics**.

3. Consequences of the Third Law

- **Heat Capacity at Low Temperatures**: As T→0, heat capacities C_V and C_P approach zero.
- **Chemical Reactions**: Reaction rates slow significantly at very low temperatures.
- **Unattainability of Absolute Zero**: No finite process can cool a system to 0 K.

4. Applications: -

- Cryogenics (liquefying gases like helium).
- Superconductivity and Bose-Einstein Condensates.
- Precise entropy calculations in chemistry.

PROPERTIES OF PURE SUBSTANCE: UNIT-IV ①

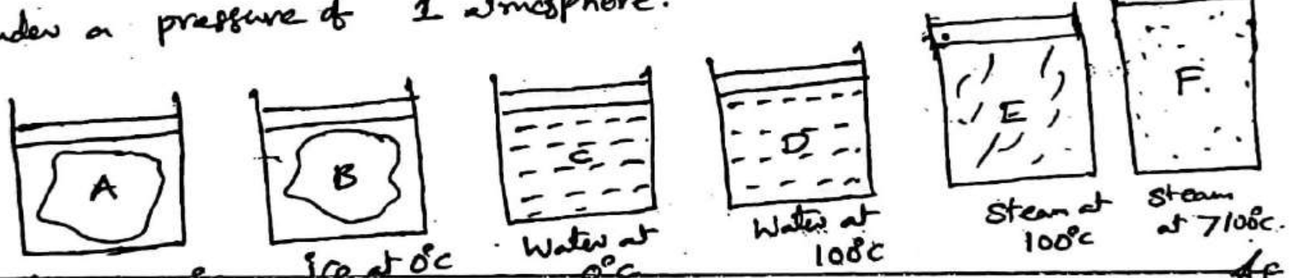
A pure substance may be defined as a substance, which is chemically homogeneous and has a fixed chemical composition. Any substance that appears with invariable chemical composition in either phase (or) a combination of phases may be treated as a pure substance. Water, nitrogen, helium and CO_2 are pure substances.

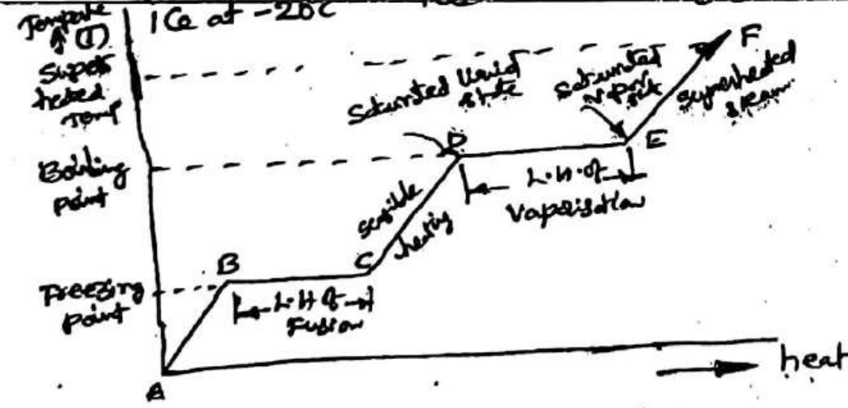
Phases of a pure substance:- There are three principle phases of a substance. solid, liquid and gaseous phases.

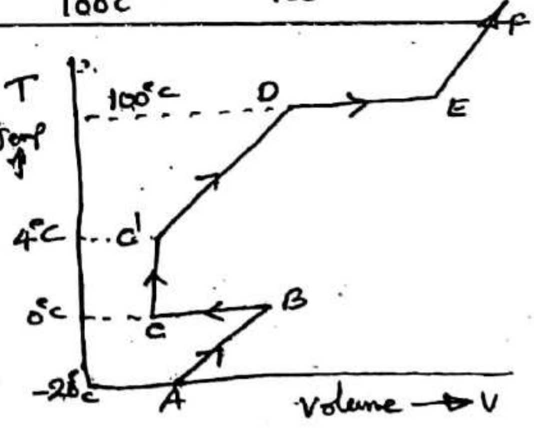
We will study the behaviour of water in all the three phases in thermodynamic plots on P-V, P-T, T-S and h-s co-ordinates.

* important.
Phase Transformation [Ice at -20°C to superheated steam above 100°C]

To understand the properties of a substance during its phase change let us consider the example of ice converting in to steam. Consider 1 kg of ice at -20°C in a cylinder under a pressure of 1 atmosphere.





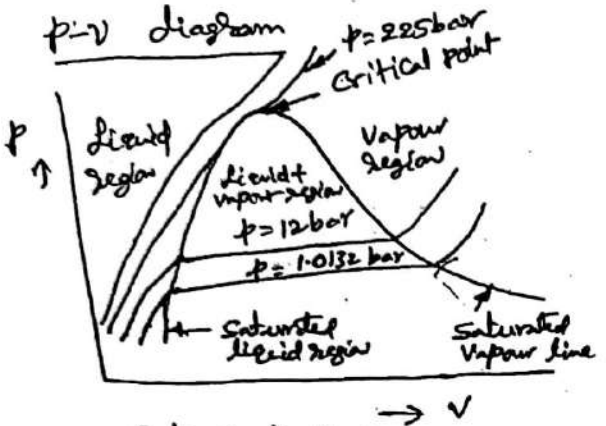


Latent heat of Fusion (Enthalpy of fusion):- The quantity of heat required to convert solid into liquid at a constant temperature is known as Latent heat of fusion (or) Enthalpy of fusion. For water latent heat of fusion at 1 atmosphere is 335 KJ/kg.

Freezing point Temperature:- The temp at which the substance changes its phase is known as freezing point temperature.
The freezing point temp. depends on the pressure. It increases with increase of pressure.

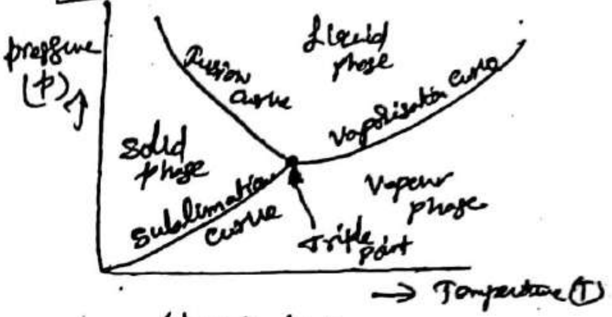
Latent heat of Vapourization:- The quantity of heat required to convert liquid into steam at constant temperature is known as latent heat of Vapourisation. For water latent heat of vapourization at 1 atmosphere is 2256·9 KJ/kg.

p-v diagram



(p-v) diagram

pressure-Temperature diagram of a pure substance (p-T) diagram.



(p-T) diagram

The p-T diagram of a pure substance is generally called phase diagram. Since it shows solid, liquid and vapour regions of a pure substance simultaneously.

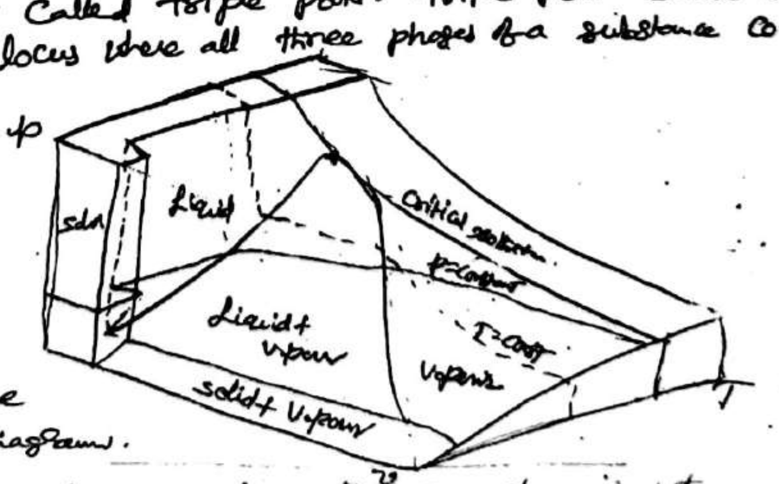
Each single phase of a pure substance is separated by saturation lines. The sublimation line separates the solid and vapour regions. The vapourization line separates the liquid and vapour regions, and the fusion line separates the solid and liquid regions.

The slope of the fusion line is negative. It indicates that the melting point of ice decreases with increasing pressure.

Triple point:- The sublimation, fusion and vapourization lines meet a point called triple point. Triple point can be defined as a locus where all three phases of a substance co-exist.

p-v-T diagram

The relationship among pressure, specific volume and temp. of a pure substance can be better understood by the three dimensional p-v-T diagram.

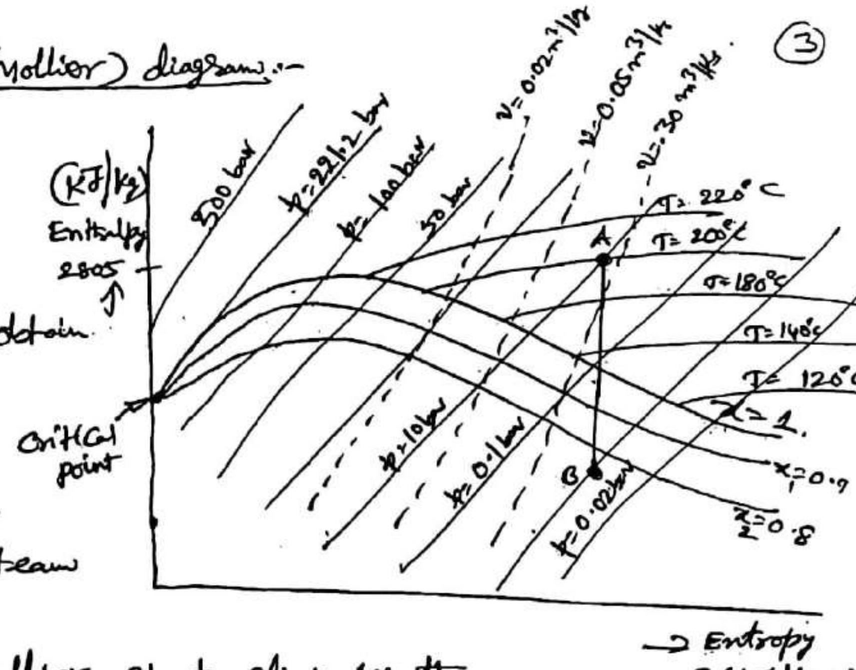


p-v-T surface for water

The figure shows a p-v-T surface for water, which expands on freezing. It shows p-v, p-T and T-v diagrams simultaneously on three dimensional plot. A constant temp. line is drawn in the figure passing through the critical point is called critical isotherm.

Enthalpy – Entropy (Mollier) diagram:-

The enthalpy – entropy diagram is referred as Mollier diagram. It is most commonly used to obtain properties of steam with reasonable accuracy, while analysing the steady flow devices such as steam turbines, nozzles etc.,



The use of the mollier chart eliminates the complex calculation of work and it is also convenient to use.

In (h-s) chart, pressure range is from 0.01 bar to 1000 bar and a temperature up to 800°C. The saturation curve where x=1, below saturation line, the dryness fraction is below 1, and called wet region. The properties above x=1 called dry & superheated region.

Important Terms for Steam

1. Wet Steam:- steam contains moisture (or) particles of water in suspension is called wet steam. Evaporation of water is not complete.

2. Dry Steam:- When wet steam is further heated, it does not contain any suspended particles of water is known as dry saturated steam. It behaves as a perfect gas. Steam absorbed full latent heat.

3. Superheated Steam:- When dry steam is further heated at constant pressure, thus raising its temperature, it is said to be superheated steam. Since pressure is constant, the volume of superheated steam increases. Superheated steam is obtained in a super heater.

4. Dryness fraction (or) Quality of Steam:- It is the ratio of the mass of the actual dry steam to the mass of dry steam + ~~the~~ mass of wet steam.

$$\therefore x = \frac{m_d}{(m_d + m_w)} = \frac{m_d}{m}$$, Where $m_d \to$ Mass of dry steam
$m_w \to$ Mass of wet steam.

5. Sensible heat of water:- It is the amount of heat absorbed by 1 kg of water, when heated at constant pressure without phase change.

$\therefore$ Sensible heat = Mass of water × Specific heat × Rise in temperature

$$\therefore h_f = m_w \times 4.187 \, (dT).$$

6. Latent heat of Vaporization:- It is the amount of heat absorbed to evaporate 1 kg of water at its boiling temperature (or) saturation temperature without change of temperature. It is denoted by h_{fg}.

If it is wet steam, then latent heat of vaporization $= x \cdot h_{fg}$.

7. Enthalpy (or) Total heat of steam: It is the amount of heat absorbed by water to its saturation temperature plus heat absorbed during evaporation.

Enthalpy (or) Total heat of steam = sensible heat + latent heat.

$$h = h_f + h_{fg} = h_g \rightarrow \text{Dry steam}$$

$$h = h_f + x \times h_{fg} \rightarrow \text{wet steam}$$

* $[T_{sup} - T_{sat}] \rightarrow$ Degree of superheat

$$h = h_g + C_p\,[T_{sup} - T_{sat}] \rightarrow \text{Superheated steam}$$

8. Specific volume of steam:-

It is the volume occupied by the steam per unit mass at a given temperature and pressure, and is expressed by m^3/kg.

Volume of wet steam $= x \cdot v_g + (1-x) v_f$

$v_f \rightarrow$ volume of water per kg.
$v_g \rightarrow$ volume of Dry steam per kg.

Since v_f is very small,

$\therefore$ Volume of 1 kg of wet steam $= v = x v_g$, m^3/kg.

For Dry steam:- v_g m^3/kg.

For Super heated steam, $\dfrac{v_{sup}}{T_{sup}} = \dfrac{v_g}{T_{g\ saturation}}$

Steam Tables and their use:-

The properties of dry saturation steam like its temperature of formation [saturation temp], sensible heat, latent heat, enthalpy, total heat, specific volume, entropy vary with pressure can be found expediently.

Internal energy of steam (u) It is the actual heat energy stored in steam, above the freezing point of water.

Internal energy of steam = Enthalpy (or) total heat − External Workdone during evaporation.

For Wet steam, internal energy, $u = h_f + x \cdot h_{fg} - 100\, p x \cdot v_g$ KJ/kg

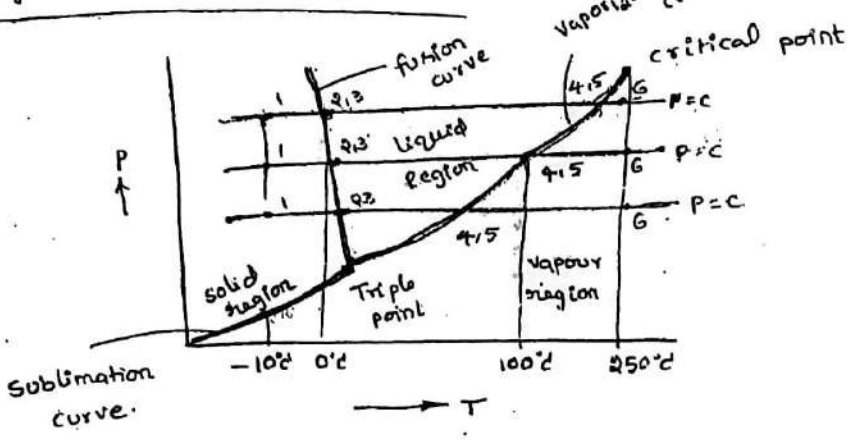
For Dry steam, 〃 $u = h_f + h_{fg} - 100\, p v_g$, KJ/kg

For superheated steam, $u = h_g + c_p (t_{sup} - t_{sat}) - 100\, p v_{sup}$.

Measurement of Dryness fraction of Steam

1. Barrel calorimeter 2. Separating calorimeter 3. Throttling calorimeter
4. Combined separating and throttling calorimeter.

P-T Diagram for a pure substance:



phase Equilibrium Diagram on P-T coordinates

The state changes of a pure substance upon slow heating at diff. constant pressures are shown in fig. If these state changes are plotted on P-T coordinates the diagram as shown in fig. If the heating of ice at −10°c to steam at 250°c at the constant pressure of 1 atm is considered 1-2 is the solid (ice) heating 2-3 is the melting of ice at 0°c, 3-4 is the liquid heating 4-5 is the vaporization of water at 100°c and 5-6 is the heating in the vapour phase. The process will be reversed from state 6 to state 1 upon cooling. The curve passing through the 2,3 points is called the fusion curve and the curve passing through 4,5 points [which indicate the vaporization or condensation at diff. temp. & pressures] is called the vaporization curve. If the vapor pressure of a solid is measured at diff. temperatures and these are plotted the sublimation curve will be obtained. The fusion curve, the vaporization curve and the sublimation curve meet at the triple point.

The slopes of the sublimation and vaporization curves for all substances are positive. The slope of the fusion for most substances is positive but for water it is negative.

PROB Calculate the enthalpy of 1 kg of steam at a pressure of 8 bar and dryness fraction of 0.8. How much heat would be required to raise 2 kg of this steam from water at 20°C ?

Sol. Enthalpy of 1 kg of steam.

From steam tables, corresponding to a pressure of 8 bar, we find that

$h_f = 720.9$ kJ/kg and $h_{fg} = 2046.5$ kJ/kg.

We know that enthalpy of 1 kg of wet steam,

$h = h_f + x \times h_{fg} = 720.9 + 0.8 \times 2046.5 = 2358.1$ kJ.

Heat required to raise 2 kgs of this steam from water at 20°C.

heat already in water $= 4.2 \times 20 = 84$ kJ.

and heat required per kg of steam,

$= 2358.1 - 84 = 2274.1$ kJ.

heat required for 2 kgs of steam $= 2 \times 2274.1 = 4548.2$ kJ.

PROB Determine the quantity of heat required to produce 1 kg of steam at a pressure of 6 bar at a temperature of 25°C, under the following conditions.

1) When the steam is wet having a dryness fraction of 0.9
2) When the steam is dry saturated
3) When the steam is superheated at a constant pressure at 250°C assuming the mean specific heat of superheated steam to be 2.3 kJ/kgK.

SOL. Given, pressure, $p = 6$ bar, $t_w = 25°C$; $x = 0.9$; $t_{sup} = 250°C$

$C_p = 2.3$ kJ/kgK.

From steam tables corresponding to a pressure of 6 bar, we find that

$h_f = 670.4$ kJ/kg ; $h_{fg} = 2085$ kJ/kg and t_{sat} 158.8°C.

1) When the steam is wet,

enthalpy (or) total heat of 1 kg of steam,

$h = h_f + x \cdot h_{fg} = 670.4 + 0.9 \times 2085 = 2546.9$ kJ.

Since the water ~~at~~ is at a temperature of 25°C,

Heat already in water $= 4.2 \times 25 = 105$ kJ.

Heat actually required $= 2546.9 - 105 = 2441.9$ kJ. ✓

2) When the steam is dry saturated

$h_g = h_f + h_{fg} = 670.4 + 2085 = h_g = 2755$ kJ/kg

Heat actually required $= h_g - 105 = 2755 - 105 = 2650.4$ kJ.

3. When the steam is superheated

$h_{sup} = h_g + C_p\,[t_{sup} - t_{sat}] = 2755.4 + 2.3(250 - 158.8) = 2965.16$ KJ/Kg

Heat actually received $= 2965.16 - 105 = 2860.16$ KJ ✓

PROB Determine the condition of steam in the following cases.

1. At a pressure of 10 bar and temperature 200°C
2. At a pressure of 10 bar and volume $0.175\ m^3/Kg$.

1. At a pressure of 10 bar and temperature 200°C

From steam tables, corresponding to a pressure of 10 bar, we find that

$v_g = 0.194\ m^3/Kg$; $h_f = 762.6$ KJ/Kg; and

$t_{saturation} = 179.9°C$ ✓

Since the saturation temperature at 10 bar is 179.9°C is lower than the given temperature of steam 200°C, the given steam is superheated.

The degree of superheat $= T_{sup} - T_{sat} = 200 - 179.9 = 20.1°C$ ✓

2. Condition of steam at a volume of $0.175\ m^3/Kg$

Since the volume of given steam ($0.175\ m^3/Kg$) is less than specific volume of dry saturated steam ($0.194\ m^3/Kg$), therefore, the given steam is wet. The dryness fraction $= \dfrac{V_g \text{ wet steam}}{V_g \text{ dry steam}} = \dfrac{0.175}{0.194} = 0.902$ ✓

PROB. Steam enters an engine at a pressure of 12 bar with a 67°C of superheat. It is exhausted at a pressure of 0.15 bar and 0.95 dry. Find the drop in enthalpy of the steam.

SOL. From steam tables, corresponding to 12 bar, $h_g = h_f + h_{fg} = 2782$ KJ/Kg

Enthalpy (or) total heat of 1kg of steam (superheated) is

$h_{sup} = h_g + C_p\,[T_{sup} - T_{sat}] = 2782 + 2 \times 67°C$.

$= 2916.7$ KJ/Kg

[∴ since $C_p = 2$ KJ/KgK taken $T_{sup} - T_{sat} = 67°$ given]

From steam tables, at pressure of 0.15 bar,

$h_f = 226$ KJ/Kg, $h_{fg} = 2373.2$ KJ/Kg

Enthalpy (or) total heat of 1 kg of wet steam

$= h_{wet} = h_f + x\,h_{fg} = 226 + 0.95 \times 1984.3 = 2111$ KJ/kg.

Drop in enthalpy of steam $= h_{sup} - h_{wet} = 2916.7 - 2111 = 805.7$ KJ/Kg.

PROB Determine the volume of 1 kg of superheated steam at a pressure of 20 bar and a temp of 300°C.

SOL Given, $P = 20$ bar; $T_{sup} = 300°C = 300 + 273 = 573K$.

From steam tables at a pressure of 20 bar,

$t_{sat} = 212.4°C + 273 = 485.4K$

$v_g = 0.1\ m^3/Kg$

we know that, the superheated steam obeys <u>charle's law</u>

$$\frac{v_g}{T_{sat}} = \frac{v_{sup}}{T_{sup}}$$

$$v_{sup} = \frac{v_g}{T_{sat}} \times T_{sup} = \frac{0.1}{485.4} \times 573 = 0.118 \ \underline{m^3/kg} \checkmark$$

PROB. A boiler is supplied with feed water at a pressure of 45°C. The water is converted in to steam at a pressure of 5.5 bar and a temperature of 188°C. Determine the quantity of heat supplied per kg of steam.

SOL. <u>At a pressure of 5.5 bar</u>

$h_g = 2751.7$ KJ/kg, $T_{sat} = 155.5°C$

∴ since the given temp of steam (188°C) higher than saturation temperature

$h_{sup} = h_g + C_p[t_{sup} - t_{sat}] = 2751.7 + 2.1[188 - 155.5] = \underline{2820 \text{ KJ/kg}}$

since, water is supplied at <u>45°C</u>, the heat in feed water $= 4.2 \times 45 = 189$ KJ.

∴ Heat actually required $= 2820 - 189 = \underline{2631 \text{ KJ/kg}}$ ✓

<u>Internal energy of steam:-</u>

It is the actual heat energy stored in steam, above freezing point of water

For wet steam, internal energy of steam = Enthalpy (or) total heat − External work done during evaporation

$u = h - 100\, p x v_g$ — ① wet steam

$u = h_g - 100\, p v_g$ — ② dry

$u = \cancel{h_g}\ h_{sup} - 100\, p v_{sup}$ — ③ superheated.

PROB. Calculate the internal energy of 1kg of steam at a pressure of 10 bar when the steam is ⓐ 0.9 dry ⓑ dry saturated.

<u>From steam tables, corresponding to a pressure of 10 bar,</u>

$h_f = 762.6$ KJ/kg ; $h_{fg} = 2013.6$ KJ/kg ; $v_g = 0.1943$ m³/kg

ⓐ internal energy of 1kg of steam when it is 0.9 dry $(x = 0.9)$

$u = h_f + x h_{fg} - 100\, p x v_g = 762.6 + 0.9 \times 2013.6 - 100 \times 10 \times 0.9 \times 0.1943$

$= \underline{2400 \text{ KJ}}$ ✓

ⓑ <u>internal energy of 1kg of steam when it is dry saturated</u>

$u = h_f + h_{fg} - 100\, p v_g = 762.6 + 2013.6 - 100 \times 10 \times 0.1943$

$= 2581.9$ KJ.

PROB Steam at 18 bar and dryness 0.9 is heated at constant pressure until dry and saturated. Find the increase in volume, heat supplied and workdone per kg of steam.

If the volume is kept constant, find how much heat must be extracted to reduce the pressure to 14 bar.

SOL: Given, $p = 18$ bar ; $x = 0.9$; $p_1 = 14$ bar.

From steam tables corresponding to a pressure of 18 bar, we find

$h_f = 884.5$ KJ/kg, $h_{fg} = 1910.3$ KJ/kg; $h_g = 2794.8$ KJ/kg

$v_g = 0.1103$ m³/kg.

Increase in volume

= Volume of dry steam − Volume of wet steam

$= v_g - x \times v_g = 0.1103 - 0.9 \times 0.1103 = 0.011$ m³/kg.

Increase in Heat Supplied

$= h_g - h_{wet} =$ ~~2760308~~ $2794.8 - [h_f + x \times h_{fg}]$

$= 2794.8 - [884.5 + 0.9 \times 1910.3] = 191$ KJ/kg.

Increase in Workdone

$= 100\,p\,[v_g - x v_g] = 100 \times 18\,[0.1103 - 0.0993] = 19.8$ KJ/kg

Heat extracted to reduce the pressure to 14 bar

During constant for volume process, no work is done and extraction of heat will result in the reduction of internal energy of steam.

From steam tables, corresponding to a pressure of 14 bar,

$h_{f_1} = 830.1$ KJ/kg, $h_{fg_1} = 1957.7$ KJ/kg ; $v_{g_1} = 0.1407$ m³/kg.

x_1 = Dryness fraction of steam :

Since the volume is constant,

$$v_g = x_1 v_{g_1} \quad \text{(or)} \quad x_1 = \frac{v_g}{v_{g_1}} = \frac{0.1103}{0.1407} = 0.78$$

Now, internal energy of steam at a pressure of 18 bar,

$u = h_g - 100\,p\,v_g = 2794.8 - 100 \times 18 \times 0.1103 = 2596.3$ KJ/kg

internal energy of steam at a pressure of 14 bar,

$u_1 = h_{f_1} + x_1 h_{fg_1} - 100\,p_1 x_1 v_{g_1}$

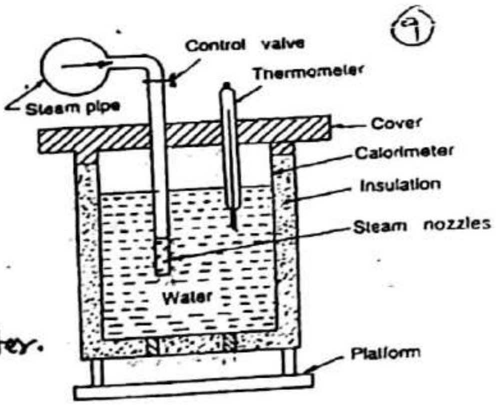
$= 830.1 + 0.78 \times 1957.7 - 100 \times 14 \times 0.78 \times 0.1407$

$= 2203$ KJ/kg.

Heat extracted to reduce pressure $= u - u_1 = 2596.3 - 2203 = 393.3$ KJ/kg

⑨

Barrel caldimeter



Barrel calorimeter.

In barrel caldimeter, the known mass of steam sample and of known pressure is condensed by mixing it with a known mass of cold water. The steam condenses into water, there by increasing the mass of and temperature of the water in the caldimeter. The heat supplied by the condensing steam is determined, with the help of the initial and final temperatures of the water and caldimeter.

Let p = pressure of the steam in bar

t = Temp. of steam formed

h_{fg} = latent heat of steam at pressure p (from steam tables)

m_c = mass of the calorimeter.

C_c = specific heat of the calorimeter.

m_e = water equivalent of the calorimeter $= m_c \times C_c$.

m_s = mass of steam condensed

m_w = mass of cold water in calorimeter.

t_1 = initial temp. of water and caldimeter.

t_2 = final temp of water and caldimeter

C_w = specific heat of water.

x = Dryness fraction of steam sample.

According to law of conservation of energy, heat lost by steam is equal to heat gained by water and caldimeter.

$$\boxed{m_s[x h_{fg} + C_w(t - t_2)] = (m_w C_w + m_c C_c)(t_2 - t_1)}$$

From this expression, the dryness fraction of steam (x) may be determin

PROB In a laboratory experiment on wet steam by a barrel calorimeter, the following observations were recorded.

Mass of copper caldimeter = 1 kg

Mass of caldimeter + water = 3.8 kg

Mass of calorimeter + water + steam = 4 kg

Initial temperature of water = 10°C

Final temperature of water = 50°C

Steam pressure = 5.5 bar

If the specific heat of copper is 0.406 kJ/kgK, determine dryness fraction of steam.

SOL: Mass of steam, $m_s = (4 - 3.8) = 0.2$ kgs.

From steam tables, corresponding to a pressure of 5.5 bar,

$t = 155.5°C$, $h_{fg} = 2095.5$ kJ/kg.

x = Dryness fraction of steam.

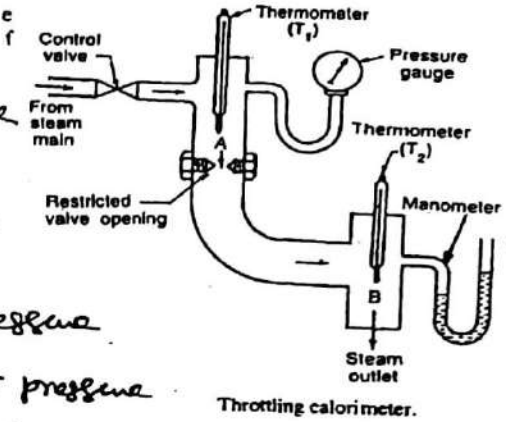
According to law of conservation of energy,
Heat lost by steam = Heat gained by water

$$m_s[x \cdot h_{fg} + c_w(t - t_2)] = [m_w c_w + c_c m_c](t_2 - t_1)$$

$$0.2[x \times 2095.5 + 4.2(155.5 - 50)] = (2.8 \times 4.2 + 1 \times 0.406)(50 - 10)$$

Dryness fraction, $\underline{x = 0.95}$ ✓

Throttling calorimeter



Throttling calorimeter.

A throttling calorimeter used to determine the dryness fraction of steam.
It consists of a separator A into which steam is admitted through a control valve from the steam main. The pressure and temperature are measured by the pressure gauge and the thermometer T_1 provided in this section.
The steam is then throttled through a narrow aperture of restricted valve openings, its total heat remaining constant. The steam is in superheated state after throttling at a lower pressure than previous. The temperature and pressure of steam leaving the calorimeter B is noted by thermometer T_2 and manometer respectively.

Total heat before throttling = Total heat after throttling

At pressure P_1 $\quad h_{f1} + x\, h_{fg1} = h_{g2} + C_p[T_{sup} - T_{sat_2}]$. At pressure P_2.

PROB. On a throttling calorimeter, the steam is admitted at a pressure of 10 bar. If it is discharged at atmospheric pressure and 110°C after throttling, determine the dryness fraction of steam. Assume, specific heat of steam as 2.2 KJ/kgK.

Sol. $P_1 = 10$ bar ; $P_2 = 1.013$ bar ; $T_{sup} = 110°C$; $C_p = 2.2$ KJ/kgK.
x = Dryness fraction of steam.

From steam tables, corresponding to a pressure of 10 bar,
$h_{f1} = 762.6$ KJ/kg ; $h_{fg1} = 2013.6$ KJ/kg.
and corresponding to a pressure of 1.013 bar,
$h_{g2} = 2676$ KJ/kg ; $T_{sat_2} = 100°C$

∴ We have, $h_{f1} + x\, h_{fg1} = h_{g2} + C_p[T_{sup} - T_{sat_2}]$

$$762.6 + x \times 2013.6 = 2676 + 2.2(110 - 100)$$

Dryness fraction $\therefore x = \frac{2698 - 762.6}{2013.6} = \underline{0.961}$ ✓

Separating Calorimeter,-

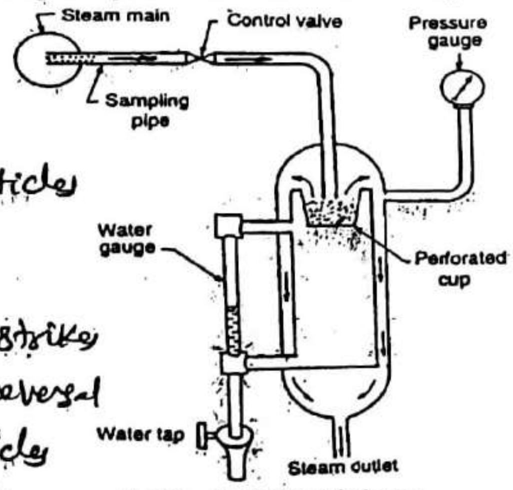


Fig. [illegible]. Separating calorimeter.

The separating calorimeter is used to determine the dryness fraction of steam by mechanically separating the water particles from the wet steam.

The wet steam enters at the top of the calorimeter through a control valve. It strikes the perforated cup and thereby quick reversal of direction of motion. The water particles due to their greater moment of inertia tend to move on, and consequently get separated from the mixture. The separated water gets collected at the bottom of the inner chamber.

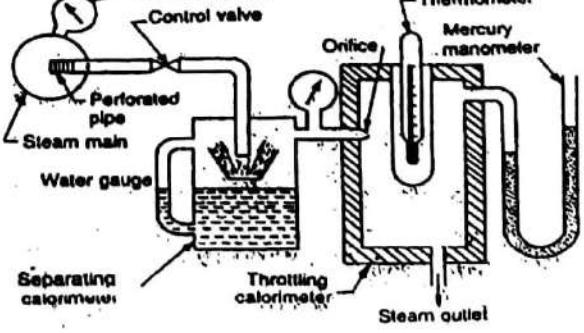
The amount of dry steam leaving at the outer chamber of the calorimeter may be measured by condensing it in a weighed quantity of cold water.

Let m = Mass of water collected in a certain time
M = Mass of dry steam passing in the same time
x = Dryness fraction of wet steam.

$$\therefore \text{Dryness fraction, } x = \frac{\text{Mass of Dry steam}}{\text{Mass of dry steam} + \text{Mass of water}}$$

$$\boxed{x = \frac{M}{M+m}}$$

Combined separating & throttling calorimeter



Combined separadine and throttling calorimeter.

In this calorimeter, the wet steam is first collected in a perforated collecting pipe and then passed through a separating calorimeter.

A part of the water is removed by a separating calorimeter owing to quick change of direction of flow.

The resulting semi-dry steam is throttled into a throttling calorimeter. This method ensures that the steam will be superheating after throttling.

Let x_1 = Dryness fraction of steam considering separating calorimeter
x_2 = Dryness fraction of steam entering the throttling calorimeter

Actual dryness fraction of steam in the steam main. $x = x_1 \times x_2$

Entropy of steam: The entropy of steam is also an important property, which increases with the addition of heat and decreases with its removal.

The ~~[illegible]~~ entropy of steam consists of

1. Increase in entropy of water during heating from freezing point to boiling point corresponding to pressure at which water is being heated
2. Increase in entropy during evaporation
3. Increase in entropy during superheating.

Entropy of wet steam:- $S_f + x\frac{h_{fg}}{T} = S_f + x \cdot S_{fg}$

Entropy of dry steam:- $S_f + S_{fg} = S_g$

Entropy of superheated steam:- $S_g + C_p \ln\frac{T_{sup}}{T_{sat}}$.

PROB. Find the entropy of 1 kg of dry saturated steam at a pressure of 5.2 bar. The boiling point of water at this pressure is given as 152.6 °C and its total heat at this temperature is 2110 KJ/kg.

SOL. The value of entropy of dry saturated steam (S_g) may be directly read from steam tables corresponding to a pressure of 5.2 bar.

From steam tables at 5.2 bar; $S_f = 1.86$ KJ/kgK

$S_{fg} = 4.96$ KJ/kgK

$\therefore S_g = S_f + S_{fg} = 1.86 + 4.96 = \underline{6.82 \text{ KJ/kgK}}$ ✓

PROB. Calculate entropy of 1 kg of wet steam with dryness fraction of 0.9 at a pressure of 8.4 bar.

SOL. From steam tables at 8.4 bar,

$S_f = 2.066$ KJ/kgK ; $S_{fg} = 4.577$ KJ/kgK.

$\therefore$ Entropy of 1 kg of wet steam, $S = S_f + x S_{fg} = 2.066 + 0.9 \times 4.577$

$= 6.186$ KJ/kgK.

PROB Determine the entropy of per kg of superheated steam at a pressure of 20 bar and a temp. of 250°C. Assume C_p for superheated steam as 2.2 KJ/kg K.

SOL. $p = 20$ bar; $T_{sup} = 250°C = 250 + 273 = 523$ K; $C_p = 2.2$ KJ/kgK.

From steam tables, corresponding to 20 bar pressure,

$T = 212.4°C = 212.4 + 273 = 485.4$ K; $S_g = 6.337$ KJ/kgK.

Entropy of 1 kg of superheated steam

$S_{sup} = S_g + C_p \ln\frac{T_{sup}}{T_{sat}} = 6.337 + 2.3 \ln\frac{523}{485.4}$

$= \underline{6.5 \text{ KJ/kgK}}$ ✓

UNIT-4.

Vapour processes:- The following steps are suggested to solve vapour process problems :-

① Find final condition of steam ; $V_{wet_2} = x \cdot v_{g_2}$ (or) $V_{dry_2} = v_{g_2}$ (or) $v_{sup_2} = T_{sup_2} \times \frac{v_g}{T_{sat}}$

② change in internal energy, $u_2 - u_1 =$ ~~[illegible]~~ $(h_2 - 100 p_2 v_2) - (h_1 - 100 p_1 v_1)$

$[h_{wet} = h_f + x \cdot h_{fg}$; $h_{dry} = h_f + h_{fg} = h_g$; $h_{sup} = h_g + c_{ps}[T_{sup} - T_{sat}]$

③ Workdone, $W_{1-2} = \int p\,dv$ $\left[\begin{array}{c|c|c|c|c} W_{1-2} = 0 & W_{1-2} = p_2[v_2 - v_1] & W_{1-2} = p_1 v_1 \ln \frac{v_2}{v_1} & W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{n-1} & W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{\gamma - 1} \\ \text{const. volume} & \text{const. pressure} & \text{isothermal} & \text{polytropic} & \text{adiabatic} \end{array}\right]$

④ obtain Heat transfer, $Q_{1-2} = (u_2 - u_1) + W_{1-2}$.

① **Constant volume process**

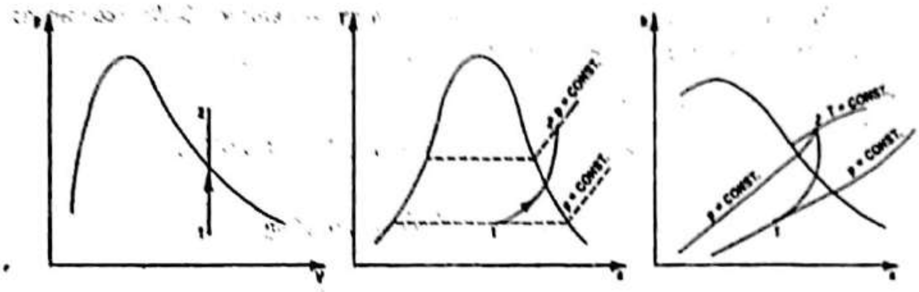


Fig. 7.12 Constant Volume Process

consider 1 kg of wet steam at pressure p_1, dryness fraction x_1 heated to pressure p_2 at const. volume process.

since, volume is constant

$x_1 v_{g_1} = x_2 v_{g_2} \Rightarrow x_2 = \frac{x_1 v_{g_1}}{v_{g_2}}$; If $x_2 > 1$, then final state is superheated.

$\therefore x_1 v_{g_1} = v_{sup_2} = \left(\frac{v_{g_2}}{T_{sat_2}}\right) \times T_{sup_2}$

② $u_2 - u_1 = (h_2 - 100 p_2 v_2) - (h_1 - 100 p_1 v_1)$

③ $W_{1-2} = 0$; ④ $Q_{1-2} = (u_2 - u_1) + 0 = (u_2 - u_1)$.

PROB- The steam contained in a closed vessel of fixed volume $0.14\,m^3$, exerts a pressure of 10 bar at 250°C. If the vessel is cooled to pressure falls to 3.5 bar. determine the heat transfer and change in entropy.

SOL: From steam tables At pressure $p_1 = 10$ bar ; $t_{sat_1} = 138.9°c$, so the superheated ~~tem~~ steam temp is 250°c which is more than t_{sat_1}.

$\therefore$ At 10 bar and 250°c ; $v_{sup_1} = 0.2328\,m^3/kg$; $h_{sup_1} = 2943$ kJ/kg ; $S_1 = 6.926$ kJ/kgK.

mass of steam in the vessel, $m = \frac{V}{v_{sup_1}} = \frac{0.14}{0.2328} = 0.6014$ kgs.

At: 3.5 bar (p_2) ; $h_{f_2} = 584.3$ kJ/kg ; $h_{fg_2} = 2147.3$ kJ/kg ; $v_{g_2} = 0.52397\,m^3/kg$

$S_{f_2} = 1.727$ kJ/kgK $S_{fg_2} = 5.212$ kJ/kgK.

Final state dryness fraction $v_{sup_1} = x_2 v_{g_2} \Rightarrow x_2 = \frac{v_{sup_1}}{v_{g_2}} = \frac{0.2328}{0.5239} = 0.4443$ (wet).

$\therefore$ Change in enthalpy $(u_2 - u_1)$ $= [h_2 - 100 p_2 v_2] - [h_1 - 100 p_1 v_1] = [h_{f_2} + x_2 h_{fg_2} - 100 p_2 v_2] - [h_{sup_1} - 100 p_1 v_{sup_1}]$

$= [(584.3 + 0.4443 \times 2147.3) - (100 \times 3.5 \times 0.4443 \times 0.5239)] -$

$[(2943 - 100 \times 10 \times 0.2328)] = 1436.86$ kJ/kg $- 2710.2$ kJ/kg

[illegible]

$\therefore$ Heat Transfer, $Q_{1-2} = m \cdot [u_2 - u_1]$
$= 0.6014[-1253.34] = -753.76$ kJ

Change in entropy, $S_2 - S_1 = m \cdot \left\{ \left(S_{f_2} + x_2 \cdot S_{fg_2}\right) - \overset{S_1 \text{ (in Sup)}}{\cancel{\left(S_{f_1} + x_1 S_{fg_1}\right)}} \right\}$
$= 0.6014\{(1.727 + 0.4443(5.212) - 6.926\}$
$= -0.6014 \times 2.883 = -1.734$ kJ/kgK.

Constant pressure process:-

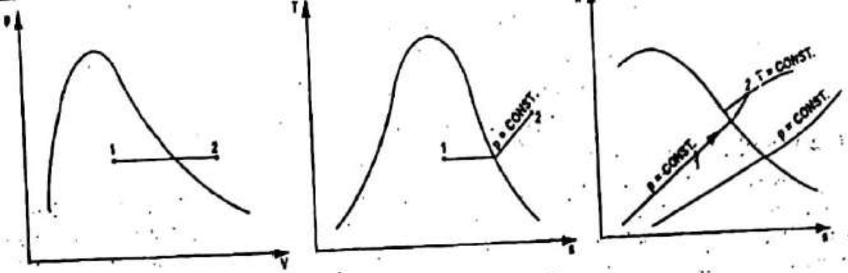


Fig. 7.13 Constant Pressure Process

Consider 1 kg of steam with dryness fraction x_1 heated at constant pressure to final condition 2.

② W_{1-2} = Workdone = $p_2[v_2 - v_1]$
③ change in internal energy, $(u_2 - u_1) = (h_2 - 100p_2v_2) - (h_1 - 100p_1v_1)$
④ Heat transfer, $Q_{1-2} = W + (u_2 - u_1) = (h_2 - h_1)$.

PROB. one kg of steam at pressure of 20 bar and dryness fraction 0.85 is heated at a constant pressure to 300°C. Determine (a) Heat transferred (b) workdone (c) change in internal energy.

SOL: At 20 bar, t_g or $t_{sat} = 212.4°C$. The final condition (state 2) is superheated with a temperature of 300°C.

At 20 bar, $h_f = 908.6$ kJ/kg; $h_{fg} = 1888.7$ kJ/kg
$v_{g_1} = 0.099549$ m³/kg.
$h_1 = h_{wet\,1} = h_{f_1} + x_1 h_{fg_1} = 908.6 + 0.85(1888.7)$
$= 2514$ kJ/kg.

and final condition (state 2)
At 200 bar $(p_1 = p_2)$ and <u>300°C</u> (t_{sup})
$h_2 = 3025$ kJ/kg ; $v_2 = v_{sup_2} = 0.1255$ m³/kg.
$\therefore$ Heat transfer, $Q_{1-2} = (h_2 - h_1) = 3025 - 2514 = 511$ kJ/kg.
workdone, $W_{1-2} = 10^2\{p_2v_2 - p_1v_1\} = 10^2[20 \times 0.1255 - 0.85 \times 0.09954]$
$= 81.767$ kJ/kg.
$\therefore$ change in internal energy, $(u_2 - u_1) = Q - W = 511 - 81.767$
$= 429.23$ kJ/kg.

Constant tem- -perature process

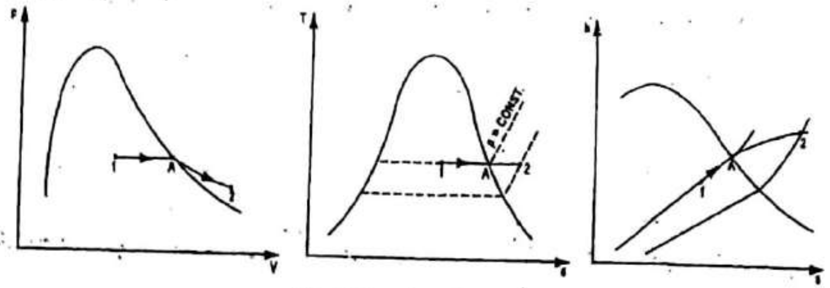


Fig. 7.14 Isothermal Process

Isothermal (Constant temperature process):

Consider 1 kg of steam expands from state 1 to 2 isothermally.

The law of governing isothermal process: $p_1 v_1 = p_2 v_2$.

$p_1 (x_1 v_{g1}) = p_2 (x_2 v_{g2})$

If x_2 = less than 1; $v_2 = x_2 v_{g2}$

If $x_2 > 1$; $v_{sup_2} = T_{sup_2} \times \frac{v_{g2}}{T_{sat_2}} = v_2$.

$\therefore W_{1-2} = p_1 v_1 \ln \frac{v_2}{v_1}$

$u_2 - u_1 = (h_2 - 100\, p_2 v_2) - (h_1 - 100\, p_1 v_1)$

$\therefore Q = W + (u_2 - u_1)$

PROB. A quantity of dry saturated steam occupies $0.2634\ m^3$ at 15 bar. Determine the final condition of steam if it is compressed until the volume is halved. If the compression is carried out in an isothermal manner, determine heat rejection during the compression.

SOL. At 15 bar, dry satured ($x=1$) $v_g = 0.1317\ m^3/kg$ $h_f = 844.7\ kJ/kg$ $h_{fg} = 1945\ kJ/kg$ $h_g = 2789\ kJ/kg$.

Mass of steam, $m = \frac{V}{v_g} = \frac{0.2634}{0.1317} = 2\ kg$.

Final condition; $v_2 = \frac{v_1}{2} = \frac{0.1317}{2} = 0.0659\ m^3/kg$.

Condition:- Since the steam is in wet region; the pressure also remains constant [for wet steam, P&T are constant].

$x_2 \cdot v_{g2} = v_2 \Rightarrow x_2 = \frac{0.0659}{0.1317} = 0.5$

$h_2 = h_{f2} + x_2 \cdot h_{fg2} = 844.7 + 0.5(1945.2) = 1817\ kJ/kg$

$\therefore$ Heat transferred, $Q = m[h_2 - h_1] = 2[1517.3 - 2789.9]$

$= -1945.2\ kJ$ [Heat rejection]

polytropic process: -

polytropic process is given by

pv^n = constant

For polytropic expansion

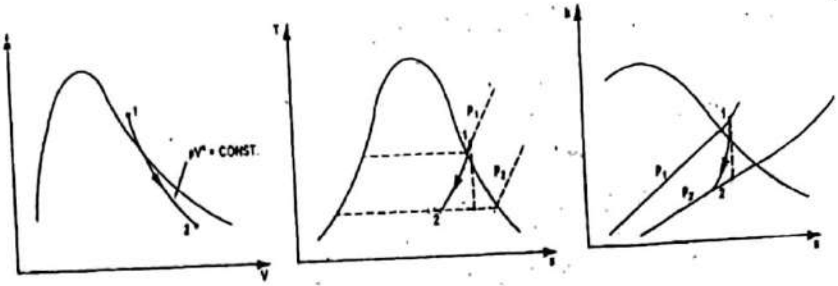


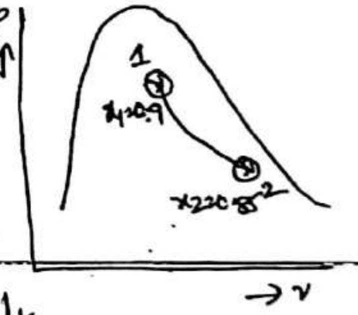
Fig. 7.16 polytropic process

$$\Rightarrow x_2 = \left(\frac{p_1}{p_2}\right)^{1/n} \cdot \frac{x_1 v_{g_1}}{v_{g_2}} \qquad \text{If } x_2 < 1;\ v_2 = x_2 \cdot v_{g_2}$$
$$\text{If } x_2 > 1;\ v_2 = T_{sup_2} \times \frac{v_{g_2}}{T_{sat_2}}.$$

$$\therefore W_{1-2} = \frac{p_1 v_1 - p_2 v_2}{n-1}$$

$$Q_{12} = (u_2 - u_1) + W \ ; \ (u_2 - u_1) = (h_2 - 100\, p_2 v_2) - (h_1 - 100\, p_1 v_1)$$

PROB: steam at 3 bar and 0.9 dry expands in a cylinder till the volume is 4 times at the beginning. The law of expansion is $pv^{1.1}$ = constant. Find the change in internal energy, work done and steam condition at the end of the process.



Sol: From steam tables at $p_1 = 3$ bar, $h_{f_1} = 561.4$ kJ/kg, $h_{fg_1} = 2163$ kJ/kg

The specific volume of vapour, $v_{g_1} = 0.6058\ m^3/kg$.

$\therefore$ Initial volume, $v_1 = x_1 v_{g_1} = 0.9 \times 0.6058$
$= 0.545\ m^3/kg$

Final volume, $v_2 = 4 \cdot v_1 = 4 \times 0.545 = 2.18\ m^3/kg$.

According to law of expansion, $p_1 v_1^{1.1} = p_2 v_2^{1.1} \Rightarrow p_2 = p_1 \left(\frac{v_1}{v_2}\right)^{1.1}$

Final pressure $\therefore$ $p_2 = 3\left[\frac{1}{4}\right]^{1.1} = 0.6529$ bar

$\therefore$ We know the value, $v_2 = 2.18\ m^3/kg$

From steam tables, ~~Final value~~, At $p_2 = 0.652$ bar, $v_{g_2} = 2.548\ m^3/kg$.

To find final condition of steam. $v_2 = x_2 \cdot v_{g_2}$; $\Rightarrow 2.18 = x_2 \times 2.548 \Rightarrow x_2 = 0.85$ (wet)

$\therefore$ At $p_2 = 0.652$ bar; $h_{f_2} = 368$ kJ/kg; $h_{fg_2} = 2492$ kJ/kg.

$\therefore$ Initial enthalpy; $h_1 = h_{f_1} + x_1 h_{fg_1} = 561.4 + 0.9 \times 2163 = 2508$ kJ/kg.

$h_2 = h_{f_2} + x_2 h_{fg_2} = 368 + 0.85 \times 2492 = 2486$ kJ/kg

Change in internal energy $(u_2 - u_1) = (h_2 - 100\, p_2 v_2) - (h_1 - 100\, p_1 v_1)$

$= (2486 - [illegible]\ 2.18) - (2508 - 100 \times 3 \times 0.545)$

Workdone, $W_{1-2} = \frac{p_1v_1 - p_2v_2}{n-1} = \frac{(100\times3\times0.545-\overset{100}{40}.65\times2.18)}{1.1-1}$

$= \underline{218\ \text{KJ}/\text{Kg}}$

Adiabatic process [Isentropic process] :-

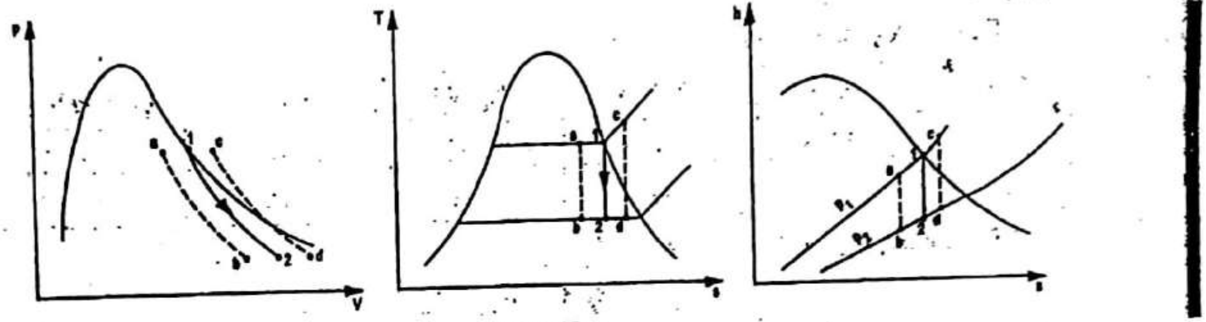


Fig 7.18

In Adiabatic process, no heat transfer takes place, but work is done due to expense of internal energy. As there is no heat transfer, entropy remains constant. Therefore, adiabatic process is also referred as isentropic process. It is represented by vertical line on h-s and T-S diagrams.

Consider 1 Kg of steam expands isentropically from p_1 to p_2.

Entropy before expansion = Entropy after expansion ; $\boxed{S_1 = S_2}$

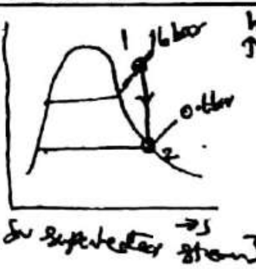
For Adiabatic process, $p_1v_1^n = p_2v_2^n$; $W_{1-2} = \frac{p_1v_1 - p_2v_2}{n-1}$

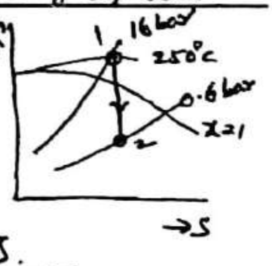
$n \rightarrow$ 1.13 for wet steam

1.3 for superheated steam $Q_{1-2} = 0$

1.135 for Dry steam

PROB. 4 Kgs of steam expands adiabatically from 16 bar and 250°c to 0.6 bar in a steam turbine such that steam is dry and saturated at the end of expansion. calculate workdone by steam.





From superheated steam tables At $p_1 = 16$ bar & $T_{sup_1} = 250°c$

$v_1 = v_{sup_1} = 0.1483\ m^3/Kg$.

For superheated steam initially $p_1v_1^{1.3} = p_2v_2^{1.3}$ [$n=1.3$ for superheated steam].

$\Rightarrow v_2 = v_1\left[\frac{p_1}{p_2}\right]^{1/1.3} = 0.1483\left[\frac{16}{0.6}\right]^{1/1.3} = 0.1483[26.6]^{0.769} = 1.85\ m^3/Kg$.

$\therefore$ Workdone, $W_{1-2} = \frac{p_1v_1 - p_2v_2}{n-1} = 100\frac{[16\times0.1483 - 0.6\times1.85]}{1.3-1} = 420.9\ \text{KJ}/\text{Kg}$

For 4 Kgs ; $W_{1-2} = 4\times420.9 = \underline{1683\ \text{KJ}/\text{Kg}}$.

Throttling process :-

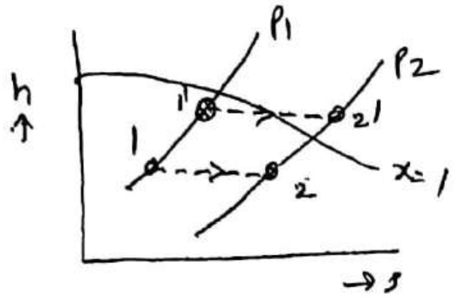
Flow of fluid through a restricted passage causes pressure drop is called Throttling process. For example, flow through partially opened valve, capillary tube and porous plug is regarded as throttling process. During throttling process, Enthalpy remains constant, but quality of steam is improved due to internal friction.

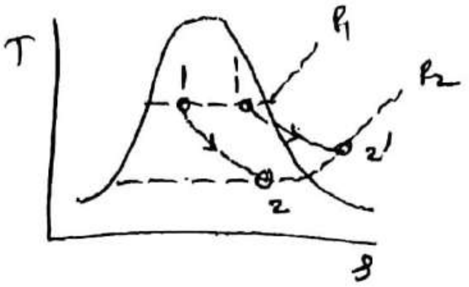
For throttling process, $h_1 = h_2$

[illegible]

For final condition is superheated,

$$h_{f_1} + x_1 h_{fg_1} = h_{g_2} + C_p [t_{sup_2} - t_{sat_2}].$$





PROB. Steam initially at a pressure of 10.5 bar and 0.96 dry throttled at a pressure of 1 bar. Find final condition of steam. Also calculate change in entropy per kg of steam.

P bar	t_{sat}, °C	h_f, kJ/kg	h_{fg}, kJ/kg	h_g kJ/kg	s_f kJ/kgK	s_g kJ/kgK
10.5	182	772.0	2006	–	2.159	6.566
1	99.63	–	–	2675.4	–	7.36

Take C_{p_s} for superheated steam = 2.1 kJ/kgK.

SOL For, Throttling process

$$h_{f_1} + x_1 h_{fg_1} = h_{g_2} + C_p (t_{sup_2} - t_{sat_2})$$

$$772 + 0.96 (2006) = 2675 + 2.1 (t_{sup_2} - 99.63)$$

$$t_{sup_2} = 110.27°C$$

Entropy at 10.5 bar and 0.96 dry

$$S_1 = S_{f_1} + x_1 S_{fg_1} = S_{f_1} + x_1 (S_{g_1} - S_{f_1})$$

$$= 2.159 + 0.96 (6.566 - 2.159) = 6.3897 \text{ kJ/kgK.}$$

Entropy at 1 bar and 110.27°C

$$S_2 = S_{g_2} + C_{p_3} \ln \frac{T_{sup_2}}{T_{sat_2}} = 7.36 + 2.1 \ln \frac{(110.27+273)}{(99.63+273)}$$

$$= 7.419 \text{ kJ/kg K.}$$

∴ Change in Entropy, $S_2 - S_1 = 7.419 - 6.3897$
$= 1.0293$ kJ/kg K.

UNIT-V

AIR REFRIGERATION CYCLE

Definition of Refrigeration and Unit of Refrigeration.

- The term Refrigeration may be defined as the process of removing heat from a substance under controlled condition.
- It also includes the process of reducing and maintaining the temperature of a body below the general temp. of its surrounding.

Unit of Refrigeration:

- Unit of refrigeration is "Tonne of Refrigeration".
- It is denoted by TR

A tonne of refrigeration is defined as the amount of refrigeration effect produced by the uniform melting of one tonne of ice from and at 0^0C in 24 hours.

But latent heat of Ice is 335 KJ/Kg

So, 1 TR = 335 X 1000 KJ in 24

hours

$$= \frac{1000X335}{24x60} = 232.6 \text{ KJ/min}$$

❖ But in actual practice 1 TR = 210 KJ/min

Definition of Co-efficient of performance (COP):

- COP is defined as the ratio of heat extracted in the refrigerator to the work done on the refrigerator.
- It is also called Theoretical COP

$$\textbf{COP} = \frac{Q}{W}$$

Where

Q = Amount of heat extracted in the refrigerator

W = Amount of work done

- Value of COP is always greater than one.

Refrigeration Effect (RE) :

Refrigeration Effect is "the quantity of heat that each pound of refrigerant absorbs from the refrigerated space to produce useful cooling"

Principle of working of open and closed air system of refrigeration

Air Refrigeration Cycle :

- Here air is used as working medium to extract heat
- Heat carrying capacity per Kg of air is very less.
- Its COP is very less.
- It is used in air refrigeration unit due to low weight and volume of the equipment.

Open Air Refrigeration Cycle :

- In this cycle, air is directly led to the space to be cooled, allowed to circulated through the cooler and then returned to the compressor to start another cycle.

Disadvantages:

1. Size of compressor and expander is large
2. Moisture is regularly carried away.
3. Frost is formed which can clog the line
4. A drier is used

Closed Air Refrigeration Cycle :

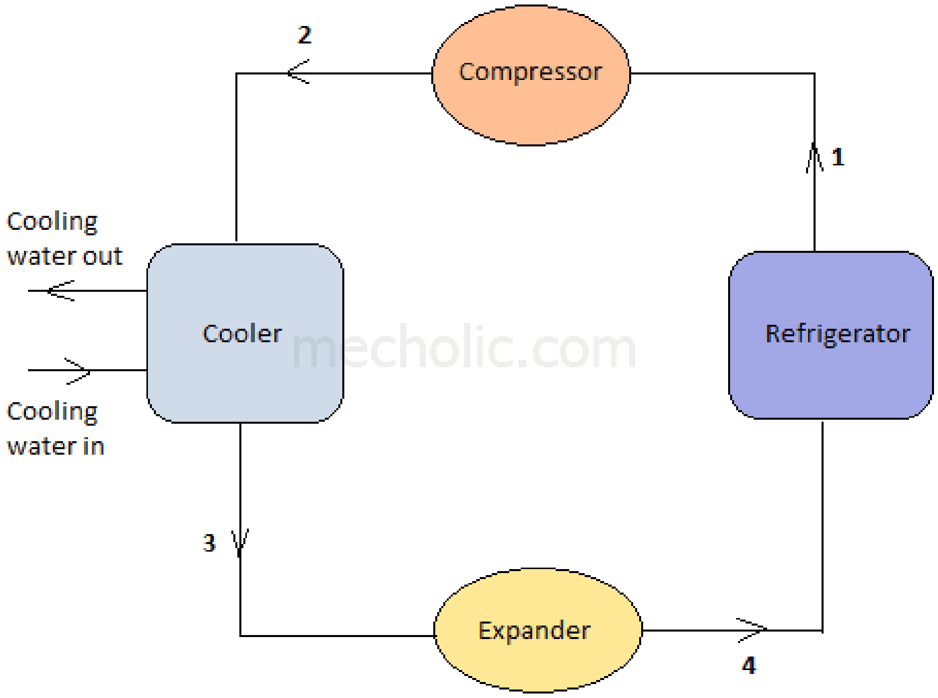
- Here the air is passed through the pipes.
- Air is used for absorbing heat from the other fluid (Brine) and thus cooled brine is circulated in the space to be cooled.

Advantages:

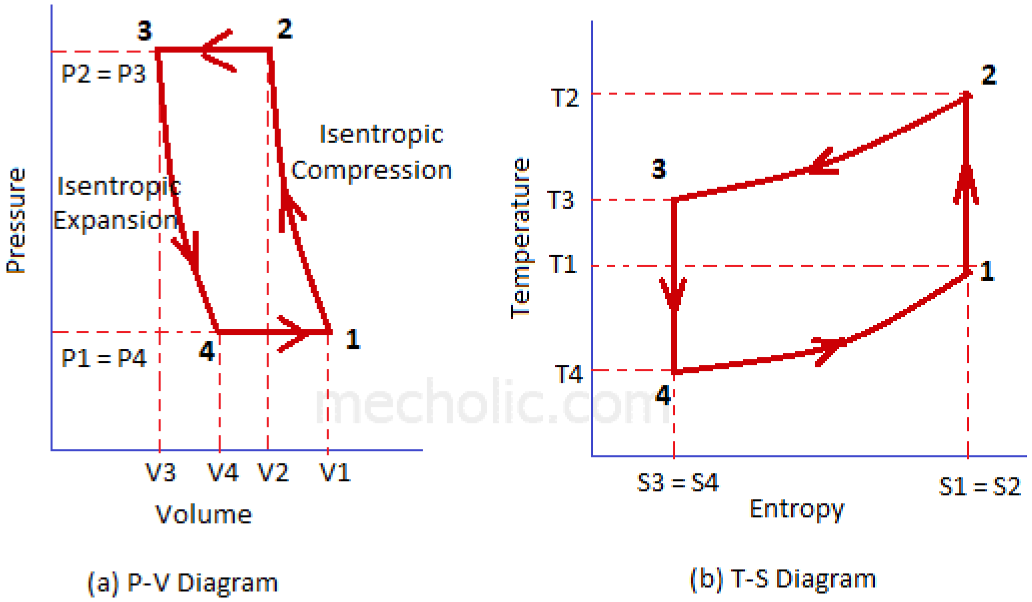
1. It can work at higher suction pressure
2. Volume of air handled by Compressor and expander is less
3. Operating pressure ratio can be reduced
4. Higher COP

Bell-Coleman Cycle (Reverse Brayton Cycle) :

- It is a air refrigeration cycle where refrigerant is air.
- It consists of Compressor, A Cooler, an Expander and Refrigerator.



Bell-Coleman cycle is represented in P-V and T-S diagram below. It consists of two isentropic process and two isobaric process.



(a) P-V Diagram (b) T-S Diagram

Process 1-2 : Isentropic Compression Process :

- The cold air from the refrigerator enters the compressor

- Its pressure Increased by the compressor; hence temp. also increases.
- No heat added or extracted during this process.

Process 2-3 : Constant Pressure Cooling Process :

- Warm air passes through the cooler.
- Temp. reduced from T_2 to T_3 at constant pressure.
- Heat rejected by the air during this process

$$\mathbf{Q_R = Q_{2\text{-}3} = C_p\,(T_2 - T_3)}$$

Process 3-4 : Isentropic Expansion Process :

- Air enters the expander and expanded from pressure P_3 to P_4 .
- Temp. decreases from T_3 to T_4.
- No head added or extracted.

Process 4-1 : Constant Pressure Expansion Process :

- The cold air passes through refrigerator
- It is expanded at constant pressure.
- Temp. increases from T_4. To T_1
- Head absorbed by the air during this process

$$\mathbf{Q_A = Q_{4\text{-}1} = C_p\,(T_1 - T_4)}$$

We know that the work done during the cycle per kg of air

= Heat rejected – Heat absorbed

$$= \mathbf{Q_R - Q_A = C_p\,(T_2 - T_3) - C_p\,(T_1 - T_4)}$$

Coefficient of performance,

$$\text{COP} = \frac{\text{Heat absorbed}}{\text{Work done}}$$

$$= \frac{C_P(T_1 - T_4)}{C_P(T_2 - T_3) - C_P(T_1 - T_4)}$$

$$= \frac{(T_1 - T_4)}{(T_2 - T_3) - (T_1 - T_4)}$$

$$\text{COP} = \frac{T_4\left(\frac{T_1}{T4} - 1\right)}{T_4\left(\frac{T_2}{T_3} - 1\right) - T_4\left(\frac{T_1}{T_4} - 1\right)}$$

where $\gamma = Cp/Cv$

For isentropic expansion process 3-4:

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{y-\mathbf{1}}{y}}$$

Since, $P_2 = P_3$ and $P_1 = P_4$, therefore from the above equations:

$$\frac{T_2}{T_{14}} = \frac{T_3}{T_4} \text{ or } \frac{T_2}{T_3} = \frac{T_1}{T_4}$$

Substituting this in the COP equation:

$$\textbf{COP} = \frac{\boldsymbol{T_4}}{\boldsymbol{T_3 - T_4}} = \frac{\mathbf{1}}{\frac{\boldsymbol{T_3}}{\boldsymbol{TT}} - \mathbf{1}}$$

$$= \frac{\mathbf{1}}{\left(\frac{\boldsymbol{P_3}}{\boldsymbol{P_4}}\right)^{\frac{y-\mathbf{1}}{y}} - \mathbf{1}}$$

$$= \frac{\mathbf{1}}{\left(\frac{\boldsymbol{P_2}}{\boldsymbol{P_1}}\right)^{\frac{y-\mathbf{1}}{y}} - \mathbf{1}}$$

$$\textbf{COP} = \frac{\mathbf{1}}{(\boldsymbol{r_p})^{\frac{y-\mathbf{1}}{y}} - \mathbf{1}}$$

$\boldsymbol{r_p}$ **= Compression or expansion ration =** $\frac{\boldsymbol{P_2}}{\boldsymbol{P_1}} = \frac{\boldsymbol{P_3}}{\boldsymbol{P_4}}$

Advantages of the Bell Coleman air refrigeration system

1. Cheap and abundant refrigerant, highly reliable: Air is used as refrigerant, which is easily available and inexpensive.
2. Charging of refrigerant is very easy.
3. Design and construction are simple, no complicated parts and its maintenance cost is low.
4. Refrigerant (Air) is non-toxic, non-flammable, non-corrosive. There is no danger of any kind of leakage.
5. There is no phase change (liquid- gas) during the operation of system.
6. The cold air can be directly used for refrigeration; it is useful in aircraft refrigeration at high altitude.
7. There would be no significant change in the performance of air refrigeration if it is operated much away from its design conditions.
8. It can produce very high temperature differences between hot and cold region. So, the same system can be used for both cooling and heating effects. It also helps to achieve very low temperature.

9. Air refrigeration is used in aircraft due to availability cold air at high altitude and it can achieve both air-conditioning, as well as the pressurization of the cabin.

Disadvantages of the Bell Coleman air refrigeration system

1. Lower C.O.P. compared to other refrigeration cycle.
2. Running cost is high.
3. The mass of air required to circulate in the system is very high when compared to other type of refrigeration cycle due to low specific heat capacity.
4. System components are bulky, large space per ton of refrigeration.
5. The chance of frosting at expander is more due to moisture content in the air.
6. Air contains pollutant particle, so do regular cleaning of air filter in open system.

NUMERICALS

1. In a refrigeration plant working on Bell Coleman cycle, air is compressed to 5 bars from 1 bar. Its initial temperature is 10°C. After compression, the air is cooled up to 20°C in a cooler before expanding back to a pressure of 1 bar. Determine the theoretical C. O.P. of the plant and net refrigerating effect. Take cp = 1.005 kJ /kg K and cv = 0.718 kJ/kg K.

Solution. Given : $p_2 = p_3 = 5$ bar; $p_1 = p_4 = 1$ bar; T1 = 10°C = 10 + 273 = 283 K ; T3 = 20°C = 20 + 273 = 293 K; Cp = 1.005 kJ/kg K; cv= 0.718 kJ/kg K

The p-v and T-s diagrams for a refrigeration plant working on Bell-Coleman cycle, is shown in Fig. (a) and (b) respectively.

Let T_2 and T_4 = Temperature of air at the end of compression and expansion respectively.

We know that isentropic index for compression and expansion process,

$$\gamma = \frac{Cp}{Cv} = 1.005/0.718 = 1.4$$

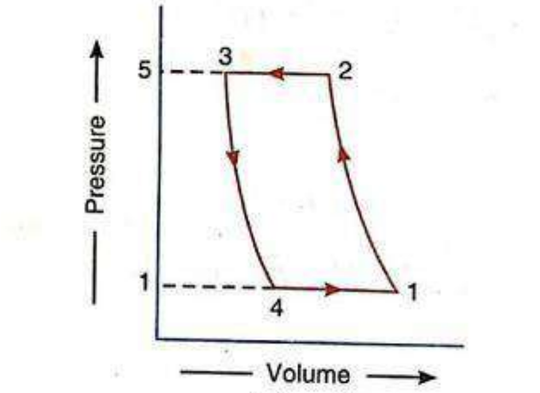
For isentropic compression 1-2,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{y-1}{y}} = \left(\frac{5}{1}\right)^{\frac{1.4-1}{1.4}} = 5^{0.286} = 1.584$$

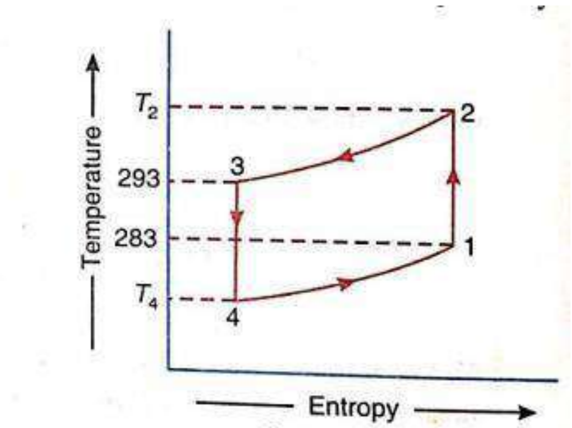
For isentropic expansion 3-4

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{y-1}{y}} = \left(\frac{5}{1}\right)^{\frac{1.4-1}{1.4}} = 5^{0.286} = 1.584$$

$$T_4 = T_3 / 1.0586 = 185 \text{ K}$$



(a) p-v diagram.



(b) T-s diagram.

Theoretical COP of the plant

$$\text{COP} = \frac{T_4}{T_3 - T_4} = \frac{185}{293 - 185} = 1.713$$

Net refrigerating effect :

$$\text{RE} = C_P\,(T_1 - T_4) = 1.005\,(283\text{-}185) = 98.5 \text{ kJ/kg}$$

2. ***A refrigerator working on Bell-Coleman cycle operates between pressure limits of 1.05 bar and 8.5 bar. Air is drawn from the cold chamber at 10°C, compressed and then it is cooled to 30°C before entering the expansion cylinder. The expansion and compression follows the law $pv^{1.3}$ = constant. Determine the theoretical C.O.P. of the system.***

Solution. Given : $p_1 = p_4 = 1.05$ bar; p_2: $= p_3 = 8.5$ bar; $T_1 = 10°C = 10 + 273 = 283$ K ; $T_3 = 30°C = 30 + 273 = 303$ K ; n = 1.3 The p-v and T-s diagrams for a refrigerator working on the Bell-Coleman cycle is shown in Fig. (a) and (b) respectively.

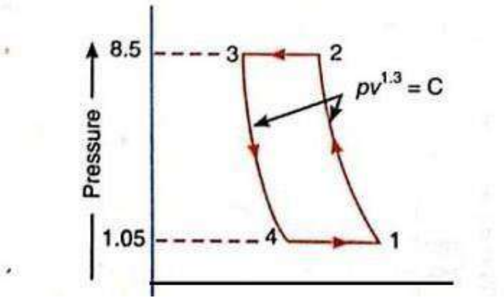
Let T_2 and T_4 = Temperature of air at the end of compression and expansion respectively. Since the compression and expansion follows the law $pv^{1.3} = C$, therefore

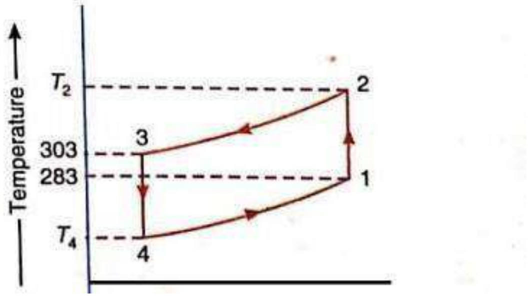
$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = \left(\frac{8.5}{1.05}\right)^{\frac{1.3-1}{1.3}} = 8.1^{0.231} = 1.62$$

$$T_2 = T_1 \times 1.62 = 283 \text{ X } 1.62 = 458.5 \text{ K}$$

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{n-1}{n}} = \left(\frac{8.5}{1.05}\right)^{\frac{1.3-1}{1.3}} = 1.62$$

$$T_4 = T_3 / 1.62 = 303 / 1.62 = 187 \text{ K}$$





We know the theoritical COP

$$\text{COP} = \frac{T_1 - T_4}{\frac{n}{n-1} \times \frac{\gamma-1}{\gamma}[(T_2 - T_3) - (T_1 - T_4)]}$$

$$= \frac{283-187}{\frac{1.3}{1.3-1} X \frac{1.4-1}{1.4} X ((458.5-303)-(283-187))}$$

$$\frac{96}{1.24 X 59.5} = 1.3$$

SHORT QUESTIONS WITH ANSWERS

1. Define COP? [2010, 2009S, 2007S, 2006S, 2012]

Ans : It is the ratio of refrigerating effect produced to the work done.

$$\text{COP} = \frac{Q}{W}$$

Q = Refrigerating effect produced

W = Work done on the system

2. Define tonne of refrigeration? Define Unit of refrigerating effect? [2020W, 2010S, 2009S, 2007S, 2006S, 2014S]

It is the amount of Refrigerating effect produced by uniform melting of 1 tonne of ICE from and at 0^0C in 24 hours.

But latent heat of Ice is 335 KJ/Kg

So, 1 TR = 335 X 1000 KJ in 24 hour

$$= \frac{1000X335}{24x60} = 232.6 \text{ KJ/min}$$

- But in actual practice 1 TR = 210 KJ/min

3. What is refrigeration? [2009S, 2009BP, 2020W]

Ans : Refrigeration is the process of cooling a body below the temperature of its surroundings.

4. Define Open Air Refrigeration Cycle? [2007S]

In this cycle, air is directly led to the space to be cooled, allowed to circulated through the cooler and then returned to the compressor to start another cycle.

5. Define Closed Air Refrigeration Cycle.

Here the air is passed through the pipes. Air is used for absorbing heat from the other fluid (Brine) and thus cooled brine is circulated in the space to be cooled.

Simple Vapour Compression Refrigeration System

Learning Objectives:

schematic diagram of simple vapors compression refrigeration system'

Types

Cycle with dry saturated vapors after compression.

Cycle with wet vapors after compression.

Cycle with superheated vapors after compression.

Cycle with superheated vapors before compression.

Cycle with sub cooling of refrigerant

Representation of above cycle on temperature entropy and pressure enthalpy diagram

Numerical on above (determination of COP, mass flow)

Introduction

A vapour compression refrigeration system is an improved type of air refrigeration system in which a suitable working substance, termed as refrigerant, is used. It condenses and evaporates at temperatures and pressures close to the atmospheric conditions. The refrigerants, usually, used for this purpose are ammonia (NH_3), carbon dioxide (CO_2) and Sulphur dioxide (SO_2). The refrigerant used, does. not leave the system, but is circulated throughout the system alternately condensing and evaporating. In evaporating, the refrigerant absorbs its latent heat from the brine (salt water) which is used for circulating it around the cold chamber. While condensing, it gives out its latent heat to the circulating water of the cooler. The vapour compression refrigeration system is, therefore a latent heat pump, as it pumps its latent heat from the brine and delivers it to the cooler.

Schematic diagram of simple vapour compression refrigeration compression:

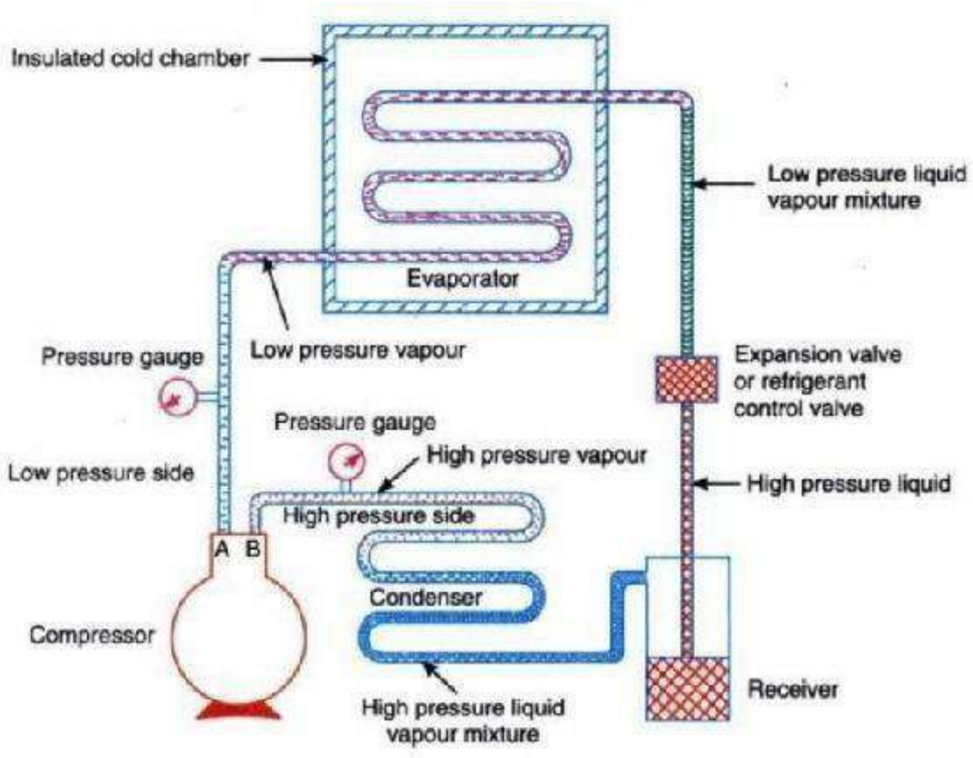


Fig. . Simple vapour compression refrigeration system.

A simple vapour compression refrigeration system consists of the following five essential parts:

- **Compressor**: The low pressure and temperature vapour refrigerant from evaporator is drawn into the compressor through the inlet or suction valve A, where it is compressed to a high pressure and temperature. This high pressure and temperature vapour refrigerant is discharged into the condenser through the delivery valve B.
- **Condenser**: The condenser or cooler consists of coils of pipe in which the high pressure and temperature vapour refrigerant is cooled and condensed. the refrigerant, while, passing through the condenser, gives up its latent heat to the surrounding condensing medium which is normally air or water.
- **Receiver**: The condensed liquid refrigerant from the condenser is stored in a vessel known as receiver from where it is supplied to the evaporator through the expansion valve or refrigerant control valve.

- **Expansion valve**: It is also called throttle valve or refrigerant control valve. The function of the expansion valve is to allow the liquid refrigerant under high pressure and temperature to pass at a controlled rate after reducing its pressure and temperature. Some of the liquid refrigerant evaporates as it passes through the expansion valve, but the greater portion is vaporized in the evaporator at the low pressure and temperature.
- **Evaporator**: An evaporator consists of coils of pipe in which the liquid-vapour refrigerant at low pressure and temperature is evaporated and changed into vapour refrigerant at low pressure and temperature. In evaporating, the liquid vapour refrigerant absorbs its latent heat of vaporization from the medium (air, water or brine) which is to be cooled.

Note: In any compression, refrigeration system, there are two different pressure conditions. One is called the high-pressure side and other is known as low pressure side. The high-pressure side includes the discharge line (i.e. piping from delivery valve B to the condenser), condenser, receiver and expansion valve. The low-pressure side includes the evaporator, piping from the expansion valve to the evaporator and the suction line (i.e. piping from the evaporator to the suction valve A).

Types of Vapours compression refrigeration system

Cycle with dry saturated vapours after compression.

Cycle with wet vapours after compression.

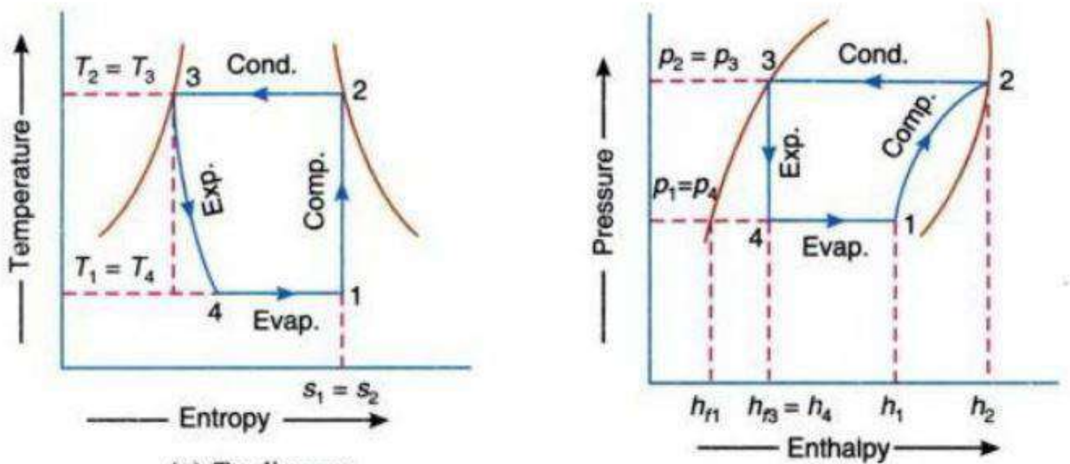
Cycle with superheated vapours after compression.

Cycle with superheated vapours before compression.

Cycle with sub cooling of refrigerant

Theoretical Vapour Compression Cycle with Dry Saturated Vapour after Compression

A vapour compression cycle with ***dry saturated vapour after compression*** is shown on T-s and p-h diagrams below.



(*a*) *T-s* diagram.

(*b*) *p-h* diagram.

Fig. Theoretical vapour compression cycle with dry saturated vapour after compression.

1. **Compression process**: The vapour refrigerant at low pressure p1 and temperature T_1 is compressed isentropically to dry saturated vapour as shown by the vertical line 1-2 on T-s diagram and by the curve 1-2 on p-h diagram. The pressure and temperature rise from p_1 to p_2 and T_1 to T_2 respectively.

The Work done during isentropic compression per kg of refrigerant is given by:

$$w = h_2 - h_1$$

Where h_1 = Enthalpy of vapour refrigerant at temperature T_I, i.e. at suction of the compressor, and h_2 = Enthalpy of the vapour refrigerant at temperature T_2, is i.e. at discharge of the compressor.

2. **Condensing process**: The high pressure and temperature vapour refrigerant from the compressor is passed through the condenser where it is completely condensed at constant pressure p_2 and temperature T_2, as shown by the horizontal line 2-3 on T-S and p-h diagrams. The vapour refrigerant is changed into liquid refrigerant. The refrigerant, while passing through the condenser, gives its latent heat to the surrounding condensing medium.

3. **Expansion process**: The liquid refrigerant at pressure $p_3 = p_2$ and temperature $T_3 = T_2$ is expanded by throttling process through the expansion valve to a low pressure p4 = p1 and temperature $T_4 = T_1$, as shown by the curve 3-4 on T-S diagram and by the vertical line 3-4 on p-h diagram. We have already discussed that some of the liquid refrigerant evaporates as it passes through the expansion valve; but the greater portion is vaporized in the evaporator. We know that during the throttling process, no heat is absorbed or rejected by the liquid refrigerant.

Notes:

(a) In case an expansion cylinder is used in place of throttle or expansion valve to expand the liquid refrigerant, then the refrigerant will expand isentropically as shown by dotted vertical line on T-S diagram. The isentropic expansion reduces the external work being expanded in running the compressor and increases the refrigerating effect. Thus, the net result of using the expansion cylinder is to increase the coefficient of performance.

Since the expansion cylinder system of expanding the liquid refrigerant is quite complicated and involves greater initial cost, therefore its use is not justified for small gain in cooling capacity. Moreover, the flow rate of the refrigerant can be controlled with throttle valve which is not possible in case of expansion cylinder which has a fixed cylinder volume.

(b) In modern domestic refrigerators, a capillary (small bore tube) is used in place of an expansion valve.

4. **Vaporizing process**: The liquid-vapour mixture of the refrigerant at pressure $p_4 = p_1$ and temperature $T_4=T_1$ is evaporated and changed into vapour refrigerant at constant pressure and temperature, as shown by the horizontal line 4-1 on T-S and p-h diagrams. During evaporation, the liquid-vapour refrigerant absorbs its latent heat of vaporisation from the medium (air, water or brine) which is to be cooled. This heat which is absorbed by the refrigerant is called refrigerating effect and it is briefly written as RE. The process of vaporisation continues up to point 1 which is the starting point and thus the cycle is completed. The refrigerating effect or the heat absorbed or extracted by the liquid-vapour refrigerant during evaporation per kg of refrigerant is given by:

$$\boldsymbol{R_E = h_1 - h_4 = h_1 - h_{f3}}$$

Where h_{f3} is the Sensible heat at temperature T_3, i.e. enthalpy of Liquid refrigerant leaving the condenser. It can be noticed from the cycle that the liquid-vapour refrigerant has extracted heat during evaporation and the work will be done by the compressor for isentropic compression of the high pressure and temperature vapour refrigerant.

$$\mathbf{COP} = \frac{\textbf{Refrigerating effect}}{\textbf{Work Done}} = \frac{(\mathbf{h1 - h4})}{(\mathbf{h2 - h1})}$$

Numerical: 01

In an ammonia vapour compression system, the pressure in the evaporator is 2 bar. Ammonia at exit is 0.85 dry and at entry its dryness fraction is 0.19. During compression, the work done per kg of ammonia is 150 kJ. Calculate the C.O.P. and the volume of vapour entering the compressor per minute, if the rate of ammonia circulation is 4.5 kg/min. The latent heat and specific volume at 2 bar are 1325 kJ/kg and 0.58 m3/kg respectively.

Solution

Given: $p_1=p_4=2$ bar; $x_1=0.85$; $x_4=0.19$; w=150kJ/kg; $m_a=4.5$kg/min;

$h_{fg}=1325$kJ/hg; $v_g=0.58 m^3/kg$ C.O.P.

Since the ammonia vapour at entry to the evaporator (i.e. at point 4) has dryness fraction (x_4) equal to 0.19, therefore enthalpy at point 4,

$h_4=x_4 \times h_{fg}=0.19\times1325=251.75$kJ/kg

Similarly, enthalpy of ammonia vapour at exit i.e. at point 1,

$h_1=x_1 \times h_{fg}=1126.25$ KJ/kg

Therefore, heat extracted from the evaporator or refrigerating effect, $RE=h_1-h_4=1126.25-251.75=874.5$KJ/Kg

We know that work done during compression,

W=150 KJ/kg

Therefore

C.O.P=RE / W =874.5/150=5.83 **(Ans)**

Volume of vapour entering the compressor per minute

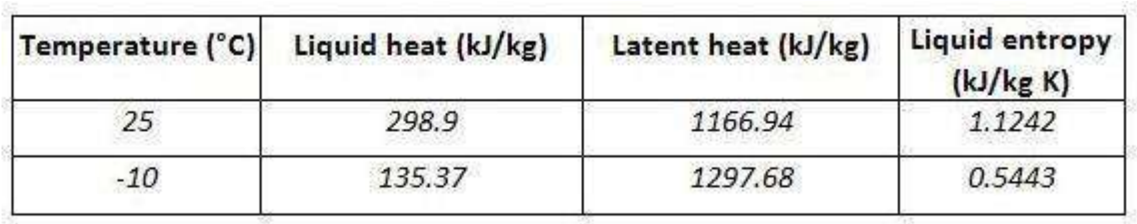
We know that volume of vapour entering the compressor per minute

= Mass of refrigerant/ min X Specific volume

= $ma \times v_g=4.5\times0.58=2.61 m^3/min$ **(Ans)**

Example-02

The temperature limits of an ammonia refrigerating system are 25° C and -10° C. If the gas is dry at the end of compression, calculate the coefficient of performance of the cycle assuming no undercooling of the liquid ammonia. Use the following table for properties of ammonia:



Temperature (°C)	Liquid heat (kJ/kg)	Latent heat (kJ/kg)	Liquid entropy (kJ/kg K)
25	*298.9*	*1166.94*	*1.1242*
-10	*135.37*	*1297.68*	*0.5443*

Solution

Given: $T_2=T_3=25°C=25+273=298K$; $T_1=T_4=-10°C=263K$; $h_{f3}=h_4=298.9KJ/kg$; $h_{fg2}=1166.94KJ/kg$; $s_{f2}=1.1242kJ/kgK$; $h_{f1}=135.37KJ/kg$; $h_{fg1}=1297.68KJ/kg$; $s_{f1}=0.5443KJ/kgK$

The T-s and p-h diagrams are shown in Fig (a) and (b) respectively.

Let x_1 = Dryness fraction at point 1.

We know that entropy at point 1,

$S_1 = S_{f1} + x_1 .. h_{fg1}/T_1$

$= 0.5443+ X_1 . (1297.68/ 263)$

$=0.5443+4.934x\ X_1$...........(i)

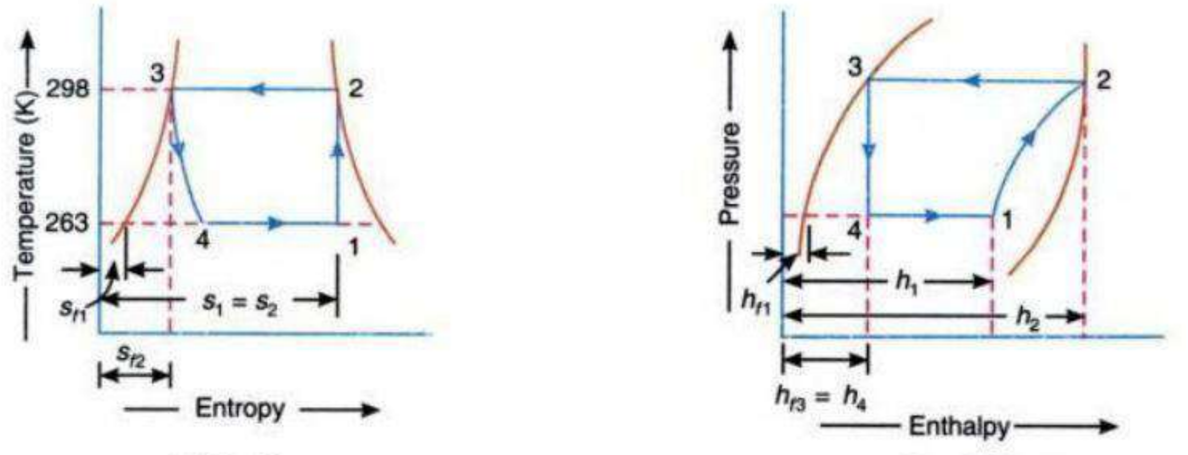
Similarly, entropy at point 2,

$S_2 = S_{f2}+ x_1 . h_{fg2}/T_2$

$=0.5443+1166.94/298=5.04$ (ii)

Since the entropy at point 1 is equal to entropy at point 2, therefore equating equations (i) and (ii),

$0.5443 + 4.934\ x_1 = 5.04$ or $x_1 = 0.91$



(*a*) *T-s* diagram.　　(*b*) *p-h* diagram.

We know that enthalpy at point 1,

$$h_1 = h_{f1} + x_1 h_{fg1} = 135.37 + 0.91 \times 1297.68 = 1316.26 \text{kJ/}$$

and enthalpy at point 2,

$$h_2 = h_{f2} + hf_{g2} = 298.9 + 1166.94 = 1465.84 \text{kJ/}$$

Therefore coefficient of performance of the cycle

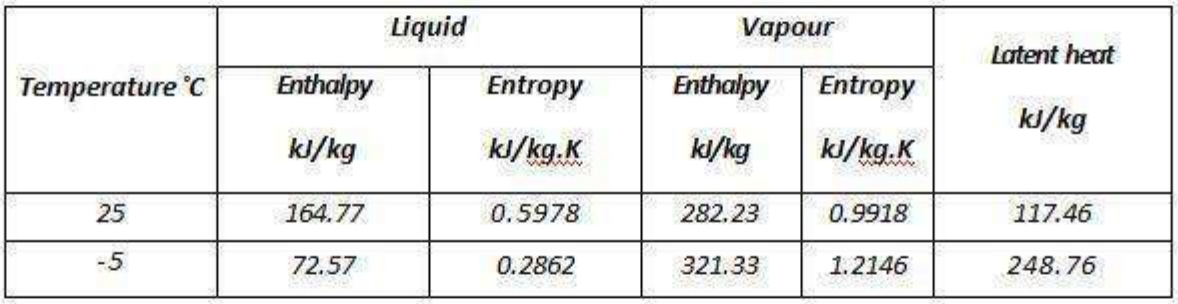
$$= \frac{h1 - hf3}{h2 - h1}$$

$$= \frac{1316.26 - 298.9}{1465.84 - 1316.26} \textbf{ (Ans)}$$

Theoretical Vapour Compression Cycle with Wet Vapour after Compression

Example 4

Find the theoretical C.O.P. for a CO_2 machine working between the temperature range of 25°C and - 5°C. The dryness fraction of CO_2 gas during the suction stroke is 0.6. Following properties of CO_2 are given



Temperature °C	Liquid		Vapour		Latent heat kJ/kg
	Enthalpy kJ/kg	Entropy kJ/kg.K	Enthalpy kJ/kg	Entropy kJ/kg.K	
25	164.77	0.5978	282.23	0.9918	117.46
-5	72.57	0.2862	321.33	1.2146	248.76

Solution

Given: $T_2=T_3=25°C=25+273=298K$; $T_1=T_4=-5°C=-5+273=268K$; $x_1=0.6$; $h_{f3}=hf2=164.77kJ/kg$; $h_{f1}=h_{f4}=72.57kJ/kg$; $s_{f2}=0.5978kJ/kgK$; $s_{f1}=0.2862kJ/kgK$; $h'_2=282.23kJ/kg$; $h'1=321.33kJ/kg$; $s'_2=0.9918kJ/kgK$; $s'_1=1.2146kJ/kgK$; $h_{fg2}=117.46kJ/kg$; $h_{fg1}=248.76kJ/kg$

The T-s and p-h diagrams are shown below.

First of all, let us find the dryness fraction at point 2, i.e. x_2.

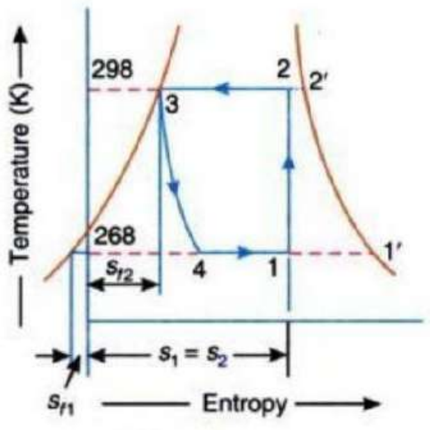
We know that the entropy at point 1,

$$S_1=S_{f1}+X_1h_{fg1}/T_1=0.2862+0.6\times 248.76/268=0.8431\ldots(i)$$

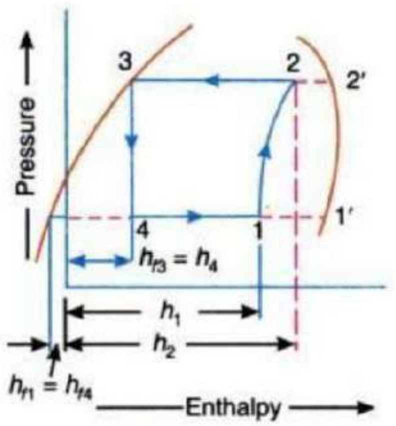
Similarly, entropy at point 2,

$$s_2=s_{f2}+X_{2.}\,hf_{g2}/T_2=0.5978+x_2\times 117.64/298s$$

$$=0.5978=0.3941x_2\ldots\ldots\ldots\ldots(ii)$$



(*a*) *T-s* diagram.



(*b*) *p-h* diagram.

OR $X_2 = 0.622$

We know that enthalpy at point 1,

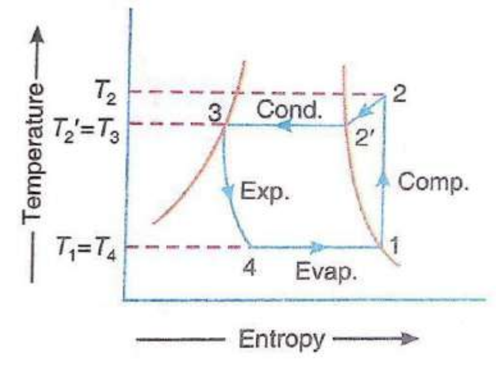
$h_1=h_{f1}+x_1\,h_{fg1} = 72057 + 0.6 \times 248.76 = 221.83$ kJ/Kg

enthalpy at point 2,

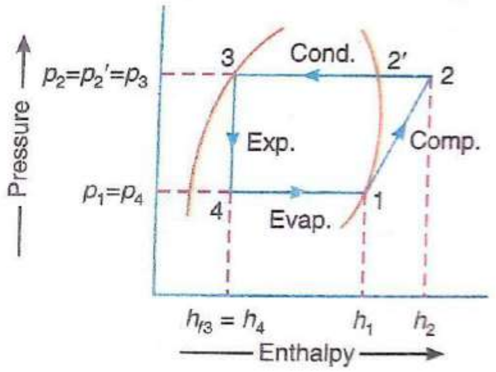
$h_1=h_{f1}+x_2\,h_{fg2} = 164.77 + 0.622 \times 117.46 = 237.83$ kJ/Kg

Theoretical COP $= = \frac{h1-hf3}{h2-h1} = \frac{221.83-164.77}{237.83-221.83} = 57.06/16 = 3.57$

Theoretical Vapour Compression Cycle with Superheated Vapour after Compression :



(a) T-s diagram.



(b) p-h diagram.

A vapour compression cycle with super-heated vapour after compression is shown on T-s and p-h diagram. In this cycle, the enthalpy at point 2 is found out with the help of degree of superheat. The degree of superheat may be found out by equating the entropies at point 1 and 2.

Now the COP can be found out by the formula

$$\text{COP} = \frac{Refrigerating\ effect}{Work\ done} = = \frac{h_1 - h_{f3}}{h_2 - h_1}$$

A little consideration will show that the superheating increases the refrigerating effect and the amount of work done in the compressor. Since the increase in refrigerating effect is less as compared to increase in work done, therefore, the net effect of superheating is to have low coefficient of performance

Example 1

A vapour compression refrigerator uses methyl chloride (R-40) and operates between temperature limits of -10°C and 45°C. At entry to the compressor, the refrigerant is dry saturated and after compression it acquires a temperature of 60°C. Find the C.O.P. of the refrigerator. The relevant properties of methyl chloride are as follows

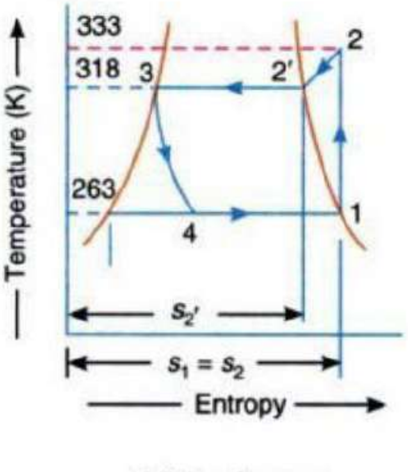
Saturation temp in ^{0}C	**Enthalpy in kJ/Kg**		***Entropy in kJ/Kg K***	
	Vapour	***Liquid***	***Liquid***	***Vapour***
-10^{0}C	***460.7***	***45.4***	***0.183***	***1.637***

45^{0}C	***483.6***	***133.0***	***0.485***	***1.587***

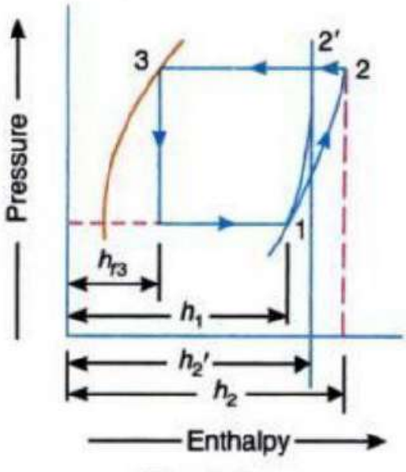
.

Solution Given : T_1= T_4 = -10° C = −10+273=263 K ;

T'_2T_3=45° C = 45+273 = 318 K ;T_2= 60° C = 60+273 = 333 K ; h_{f1}=45.4 kJ/kg ; h_{f3}=133 KJ/kg ; h1=460.7 ; $h_{2'}$=483.6 KJ/kg ; s_{f1}=0.183 kJ/kg K ; s_{f3}=0.485 KJ/kg K ;s_1=s_2=1.637 KJ/kg K ; s'_2=1.587 KJ/kg K



(*a*) *T-s* diagram.



(*b*) *p-h* diagram.

Let Cp = Cp= Specific heat at constant pressure for superheated vapour.

We know that entropy at point 2,

S_2= S_2'+2.3 $C_{p.}$ log(T_2/T'_2)

1.637=1.587+2.3 C_p log(338/318)

1.637 =1.587+2.3× C_p ×0.02=1.587+0.046cp

Therefore c_p=1.09

and enthalpy at point 2,

h_2=h_2'+ C_p × Degree of superheat

h_2=h_2'+ C_p (T_2−T'_2)

= 483.6+1.09 (333−318)= 500 kJ/kg

Therefore

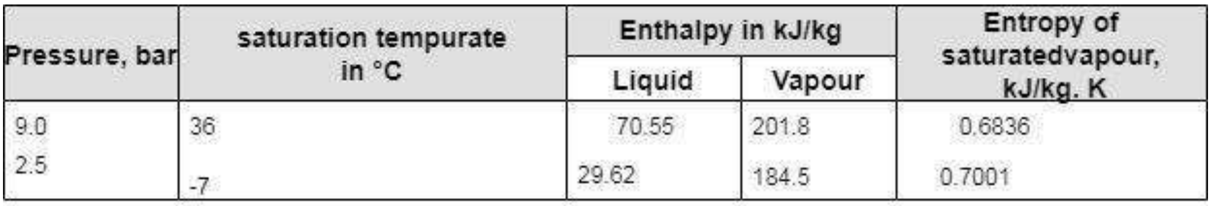
C.O.P. of refrigerator

$=\frac{h1-hf3}{h2-h1}=\frac{460.7-133}{500-46.7}$ =8.34

Example 2

A refrigeration machine using R-12 as refrigerant operates between the pressures 2.5 bar and 9 bar. The compression is isentropic and there is no undercooling in the condenser.

The vapour is in dry saturated condition at the beginning of the compression. Estimate the theoretical coefficient of performance. If the actual coefficient of performance is 0.65 of theoretical value, calculate the net cooling produced per hour. The refrigerant flow is 5 kg per minute. Properties of refrigerant are



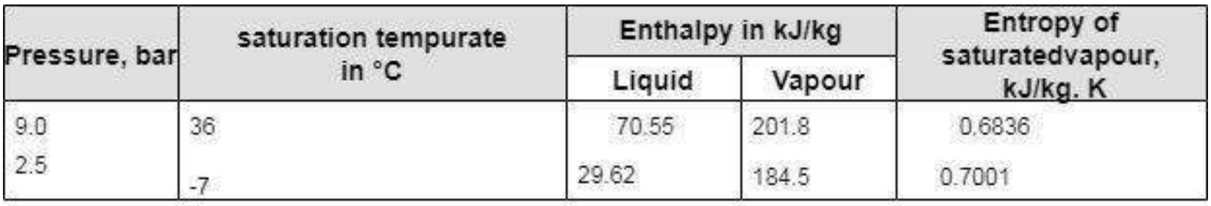
Pressure, bar	saturation tempurate in °C	Enthalpy in kJ/kg		Entropy of saturatedvapour, kJ/kg. K
		Liquid	Vapour	
9.0	36	70.55	201.8	0.6836
2.5	-7	29.62	184.5	0.7001

Take C_p for superheated vapour at 9 bar as 0.64 kJ/kg K.

Solution

Given : $T'_2=T_3= 36°C= 36+273 = 309K; T_1=T_4=-7°C=-7+273=266K;$

$T_2'=T_3=36°C=36+273=309K;T_1=T_4=-7°C=-7+273=266K;$ (C.O.P)actual=0.65 (C.O.P)th, (C.O.P)actual= 0.65 (C.O.P)th; m=5kg/min; $h_{f3}=h4=70.55$ kJ/kg; $h_{f1}=h_{f4}=29.62$kJ/kg; $h_{'2}=201.8$kJ/kg; $h_1=184.5$kJ/kg; $S'_2=0.6836$kJ/kgK; $s_1=s_2=0.7001$kJ/kgK; $c_p=0.64$kJ/kgK



Pressure, bar	saturation tempurate in °C	Enthalpy in kJ/kg		Entropy of saturatedvapour, kJ/kg. K
		Liquid	Vapour	
9.0	36	70.55	201.8	0.6836
2.5	-7	29.62	184.5	0.7001

Theoretical coefficient of performance

First of all, let us find the temperature at point 2 (T2T2)

We know that entropy at point 2,

$s_2=s_2'+2.3c_p\log(T_2/T'_2)$

$0.7001=0.6836+2.3\times0.64\log(T_2/309)$

$\log(T_2/309)=\frac{0.7001-0.6836}{2.3 X 0.64}$

$\log(\frac{T2}{309}) = 1.026$ (Taking antilog of 0.0112)

Therefore

$T_2=1.026309=317$ k

We know that enthalpy of super heated vapour at point 2,

$$h_2 = h'_2+c_p(T2-T'2)$$

$$= 201.8 + 0.64\ (317-309) = 206.92\text{kJ/kg}$$

Therefore theoretical coefficient of performance,

$$(C.O.P)th = \frac{h1-hf3}{h2-h1} = \frac{184.5-70.55}{206.92-184.5} = 5.1 \textbf{ (Ans)}$$

Net cooling produced per hour

We also know that actual C.O.P. of the machine,

$$(C.O.P)actual=0.65\times(C.O.P)th=0.65\times5.1=3.315$$

and actual work done, $W_{actual}=h_2-h_1=206.92-184.5=22.42$ KJ/Kg

We know that net cooling (or refrigerating effect) produced per kg of refrigerant

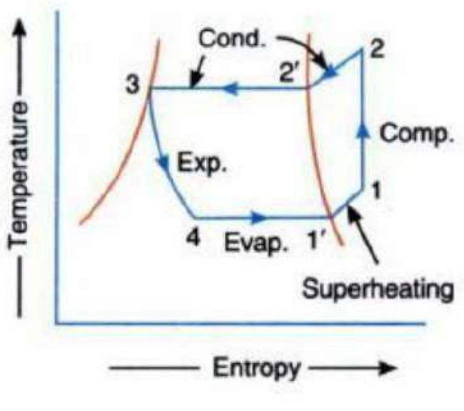
$$=W_{actual}\times(C.O.P)_{actual}=22.42\times3.315=74.3 \text{ KJ/Kg}$$

Therefore net cooling produced per hour

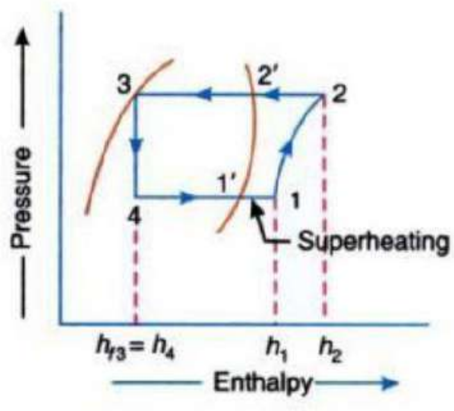
$$= m \times 74.3=5\times74.3=371.5\text{kJ/min}$$

$$= 371.5/210 = 1.77 \text{ TR}$$

2.2.4 Theoretical vapour Compression Cycle with superheated vapour before compression:



(a) T-s diagram.



(b) p-h diagram.

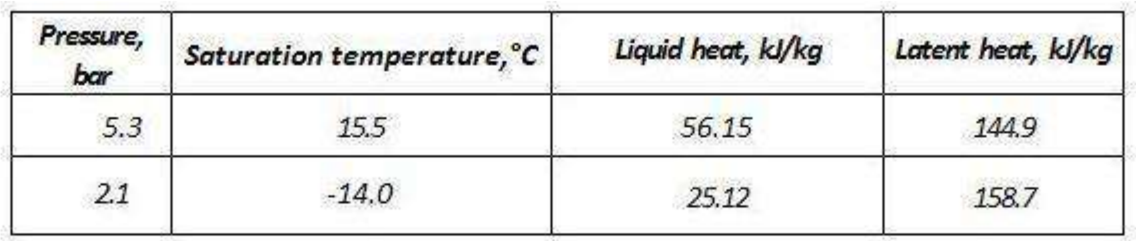
A vapour compression cycle with superheated vapour before compression is on T-s and p-h diagram. In this cycle the evaporation starts at point 4 and continues up to 1', when it is dry saturated. The vapour is now superheated before entering the compressor up to the point 1.

The COP can be found out by the formula

$$\textbf{COP} = \frac{Refrigerating\ effect}{Work\ done} = \frac{h1-hf3}{h2-h1}$$

Note: In this cycle, the heat is absorbed in two stages. Firstly, from point 4 to point 1' and secondly from point 1' to point 1. The remaining cycle is same as discussed in the previous article.

Example 1 : ***A vapour compression refrigeration plant works between pressure limits of 5.3 bar and 2.1 bar. The vapour is superheated at the end of compression, its temperature beign 37^{0}C. The vapour is superheated by 5 degree Celsius before entering the compressor. If the specific heat of superheated vapour is 0.63 kj/kg K, find the coefficient of performance of the plant. Use the date given in the table below.***



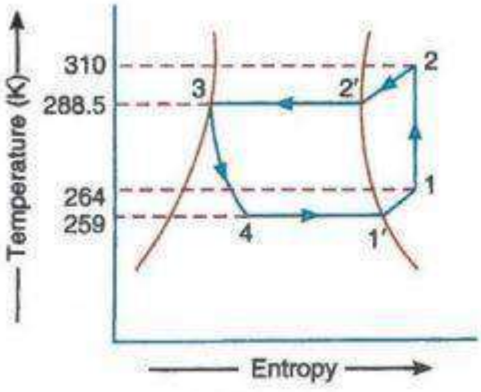
Pressure, bar	Saturation temperature,°C	Liquid heat, kJ/kg	Latent heat, kJ/kg
5.3	15.5	56.15	144.9
2.1	-14.0	25.12	158.7

Solution :

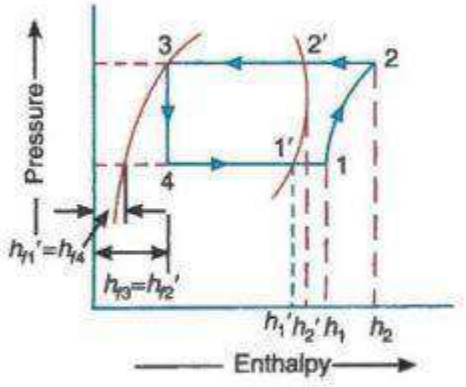
p_2=5.3bar; p_1=2.1bar; T_2=37°C =37+273=310K; $T_1-T'_1$=5°C; cp=0.63kJ /kgK ;

T'_2=15.5°C=15.5+273=288.5K; T'_1=−14°C= −14+273=259K;

h_{f3} =h'_{f2}=56.15kJ/kg; h'_{f1}=25.12kJ/kg; h'_{fg2}=144.9kJ/kg; h'_{fg1}=158.7kJ/kg



(a) T-s diagram.



(b) p-h diagram.

We know that enthalpy of vapour at point 1,

$$h_1=h'_1+c_p(T_1-T'_1)=(h'_{f1}+h'_{fg1})+c_p(T_1-T'_1)$$

$$=(25.12+158.7)+0.635=186.97$$

Similarly, enthalpy of vapour at point 2,

$$h_2=h'_2+c_p(T_2-T'_2)=(h'_{f2}+h'_{fg2})+c_p(T_2-T'_2)$$

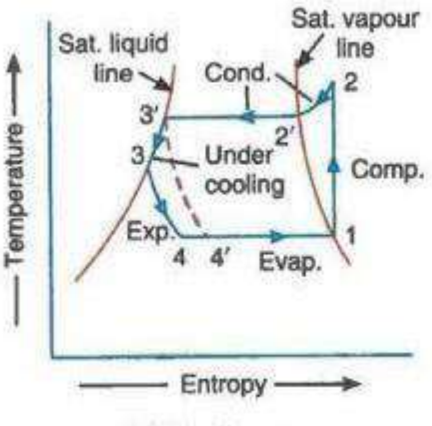
$$=(56.15+144.9)+0.63(310-288.5)=214.6$$

Therefore coefficient of performance of the plant,

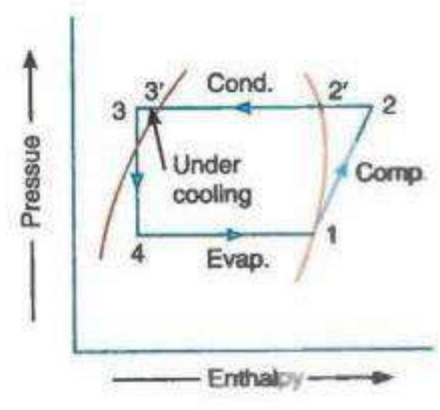
$$\text{C.O.P} = \frac{\boldsymbol{h1-hf3}}{\boldsymbol{h2-h1}} = \frac{\mathbf{186.97-56.15}}{\mathbf{214.6-186.97}} = \mathbf{4.735\ Ans}$$

2.2.5 Theoretical vapour compression cycle with under-cooling or Subcooling of refrigerant

Sometimes, the refrigerant, after condensation process 2’-3’, is cooled below the saturation temp (T3’) before expansion by throttling. Such a process is called undercooling or subcooling of the refrigerant and is generally done along the liquid line as shown in figure a and b . The ultimate effect of the undercooling is to increase the value of coefficient of performance under the same set of conditions. The process is generally brought about by circulating more quantity of cooling water through the condenser or by using water colder than the main circulating water. This act increases the refrigerating effect both by superheating and undercooling process as compared to a cycle without them



(a) T-s diagram.



(b) p-h diagram.

In this case, the refrigerating effect or heat absorbed or extracted

$$R_E = h_1 - h_4 = h_1 - h_{f3}$$

$$W = h_2 - h_1$$

$$\textbf{COP} = \frac{Refrigerating\ effect}{Work\ done} = \frac{h1 - hf3}{h2 - h1}$$

Note: The value of h_{f3} may be found out from the relation

$h_{f3} = h_{f3}'$ – Cp x Degree of undercooling

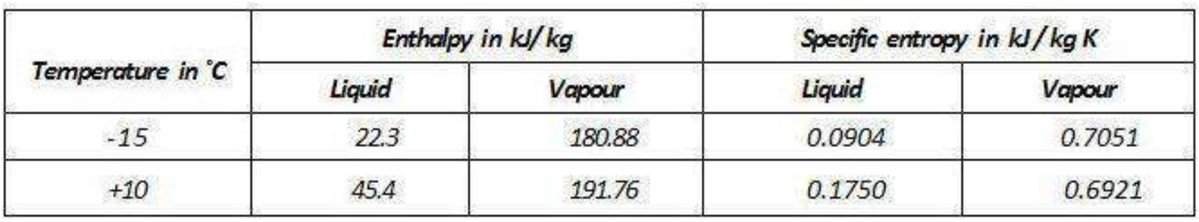
Numerical:

A vapour compression refrigerator uses R-12 as refrigerant and the liquid evaporates in the evaporator at - 15°C. The temperature of this refrigerant at the delivery from the compressor is 15°C , when the vapour is condensed at 10°C. Find the co-efficent of performance if

(i) there is no undercooling, and

(ii) (ii) the liquid is cooled by 5°C before expansion by throttling.

(iii) Take specific heat at constant pressure for the superheated vapour as 0.64 kJ/kg K and that for liquid as 0.94 kJ/kg K. The other properties of refrigerant are as follows



Temperature in °C	Enthalpy in kJ/ kg		Specific entropy in kJ / kg K	
	Liquid	Vapour	Liquid	Vapour
-15	22.3	180.88	0.0904	0.7051
+10	45.4	191.76	0.1750	0.6921

Solution

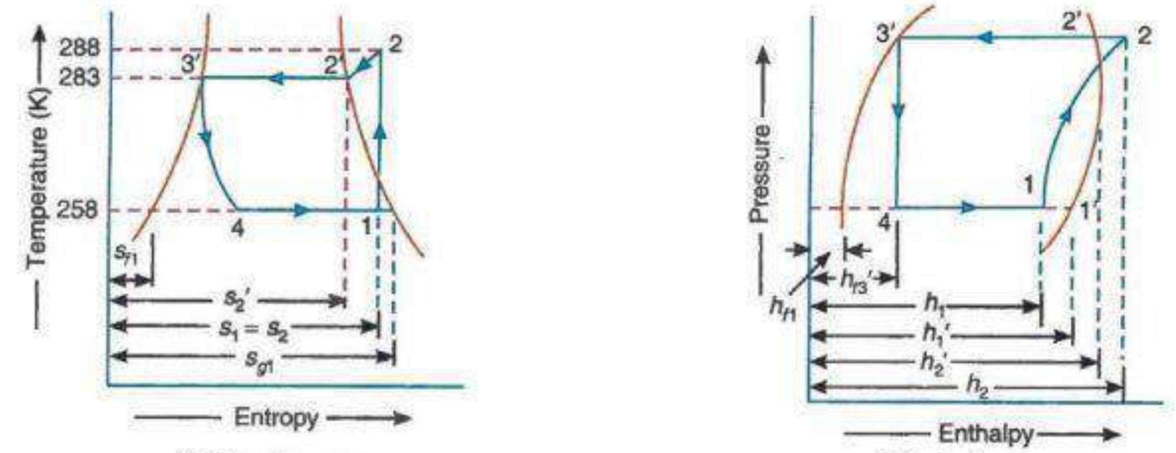
Given :

$T_1 = T_4 = -15°C = -15+273 = 258K$; $T_2 = 15°C = 15+273 = 288K$; $T'_2 = 10°C = 10+273 = 283K$; Cpv=0.64kJ/kgK; Cp1=0.94kJ/kgK;

h_{f1}=22.3kJ/kg; h_{f3}=45.4kJ/kg; h'_1= 180.88kJ/kg; h'_2=19.76kJ/kg; S_{f1}=0.0904kJ/kg; S_{f3}=0.1750kJ/kgK; S_{g1}=0.7051kJ/kgK; S'_2=0.6921kJ/kgK

(i) Coefficient of performance if there is no undercooling

The T-s and p-h diagrams, when there is no undercooling, are shown in Fig a and b respectively.



(*a*) *T-s* diagram.

(*b*) *p-h* diagram.

Let x_1=Dryness fraction of the refrigerant at point 1.

We know that entropy at point 1,

$$S_1=S_{f1}+X_1\,S_{fg1}=S_{f1}+X_1\,(S_{g1}-S_{f1})$$

$$=0.0904+X_1\,(0.7051-0.0904)$$

$$=0.0904+0.6147\,X_1 \text{..............(i)}$$

and entropy at point 2,

$$S_2=S_2'+2.3\ C_{pv}\log\left(\frac{T_2}{T_{2F}}\right)$$

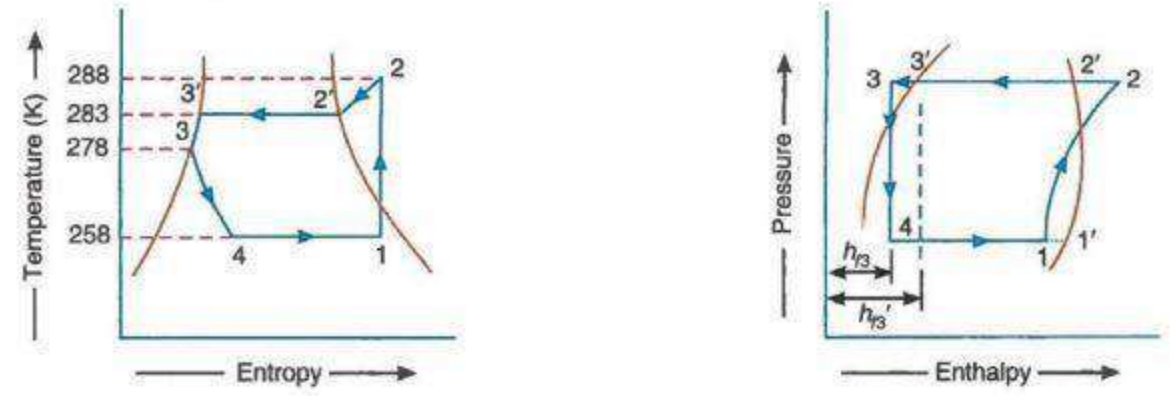
$$=0.6921+2.3\times0.64\times\log\left(\frac{288}{283}\right)$$

$$=0.7034$$

Since the entropy at point 1 is equal to entropy at point 2, therefore equating equations (i) and (ii),

$$0.0904+0.6147x_1=0.7034$$

or $x_1= 0.997$



(a) T-s diagram.   (b) T-s diagram.

Fig. 4.20

We know that the enthalpy at point 1,

$$h_1 = h_{f1} + xh_{fg1} = h_{f1} + x(h_{g1} - h_{f1})$$

$$= 22.3 + 0.997(180.88 - 22.3) = 180.4 \text{kJ/kg}$$

and enthalpy at point 2,

$$h_2 = h'_2 + Cpv\,(T_2 - T_{'2})$$
$$= 191.76 + 0.64\,(288 - 22.3) = 194.96 \text{kJ/kg}$$

Therefore

$$\text{C.O.P} = \frac{h1 - hf3}{h2 - h1} = \frac{180.4 - 45.4}{194.96 - 180.4} = \mathbf{9.27}$$

(ii) Coefficient of performance when there is an undercooling of 5 °C

The T-s and p-h diagrams, when there is an undercooling of 5^0 C, are shown in below (a) and (b) respectively.

We know that enthalpy of liquid refrigerant at point 3

$$h_{f3} = h_{f3}' - Cpl \times h_{f3} = h_{f3}' - cp1 \times \text{degree of undercooling}$$

$$= 45.4 - 0.94 \times 5 = 40.7 \text{kJ/kg}$$

Therefore

$$\text{C.O.P} = \frac{h1-hf3}{h2-h1} = \frac{180.4-40.4}{194.96-180.4} = \mathbf{9.59}$$

2.2.6 Pressure-Enthalpy (p-h) Chart

The most convenient chart for studying the behaviour of a refrigerant is the p-h chart, in which the vertical ordinates represent pressure and horizontal ordinates represent enthalpy (i.e. total heat). A typical chart is shown above. in which a few important lines of the complete chart are drawn. The saturated liquid line and the saturated vapour line merge into one another at the critical point.

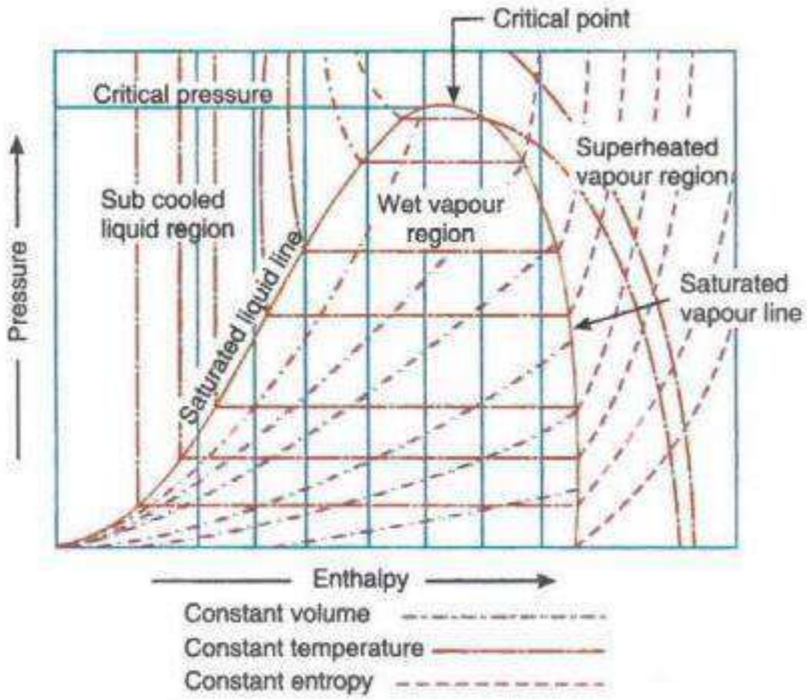


Fig. 4.2. Pressure - enthalpy (p-h) chart.

A saturated liquid is one which has a temperature equal to the saturation temperature corresponding to its pressure. The space to the left of the saturated liquid line will, therefore, be sub-cooled liquid region. The space between the liquid and the vapour lines is called wet vapour region and to the right of the saturated vapour line is a superheated vapour region.

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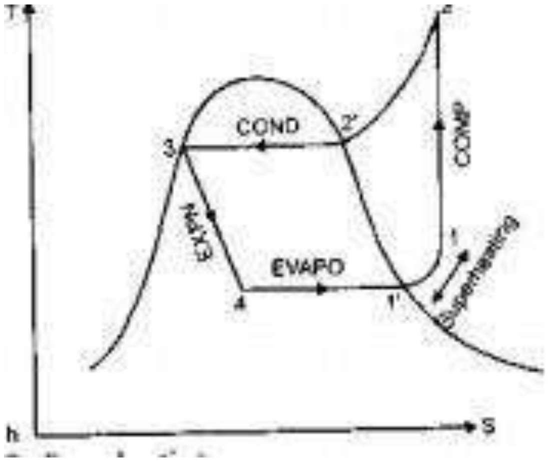
SHORT QUESTIONS WITH ANSWER

1. Draw the P-H diagram of vapour compression refrigeration system. [2009BP]

Ans:



2. Name the components of vapour compression refrigeration system? [2007S]

Ans: Compressor, Condenser, Receiver, Expansion valve/ Capillary tube, Evaporator.

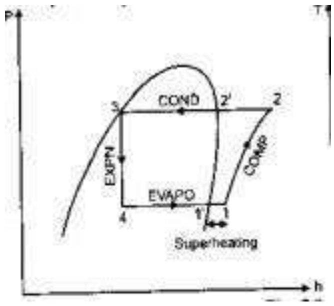
3. What will happened if we use expansion valve in place of throttle valve or capillary tube ?

In case an expansion cylinder is used in place of throttle or expansion valve to expand the liquid refrigerant, then the refrigerant will expand isentropically as shown by dotted vertical line on T-S diagram. The isentropic expansion reduces the external work being expanded in running the compressor and increases the refrigerating effect. Thus, the net result of using the expansion cylinder is to increase the coefficient of performance.

4. What is cooling tower? [2018]

Ans: A cooling tower is a specialized heat exchanger in which air and water are brought into direct contact with each other in order to reduce the water's temperature. As this occurs, a small volume of water is evaporated, reducing the temperature of the water being circulated through the tower.

5. Draw the P-h diagram with super heated refrigerant before compression. [2017S]



5. What is the function of solenoid valve in vapour compression refrigeration system? [2014W]

The solenoid valve is used in the refrigeration system to prevent the refrigerating fluid from the high-voltage part from entering the evaporator when the compressor stops. And it also avoids an excessively high low-pressure when the compressor is started next time so as to prevent compressor liquid hammer.

6. Why expansion cylinder are not used in domestic refrigerator?

Ans : Since the expansion cylinder system of expanding the liquid refrigerant is quite complicated and involves greater initial cost, therefore its use is not justified for small gain in cooling capacity. Moreover, the flow rate of the refrigerant can be controlled with throttle valve which is not possible in case of expansion cylinder which has a fixed cylinder volume.

LONG QUESTIONS:

1. Explain the vapour compression refrigeration system with neat sketch?

2. Compare between vapour compression and vapour absorption system?

3. What are the factors affecting the performance of simple vapour compression refrigeration system?

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VAPOUR ABSORPTION REFRIGERATION SYSTEM

Learning Objectives:

Simple vapor absorption refrigeration system

Practical vapor absorption refrigeration system

COP of an ideal vapor absorption refrigeration system

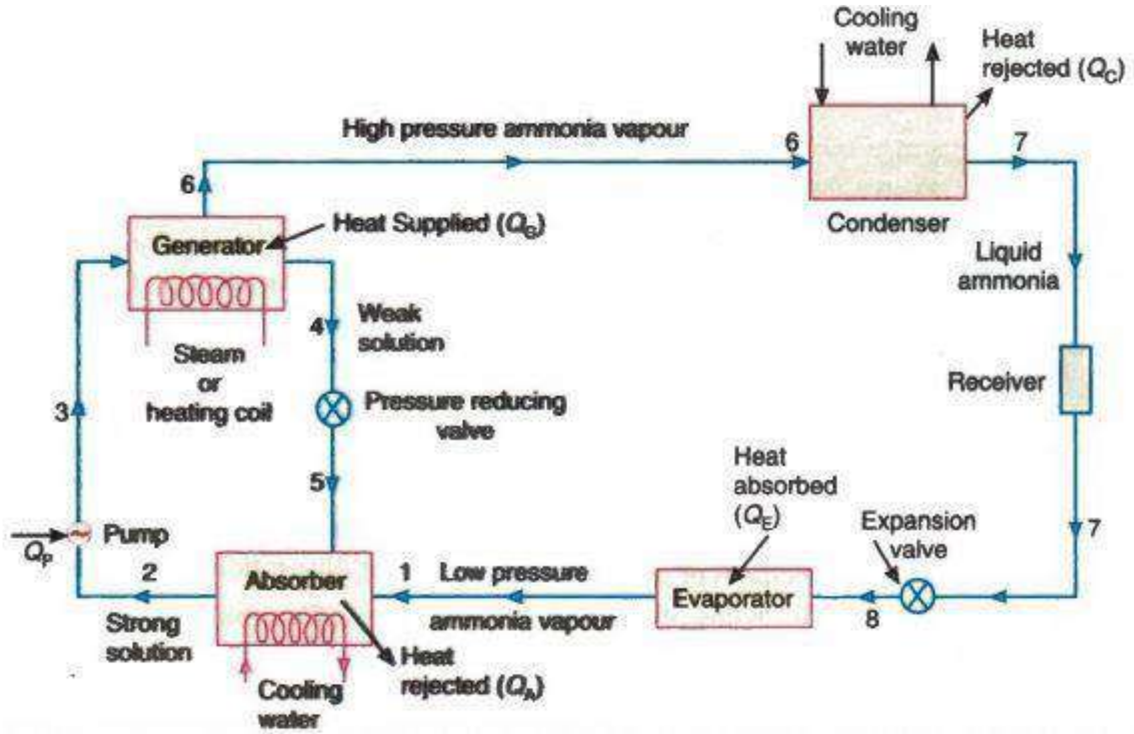
3.4. Numerical on COP.

Simple Vapour Absorption Refrigeration System:

Simple Vapour Absorption System utilizes heat energy rather than mechanical energy. In Vapour Absorption System, absorber, a pump a generator and a pressure reducing valve replace compressor. These parts play out a similar capacity as that of a compressor. In this system, vapour refrigerant comes out from the evaporator. The absorber absorbs the vapour refrigerant. It is absorbed by the weaker solution of refrigerant and forming a solution. The strong solution is pumped to the generator. It is heated by some external force. During the heating process, the vapour refrigerant is driven off by the solution. Then, it enters into the condenser where it is liquefied. The liquid refrigerant flows into the evaporator and completes the cycle. It consists of:

- an absorber
- a pump
- a generator
- a pressure reducing valve
- condenser
- receiver
- expansion valve
- evaporator

Working of the Simple Vapour absorption System



- In this system, the low-pressure ammonia vapour leaves the evaporator. Coldwater in the absorber absorbs the low-pressure ammonia vapour.
- Water lowers the pressure of ammonia in the absorber. Therefore, it draws more of ammonia vapour from the evaporator. The overall temperature of the solution is increased.
- The heat of the solution is removed by the cooling arrangement in the absorber. Water`s absorption capacity is increased. At high-temperature water absorbs less ammonia.
- The liquid pump pumps the strong solution to the generator. The ammonia in the generator is heated by some force, for example, steam or gas.
- During the heating procedure, the ammonia vapour is driven off the arrangement at high pressure. It leaves behind the weak ammonia solution in the generator.
- Weak ammonia solution flows into the absorber at low pressure after passing through the pressure reducing valve.
- High-pressure ammonia vapour from the generator is condensed in the condenser to a high-pressure liquid ammonia.
- This liquid ammonia is passed to the expansion valve through the receiver and then to the evaporator. This completes the simple vapour absorption cycle.

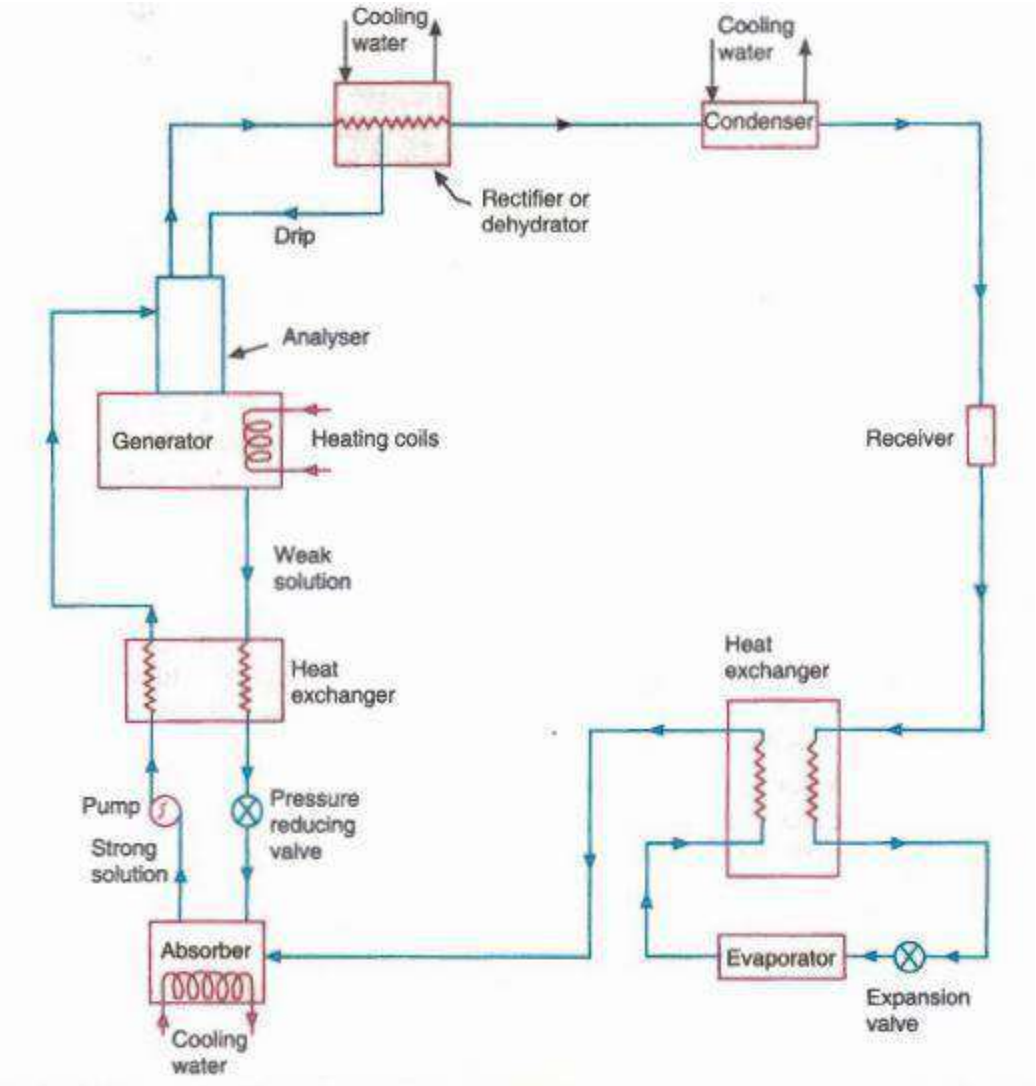
C.O.P of the Simple Vapour absorption System

In this system, the heat consumed by the refrigerant in the evaporator gives the refrigerating effect. The total energy supplied to the system is the sum of work done by the pump and the heat supplied in the generator. Therefore, Coefficient of performance of the system is given by

= Heat absorbed in evaporator / Work done by pump + Heat supplied in generator

Describe a practical vapour absorption cycle with a neat sketch for ammonia water system.

The simple absorption system is not very economical. So it is fitted with an analyzer, a rectifier and two heat exchangers as shown in figure, to make it more practical.



Analyzer: In the simple system some water also vaporizes along with ammonia in the generator. If these unwanted water particles are not removed before entering condenser, they will enter into expansion valve and will freeze and choke the pipeline.

Therefore, an analyzer is used above the generator. It consists of series of trays such that strong solution from absorber and aqua from rectifier are introduced on the top tray and flow downwards the vapor rising from generator is cooled due to exposure to considerable liquid surface area and most of water vapour condenses. Since aqua is heated by vapour, less external heat is required in generator.

Rectifier: Its function is to cool further the ammonia vapours leaving analyzer so that the vapours condense. This condensate is returned to top of analyzer by a drip return pipe. It is also known as dehydrator.

Heat Exchangers: The heat exchanger provided between pump and generator is used to cool the weak hot solution returning from generator to absorber and to heat the strong solution leaving the pump and going to generator. This reduces heat supplied to generator and amount of cooling required for absorber, thus increasing plant economy.

The heat exchanger between condenser and evaporator is called liquid sub-cooler since it sub-cools the liquid refrigerant leaving condenser by low temperature ammonia vapour from evaporator.

In this case the net refrigerating effect is the heat absorbed by the refrigerant in the evaporator. The total energy supplied to the system in the sum of work done by the pump and the head supplied in the generator. Therefore, the coefficient of performance of the system is given by

$$\textbf{C.O.P} = \frac{\boldsymbol{Heat\ absorbed\ in\ the\ evaporator}}{\boldsymbol{Work\ done\ by\ pump + Heat\ supplied\ in\ generator}}$$

Co-efficient of performance of an ideal vapour absorption refrigeration system

We have discussed earlier that an ideal vapour absorption refrigeration system

a. The heat (Q_G) is given to the refrigerant in generator.
b. The heat (Q_C)is discharged to the atmosphere or cooling water from the condenser and absorber.
c. The heat (Q_E) is absorbed by the refrigerant in the evaporator, and
d. The heat (Q_P) is added to the refrigerant due to pump work

Neglecting the heat due to pump work (Q_P) , we have according to the first law of thermodynamics,

$$Q_C = Q_G + Q_E$$

Let

T_G = Temperature at which (Q_G) is given to the generator,

T_C= Temperature at which (Q_C) discharged to the atmosphere or cooling water from the condenser and absorber,

T_E = Temperature at which (Q_E) is absorbed in the evaporator,

Since the vapour absorption system can be considered as a perfectly reversible system therefore the initial entropy of the system must be equal to the entropy of the system after the change in its condition.

$$\frac{Q_G}{T_G} + \frac{Q_E}{T_E} = \frac{Q_C}{T_C}$$

$$= \frac{Q_G \pm Q_E}{T_C}$$

$$\frac{Q_G}{T_G} - \frac{Q_G}{T_C} = \frac{Q_E}{T_C} - \frac{Q_E}{T_E}$$

$$Q_G \left(\frac{T_C - T_G}{T_G X T_C}\right) = Q_E \left(\frac{T_E - T_C}{T_C X T_E}\right)$$

$$Q_G = Q_E \left(\frac{T_E - T_C}{T_C X T_E}\right) \left(\frac{T_G X T_C}{T_C - T_G}\right)$$

$$Q_G = Q_E \left(\frac{T_C - T_E}{T_C X T_E}\right) \left(\frac{T_G X T_C}{T_G - T_C}\right)$$

$$Q_G = Q_E \left(\frac{T_C - T_E}{T_E}\right) \left(\frac{T_G}{T_G - T_C}\right)$$

Maximum COP is given by

$$\textbf{COP}_{\textbf{MAX}} = \frac{Q_E}{Q_G} = \frac{Q_E}{Q_E \left(\frac{T_C - T_E}{T_E}\right)\left(\frac{T_G}{T_G - T_C}\right)}$$

$$= \left(\frac{T_E}{T_C - T_E}\right) \left(\frac{T_G - T_C}{T_G}\right)$$

Numerical: 01

In a vapour absorption refrigeration system, heating, cooling and refrigeration take place at the temperatures of 100^{0}C, 20^{0}C and -5^{0}C respectively. Find the maximum C.O.P of the system.

Solution:

T_G=100^{0}C = 100+273= 373K, T_C = 20^{0}C = 20+273 =293 K, T_E=-5^{0}C = -5+273 = 268K

We know that maximum COP. of the system

$$\text{Maximum C.O.P.} = \left(\frac{T_E}{T_C - T_E}\right) \left(\frac{T_G - T_C}{T_G}\right)$$

$$= \left(\frac{268}{293 - 268}\right) \left(\frac{373 - 293}{373}\right) = \mathbf{3.\ 2\ Ans}$$

Numerical: 02

In an absorption type refrigerator, the heat is supplied to NH_3 generator by condensing steam at 2 bar and 90% dry. The temperature in the refrigerator is to be maintained at - 3° C. Find the maximum C.O.P. possible. If the refrigeration load is 20 tonnes and actual C.O.P. is 70% of the maximum C.O.P. find the mass of steam required per hour. Take temperature of the atmosphere as 30° C.

Solution. Given : p = 2 bar ; x = 90% = 0.9 ; = - 5^0 C = - 5 + 273 = 268 K ; Q = 20 TR ;

Actual C.O.P. = 70% of maximum C.O.P. ;

Tc = 30° C = 30 + 273 = 303 K

From steam tables, we find that the saturation temperature of steam at a pressure of 2 bar is T_C = 120.2° C = 120.2 + 273 = 393.2 K

We know that maximum C.O.P.

$$\text{Maximum C.O.P.} = \left(\frac{T_E}{T_C - T_E}\right)\left(\frac{T_G - T_C}{T_G}\right)$$

$$= \left(\frac{268}{303-268}\right)\left(\frac{393.2-293}{393.2}\right)$$

$$= 1.756 \text{ Ans}$$

Mass of steam required per hour We know that actual C.O.P. = 70% of maximum

C.O.P. = 0.7 x 1.756 = 1.229 :.

Actual heat supplied $= \frac{\text{Refrigeration load}}{\text{Actual C.O.P.}} = \frac{20 \text{ x } 210}{1.229}$ = 3417.4 kJ/min

Assuming that only latent heat of steam is used for heating purposes, therefore from steam tables, the latent heat of steam at 2 bar is

h_{fg}= 2201.6 kJ/kg :. Since its is 90% dry, so its enthalphy is

$h_{fg} = h_{fg}$ x 0.9

Mass of steam required per hour $= \frac{\text{Actual heat supplied}}{\text{hfg x0.9}}$

$$= \frac{3417.4}{1981.44} = 1.724 \text{ kg/min}$$

= 1.724x 60 = 103.48 kg /h Ans.

SHORT QUESTIONS WITH ANSWER

Q. what is the function of rectifier of a vapour absorption system? [2010 S, 2009 S]

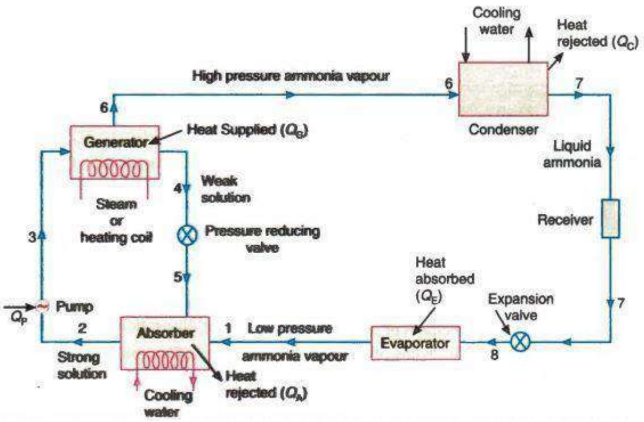
Ans : A rectifier is a water cooled heat exchanger which condenses water vapour and send back to the generator. Thus final reduction or elimination of the percentage of water vapour takes place in the rectifier.

Q. State four advantages of vapour absorption system over SVCRS . [2007S]

Ans :

- VARS Uses heat exchanger to change the condition of refrigerant
- VARS is designed to use waste heat or steam of the plant instead of electricity.
- The only moving part is pump, so noise is very less.
- Performance of VARS at part load is more than SVCRS.

Q. Draw the flow diagram of simple vapour absorption refrigeration system. [2012]



Q. In vapour absorption refrigeration system the compressor is replaced by which equipment

Ans :

Absorber, Pump, Generator, Pressure reducing valve

LONG QUESTIONS:

1. With neat sketch explain the simple vapour absorption refrigeration system.[2007S, 2010S, 2014S]

2. With neat sketch explain the practical vapour absorption refrigeration system [2012W]

3. In a vapour absorption refrigeration system, heating, cooling and refrigeration take place at the temperatures of 100^0C, 20^0C and -5^0C respectively. Find the maximum C.O.P of the system. [2020W]

4. In an absorption type refrigerator, the heat is supplied to NH_3 generator by condensing steam at 2 bar and 90% dry. The temperature in the refrigerator is to be maintained at - 3° C. Find the maximum C.O.P. possible. If the refrigeration load is 20 tonnes and actual C.O.P. is 70% of the maximum C.O.P. find the mass of steam required per hour. Take temperature of the atmosphere as 30° C. [2020W]

REFRIGERATION EQUIPMENTS

Learning Objectives:

REFRIGERANT COMPRESSORS

Principle of working and constructional details of reciprocating and rotary compressors.

Centrifugal compressor only theory

Important terms.

Hermetically and semi hermetically sealed compressor.

CONDENSERS

Principle of working and constructional details of air cooled and water-cooled condenser

Heat rejection ratio.

Cooling tower and spray pond.

EVAPORATORS

Principle of working and constructional details of an evaporator.

Types of evaporators.

Bare tube coil evaporator, finned evaporator, shell and tube evaporator.

Reciprocating Compressors

- The compressors in which the vapour refrigerant is compressed by the reciprocating motion of the piston are called reciprocating compressors.
- The reciprocating compressors are available in sizes as small as 1/12 kW which are used in small domestic refrigerators and up to about 150 kW for large capacity installations.
- The two types of reciprocating compressors in general use are single acting vertical compressors and double acting horizontal compressors.

Principle of operation of the compression cycle:

- Let us consider that the piston is at the top of its stroke as shown in Fig. (a). This is called top dead Centre position of the piston. In this position, the suction valve is held closed because of the pressure in the clearance space between the top of the piston and the cylinder head. The discharge valve is also held closed because of the cylinder head pressure acting on the top of it.
- When the piston moves downward (i.e. during suction stroke), as shown in Fig. (b), the refrigerant left in the clearance space expands. Thus the volume of the cylinder (above the piston) increases and the pressure inside the cylinder decreases.

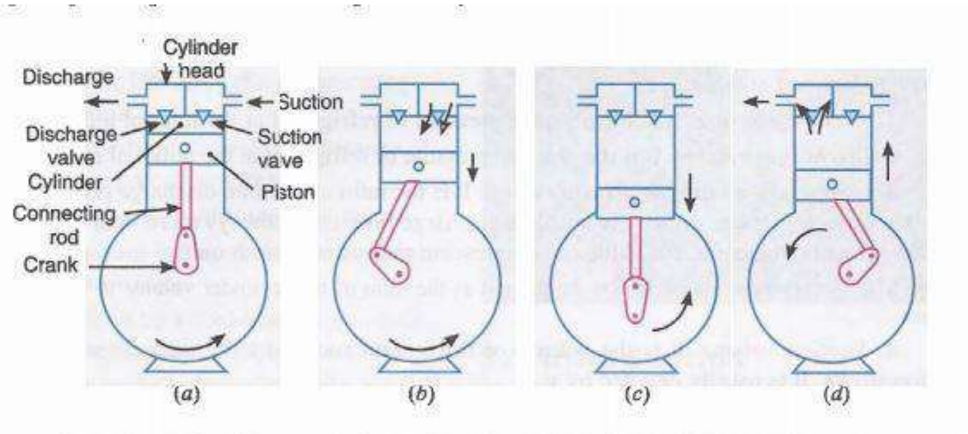


Fig. 9.1. Principle of operation of a single stage, single acting reciprocating compressor.

- When the pressure becomes slightly less than the suction pressure or atmospheric pressure, the suction valve gets opened and the vapour refrigerant flows into the cylinder. This flow continues until the piston reaches the bottom of its stroke (i.e. bottom dead Centre). At the bottom of the stroke, as shown in Fig. (c). the suction valve closes because of spring action.
- Now when the piston moves upward (i.e. during compress it stroke), as shown in Fig. (d), the volume of the cylinder decreases and the pressure inside cylinder increases.
- When the pressure inside the cylinder becomes greater than that on the top of discharge valve, the discharge valve gets opened and the vapour refrigerant is discharged into condenser and the cycle is repeated.

Rotary Compressors

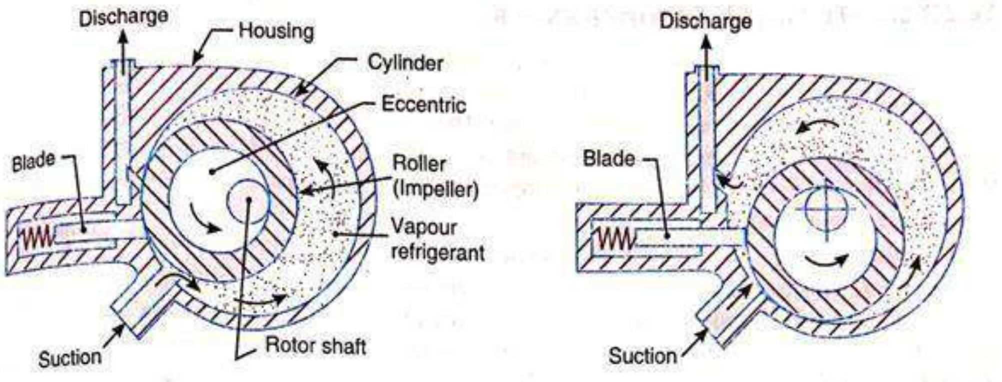
- In rotary compressors, the vapour refrigerant from the evaporator is compressed due to the movement of blades. The rotary compressors are positive displacement type compressors.
- Since the clearance in rotary compressors is negligible, therefore they have high volumetric efficiency.
- These compressors may be used with refrigerants R-12, R-22, R-114 and ammonia.

Following are the two basic types of rotary compressors:

1. Single stationary blade type rotary compressor

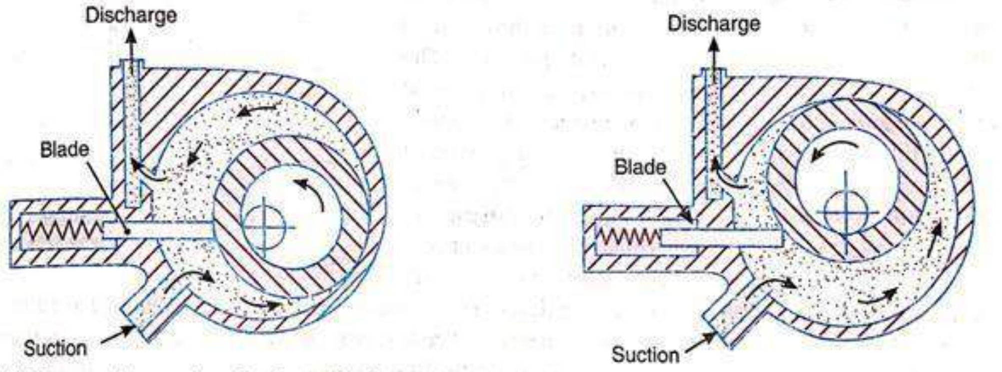
A single stationary blade type rotary compressor. It consists of a stationary cylinder, a roller (or impeller) and a shaft. The shaft has an eccentric on which the roller is mounted.

- A blade is set into the slot of a cylinder in such a manner that it always maintains contacts with the roller by means of a spring.
- The blade moves in and out of the slot to follow the rotor when it rotates.
- When the shaft rotates, the roller also rotates so that it always touches the cylinder wall.
- When the roller rotates, the vapour refrigerant ahead of the roller is being compressed and the new intake from the evaporator is drawn into the cylinder,
- As the roller turns towards mid position, more vapour refrigerant is drawn into the cylinder while the compressed refrigerant is discharged to the condenser.
- At the end of compression stroke, most of the compressed vapour refrigerant is passed through the discharge port to the condenser.
- A new charge of refrigerant is drawn into the cylinder. This, in turn, is compressed and discharged to the condenser.
- In this way, the low pressure and temperature vapour refrigerant is compressed gradually to a high pressure and temperature.



(*a*) Completion of intake stroke and beginning of compression.

(*b*) Compression stroke continued and new intake stroke started.



(*c*) Compression continued and new intake stroke continued.

(*d*) Compressed vapour discharged to condenser and new intake stroke continued.

. Stationary single blade rotary compressor.

Rotating blade type rotary compressor.

It consists of a cylinder and a slotted rotor containing a number of blades. The Centre of the rotor is eccentric with the Centre of the cylinder. The blades are forced against the cylinder wall by the centrifugal action during the rotation of the motor.

- The low pressure and temperature vapour refrigerant from the evaporator is drawn through the suction port.
- As the rotor turns, the suction vapour refrigerant entrapped between the two adjacent blades is compressed. The compressed refrigerant at high pressure and temperature is discharged through the discharge port to the condenser.
- The whole assembly of both the types of rotary compressors is enclosed in a housing which is filled with oil.

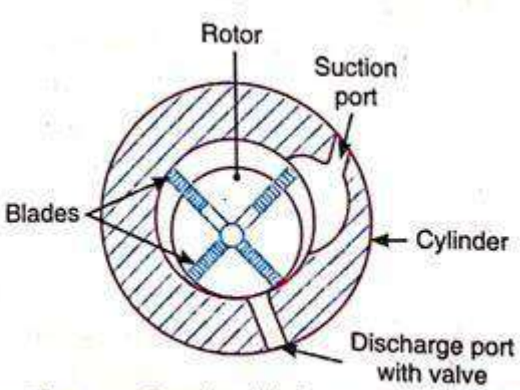


Fig. [illegible] Rotating blade type rotary compressor.

- When the compressor is working, an oil film forms the seal between the high pressure and low-pressure side.
- But when the compressor stops, this seal is lost and therefore high-Pressure vapour refrigerant will flow into low pressure side.
- In order to avoid this, a check valve is usually provided in the suction line. This valve prevents the high-pressure vapour refrigerant from flowing back to the evaporator.

Centrifugal Compressors

This compressor increases the pressure of low-pressure vapour refrigerant to a high pressure by centrifugal force.

- A single stage centrifugal compressor consists of an impeller to which a number of curved vanes are fitted symmetrically.
- The impeller rotates in an airtight volute casing with inlet and outlet points.
- The impeller draws in low pressure vapour refrigerant from the evaporator.

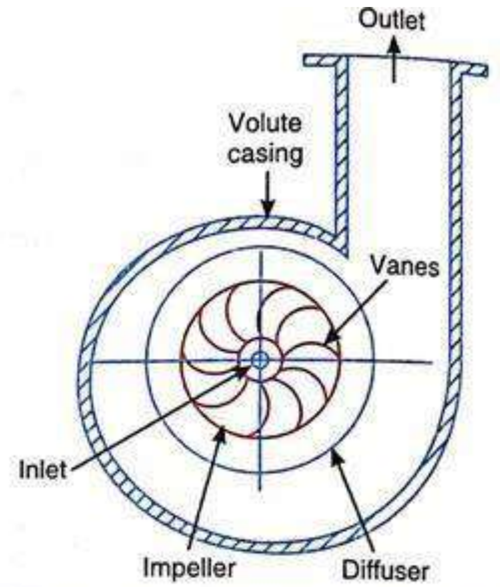


Fig. Centrifugal compressor.

- When the impeller rotates, it pushes the vapour refrigerant from the Centre of the impeller to its periphery by centrifugal force.
- The high speed of the impeller leaves the vapour refrigerant at a high velocity at the vane tips of the impeller.
- The kinetic energy thus attained at the impeller outlet is converted into pressure energy when the high velocity vapour refrigerant passes over the diffuser.
- The diffuser is normally a vaneless type as it permits more efficient part load operation which is quite usual in any air-conditioning plant.
- The volute casing collects the refrigerant from the diffuser and it further converts the kinetic energy into pressure energy before it leaves the refrigerant to the evaporator.
-

3 Important Terms:

The following important terms, which will be frequently used in this chapter, should be clearly understood at this stage:

1. **Suction pressure.** It is the absolute pressure of refrigerant at the inlet of a compressor.
2. **Discharge pressure.** It is the absolute pressure of refrigerant at the outlet of a compressor.

3. **Compression ratio (or pressure ratio).** It is the ratio of absolute discharge pressure to the absolute suction pressure. Since the absolute discharge pressure is always more than the absolute suction pressure, therefore, the value of compression ratio is more than unity. Note: The compression ratio may also be defined as the ratio of total cylinder volume to the clearance volume.
4. **Suction volume.** It is the volume of refrigerant sucked by the compressor during its suction stroke. It is usually denoted by v.
5. **Piston displacement volume or stroke volume or swept volume.** It is the volume swept by the piston when it moves from its top or inner dead position to bottom or outer dead Centre position.

Mathematically, piston displacement volume or stroke volume or swept volume,

$\mathbf{V_p = \frac{\pi}{4} D^2 \times L}$, where D = Diameter of cylinder, and L = Length of piston stroke.

6. Clearance factor.

It is the ratio of clearance volume (V_c) to the piston displacement volume (V_p). Mathematically, clearance factor, $C = \frac{Vc}{Vp}$

7. **Compressor capacity.** It is the volume of the actual amount of refrigerant passing through their compressor in a unit time. It is equal to the suction volume (v_s). It is expressed in m^2/s.

8. **Volumetric efficiency.** It is the ratio of the compressor capacity or the suction volume (v_s) to the piston displacement volume (v_p).

Mathematically, volumetric efficiency, $\eta_v = \frac{Vs}{Vp}$

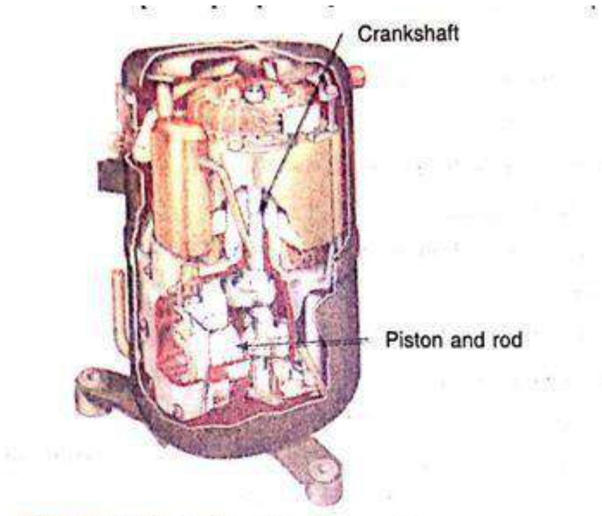
Note : A good compressor has a volumetric efficiency of 70 to 80 per cent. 0

Hermetic Sealed Compressors

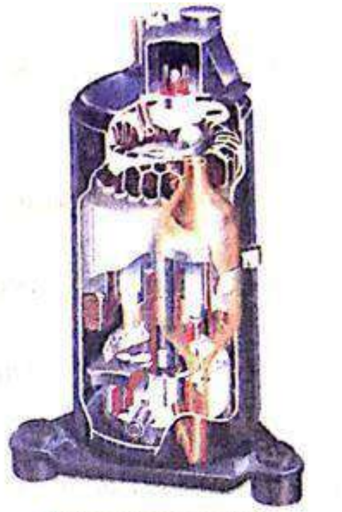
When the compressor and motor operate on the same shaft and are enclosed in a common casing, they are known as hermetic sealed compressors. These types of compressors eliminate the use of crankshaft seal which is necessary in ordinary compressors in order to prevent leakage of refrigerant. These compressors may operate on either reciprocating or rotary principle and may be mounted with the shaft in either the vertical or horizontal position. The hermetic units are widely used for small capacity refrigerating systems such as in domestic refrigerators, home freezers and window air conditioners. The hermetic sealed compressors have the following advantages and disadvantages:

Advantages

1. The leakage of refrigerant is completely prevented.
2. It is less noisy.
3. It requires small space because of compactness.
4. The lubrication is simple as the motor and compressor operate in a sealed space with the Imbricating oil.



Internal working of a welded hermetic compressor.



Rotary compressor.

Disadvantages:

1. The maintenance is not easy because the moving parts are inaccessible
2. A separate pump is required for evacuation and charging of refrigerant.

Condenser:

Working of Condenser:

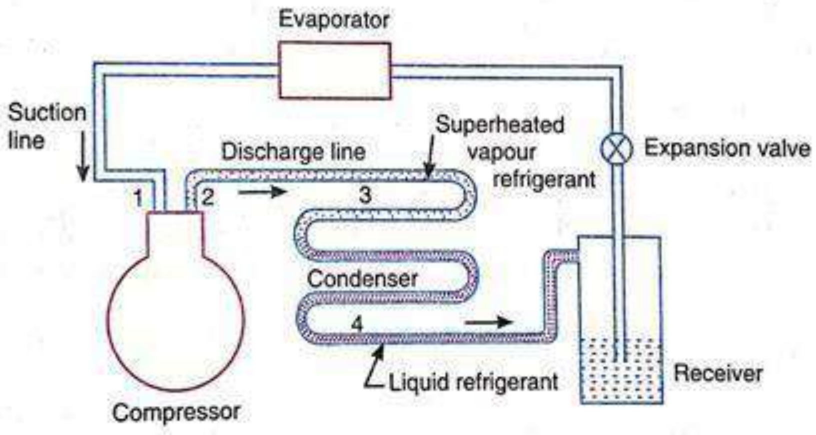
The working of a condenser may be best understood by considering a simple refrigerating system as shown in Fig. The compressor draws in the superheated vapour refrigerant that contains the heat it absorbed in the evaporator.

- The compressor adds more heat (Le. the heat of compression) to the superheated vapour.
- This highly superheated vapour from the compressor is pumped to the condenser through the discharge line.
- The condenser cools the refrigerant in the following three stages:

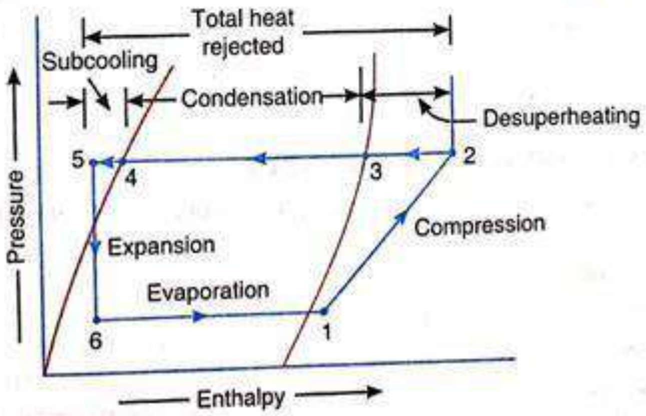
1. First of all, the superheated vapour is cooled to saturation temperature (called &superheating) corresponding to the pressure of the refrigerant. This is shown by the line 2-3 in Fig (b). The superheating occurs in the discharge line and in the first few coils of the condenser.

2. Now the saturated vapour refrigerant gives up its latent heat and is condensed to a saturated liquid refrigerant. This process, called condensation, is shown by the line 3-4.

3. The temperature of the liquid refrigerant is reduced below its saturation temperature (i.e. subcooled) in order to increase the refrigeration effect. This process is shown by the line 4-5.



(*a*) Schematic diagram of a simple refrigerating system.



Air Cooled Condenser:

An air-cooled condenser is one in which the removal of heat is done by air. It consists of steel or copper tubing through which the refrigerant flows.

- The size of tube usually ranges from 6 aim to 18 mm outside diameter, depending upon the size of condenser.
- Generally copper tubes are used because of its excellent heat transfer ability. The condensers with steel tubes are used in ammonia refrigerating systems.
- The tubes are usually provided with plate type fins to increase the surface area for heat transfer.

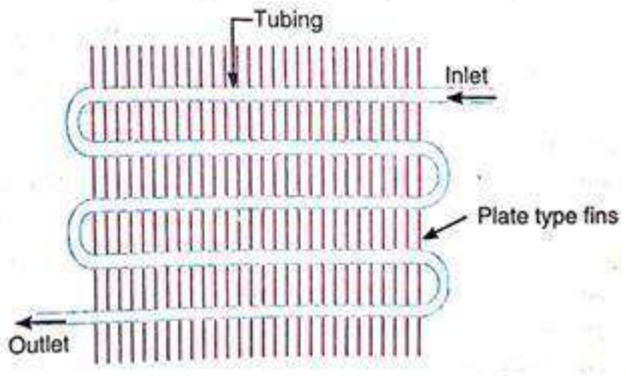


Fig. . Air-cooled condenser.

- The fins are usually made from aluminium because of its light weight. The fin spacing is Quite wide to reduce dust clogging.
- The condensers with single row of tubing provides the most efficient heat transfer.
- The air-cooled condensers may have two or more rows of tubing, but the condensers with up to six rows of tubing are common. Some condensers have seven or eight rows.

Types of Air-Cooled Condensers

Following are the two types of air-cooled condensers:

I. Natural convection air-cooled condensers.

In natural convection air-cooled condenser, the heat transfer from the condenser coils to the air is by natural convection. As the air comes in contact with the warm condenser tubes, it absorbs heat from the refrigerant and thus the temperature of air increases. The warm air, being lighter, rises up and the cold air from below rises to take away the heat from the condenser. This cycle continues in natural convection air-cooled condensers. Since the rate of heat transfer in natural convection condenser is slower, therefore they require a larger surface area as compared to forced convection condensers. The natural convection air-cooled condensers are used only in small-capacity applications such as domestic refrigerators, freezers, water coolers and room air-conditioners.

2. Forced convection air-cooled condensers.

In forced convection air-cooled condensers, the fan is used to force the air over the condenser coils to increase its heat transfer capacity. The forced convection condensers may be divided into the following two groups:

(a) Base mounted air-cooled condensers, and

(b) Remote air-cooled condensers.

Water-Cooled Condensers

A water-cooled condenser is one in which water is used as the condensing medium. They are always preferred where an adequate supply of clear inexpensive water and means of water disposal are available. These condensers are commonly used in commercial and industrial refrigerating units. The water-cooled condensers may use either of the following two water systems:

1. Waste water system, or

2. Recirculated water system.

Types of Water-Cooled Condensers

The water-cooled condensers are classified, according to their construction, into the following three groups:

1. Tube-in-tube or double-tube condensers.

The tube-in-tube or double-tube condenser, as shown in Fig., consists of a water tube inside a large refrigerant tube. In this type of condenser, the hot vapour refrigerant enters at the top of the condenser. The water absorbs the heat tram the refrigerant and the condensed liquid refrigerant flows at the bottom. Since the refrigerant tubes are exposed to ambient air, therefore some of the heat is also absorbed by ambient air by natural convection. The cold water in the inner tubes may flow in either direction

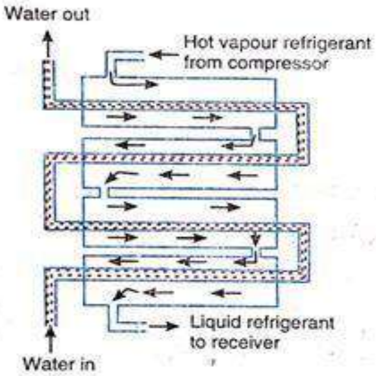


Fig. . . Tube-in-tube condenser.

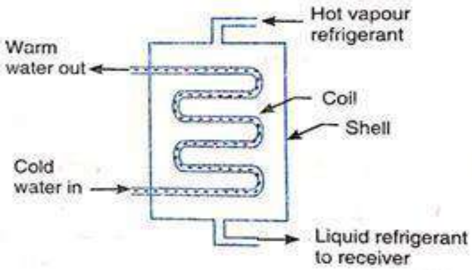
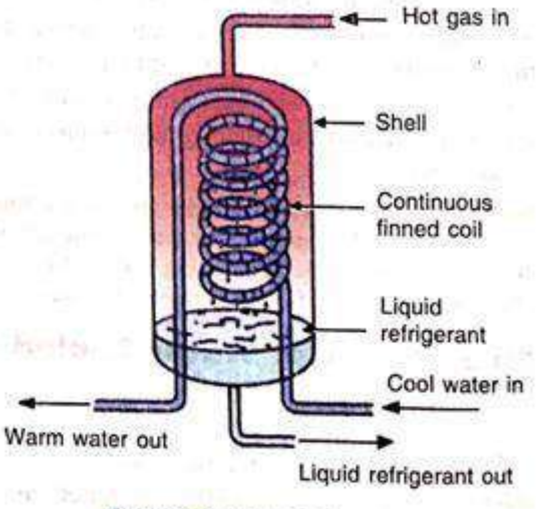


Fig. . Shell and coil condenser.

2. Shell and coil condensers.

A shell and coil condenser, as shown in Fig., consists of one or more water coils enclosed in a welded steel shell. Both the finned and bare coil types are available. The shell and coil condenser may be either vertical (as shown in the figure) or horizontal. In this type of condenser, the hot vapour refrigerant enters at the top of the shell and surrounds the water coils. As the vapour condenses, it drops to the bottom of the shell which of top Saves as a receiver. Most vertical type shell and coil condensers use counter-flow water system as it is more efficient than parallel-flow water system. In the shell and coil condensers, coiled tubing is free to expand and attract with temperature changes because of its spring action and can withstand any strain caused by temperature changes.



Shell and coil condenser.

Since the water coils are enclosed in a welded steel shell, therefore the mechanical cleaning of these coils is not possible. The coils are cleaned with chemicals. The shell sad coil condensers are used for units up to 50 tonnes capacity.

3. Shell and tube condensers.

The shell and tube condenser consists of a cylindrical steel shell containing a number of straight water tubes. The tubes are expanded into grooves in the tube sheet holes to form a vapour-tight fit. The tube sheets are welded to the shell at both the ends. The removable water boxes are bolted to the tube sheet at each end to facilitate cleaning of the condenser. The intermediate supports are provided in the shell to avoid sagging of the tubes.

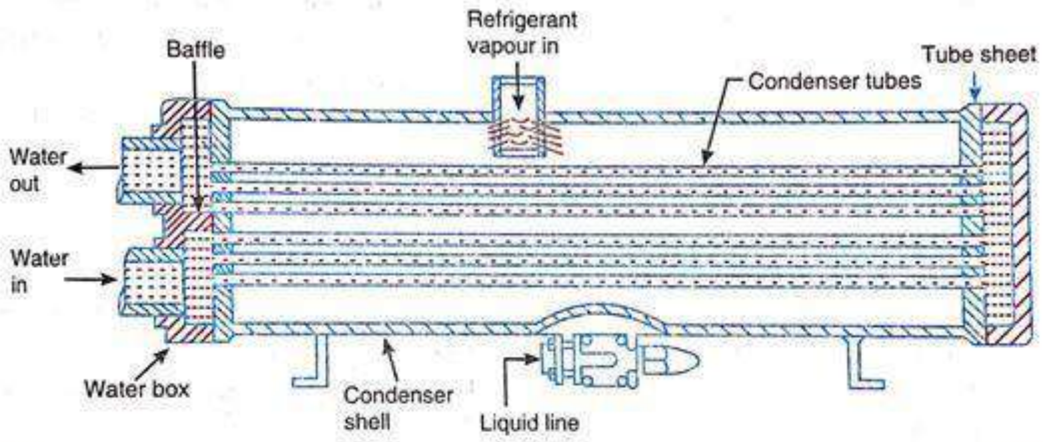


Fig. . Shell and tube condenser.

The condenser tubes are made either from steel or copper, with or without fins. The steel tubes without fins are usually used in ammonia refrigerating systems because ammonia corrodes copper tubing.

- In this type of condenser, the hot vapour refrigerant enters at the top of the shell and condenses as it comes in contact with water tubes.
- The condensed liquid refrigerant drops to the bottom of the shell which often serves as a receiver.

Cooling Towers and Spray Ponds

A cooling tower is an enclosed tower-like structure through which atmospheric air circulates to cool large quantities of warm water by direct contact.

- A spray pond consists of a piping and spray nozzle arrangement suspended over an outdoor open reservoir or pond. It can also cool large quantities of warm water.
- The cooling towers and spray ponds, used for refrigeration and air conditioning systems, cool the warm water pumped from the water-cooled condensers.
- Then the same water can be used again and again to cool the condenser. The principle of cooling the water in cooling towers and spray ponds is similar to that of evaporative condensers, i.e. the warm water is cooled by means of evaporation.
- The air surrounding the falling water droplets from the spray nozzles causes some of the water droplets to evaporate. The evaporating water absorbs latent heat of evaporation from the remaining water and thus cools it.
- The air also absorbs a small amount of sensible heat from the the remaining water. The cooled water collects in the pond or in a sump at the cooling tower which is recirculated through the condenser.

Capacity of Cooling Towers and Spray Ponds

The capacity of cooling towers and spray ponds depends upon the amount of evaporation of water that takes place. The amount of evaporation of water, in turn, depends upon the following factors:

1. The amount of water surface exposed to the air,
2. The length of the exposure time,

3. The velocity of air passing over the water droplets formed in cooling towers, and
4. The wet bulb temperature of the atmospheric air.

Types of Cooling Towers

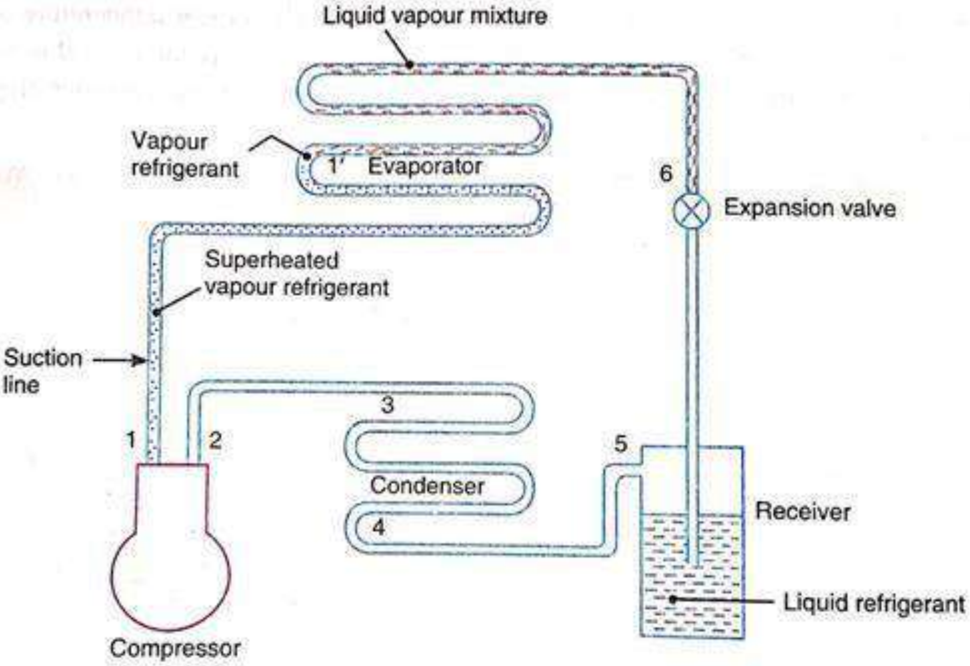
The cooling towers are mainly divided, according to their method of air circulation, into the following two groups:

1. Natural draft cooling towers, and
2. Mechanical draft cooling towers.

In natural draft cooling towers, the air circulates through the tower by natural convection Whereas in mechanical draft cooling towers, the air is forced through the tower by means of fans

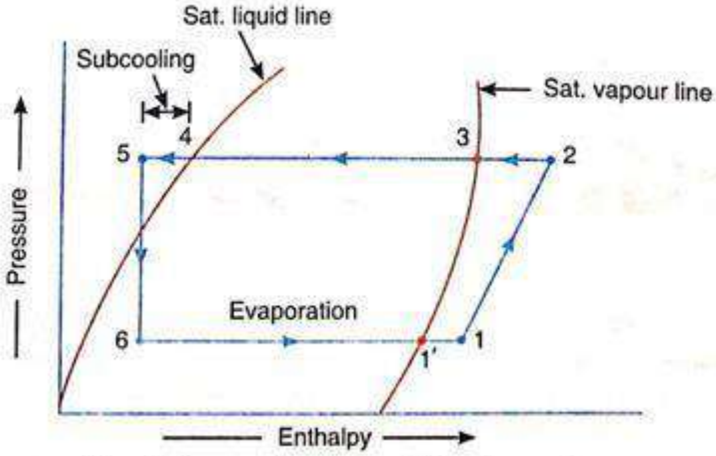
Working of an Evaporator

- The working of an evaporator may be best understood by considering the simple refrigerating system, as shown in Fig. The corresponding p-Is diagram is shown in Fig.
- The point 5 in the figure represents the entry of liquid refrigerant into the expansion valve. Under proper operating conditions, the liquid refrigerant is sub-cooled (i.e. cooled below its saturation temperature).
- The sub-cooling ensures that the expansion valve receives pure liquid refrigerant with no vapour present to restrict the flow of refrigerant through the expansion valve.
- The liquid refrigerant at low pressure enters the evaporator at point 6, as shown in Fig . As the liquid refrigerant passes through the evaporator coil, it continually absorbs heat through the coil walls, from the medium being cooled. During this, the refrigerant continues to boil



(*a*) Schematic diagram of a simple refrigerating system.

(*a*) Schematic diagram of a simple refrigerating system.



(*b*) *p-h* diagram of a simple refrigerating system.

Fig.

(*a*) Schematic diagram of a simple refrigerating system.

and evaporate. Finally at point 1', all the liquid refrigerant has evaporated and only vapour refrigerant remains in the evaporator coil. The liquid refrigerant's ability to convert absorbed heat to latent heat is now used up.

- Since the vapour refrigerant at point 1' is still colder than the medium being cooled, therefore the vapour refrigerant continues to absorb heat. This heat absorption causes an increase in the sensible heat (or temperature) of the vapour refrigerant.
- The vapour temperature continues to rise until the vapour leaves the evaporator to the suction line at point 1. At this point, the temperature of the vapour is above the saturation temperature and the vapour refrigerant is superheated.
- Fig. shows the variation of refrigerant temperature (or sensible heat) and the refrigerant heat content (or enthalpy) within the evaporator. We see that the temperature of the refrigerant is constant during evaporation of the liquid refrigerant from point 6 to and the enthalpy increases steadily.
- It shows that the latent heat is absorbed by the evaporating liquid with no change in temperature.
- Both the temperature and enthalpy of the refrigerant increases from point to 1. At point 1, all the liquid refrigerant has evaporated. The line 1'-1 shows the increase in sensible heat of the vapour refrigerant.

Types of Evaporators

Though there are many types of evaporators, yet the following are important from the subject point of view:

1. According to the type of construction

(a) Bare tube coil evaporator,
(b) Finned tube evaporator,
(c) Plate evaporator,
(d) Shell and tube evaporator,
(e) Shell and coil evaporator, and
(f) Tube-in-tube evaporator,

2. According to the manner in which liquid refrigerant is fed

(g) Flooded evaporator, and
(h) Dry expansion evaporator

3. According to the mode of heat transfer

(i) Natural convection evaporator, and
(j) Forced convection evaporator

4. According to operating conditions

a. Frosting evaporator,
b. Non-frosting evaporator, and
c. Defrosting evaporator

Bare Tube Coil Evaporators

The bare tube coil evaporators are e also known as prime-surface evaporators. Because of its simple construction, the bare compressor tube coil is easy to clean and defrost.

- This type of evaporator offers relatively little surface contact area as compared to other types of Liquid coils.
- The amount of surface area may be refrigerant increased by simply extending the length of the tube, but there are disadvantages of excessive tube length.
- The effective length of the tube is limited by the capacity of expansion valve.
- If the tube is too long for the valves capacity, the liquid refrigerant will tend to completely vaporize early in its progress through the tube, thus leading to excessive superheating at the outlet.
- The long tubes will also cause considerably greater pressure drop between the inlet and outlet of the evaporator.
- This results in a reduced suction line pressure. The diameter of the tube in relation to tube length may also be critical. If the tube diameter is too large, the refrigerant velocity will be too low and the volume of refrigerant will be too great in relation to the surface area of the tube to allow complete vaporization.
- This, in turn, may allow liquid refrigerant to enter the suction line with possible damage to the compressor (i.e. slugging). On the other hand, if the diameter is too small, the pressure drop due to friction may be too high and will reduce the system efficiency.

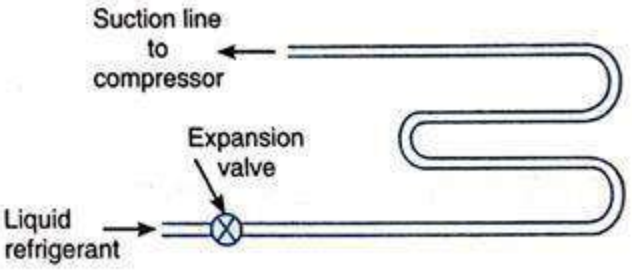


Fig. Bare tube coil evaporator.

- The bare tube coil evaporators may be used for any type of refrigeration requirement. Its use is, however, limited to applications where the box temperatures are under 0°C and in liquid cooling, because the accumulation of ice or frost on these evaporators has less effect on the heat transfer than on those equipped with fins.
- The bare tube coil evaporators are also extensively used in household refrigerators because they are easier to keep clean.

Finned Evaporators

The finned evaporator consists of bare tubes or coils over which the metal plates or fins are fastened.

- The metal fins arc constructed of thin sheets of metal having good thermal conductivity.
- The shape, size or spacing of the fins can he adapted to provide best rate of heat transfer for a given application.
- Since the fins greatly increase the contact surfaces for heat transfer, therefore the finned evaporators are also called extended surface evaporators.

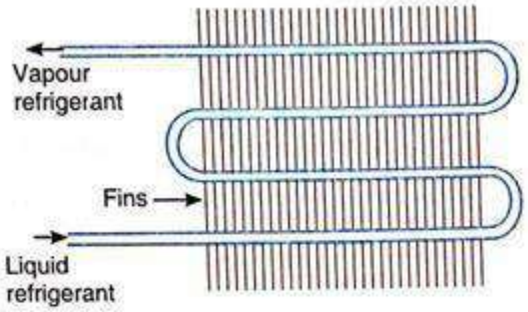


Fig. . Finned evaporator.

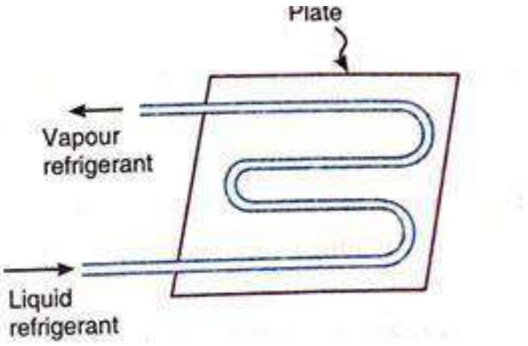


Fig. . Plate evaporator.

- The finned evaporators are primarily designed for air conditioning applications where the refrigerator temperature is above 0°C. Because of the rapid heat transfer of the finned evaporator, it will defrost itself on the off cycle when the temperature of the coil is near 0°C.
- A finned coil should never be allowed to frost because the accumulation of frost between the fins reduces the capacity. The air conditioning coils, which operate at suction temperatures which are high enough so that frosting never occurs, have fin spacing as small as 3 mm.
- The finned coils which frost on the on cycle and defrost on the off cycle have wider fin spacing.

Plate Evaporators

In this type of evaporator, the coils are either welded on one side of a plate or between the two plates which are welded together at the edges. The plate evaporators are generally used in household refrigerators, home freezers, beverage coolers, ice cream cabinets, locker plants etc.

Shell and Tube Evaporators

The shell and tube evaporator is similar to a shell and tube condenser. It consists of a number of horizontal tubes enclosed in a cylindrical shell. The inlet and outlet headers with perforated metal tube sheets are connected at each end of the tubes.

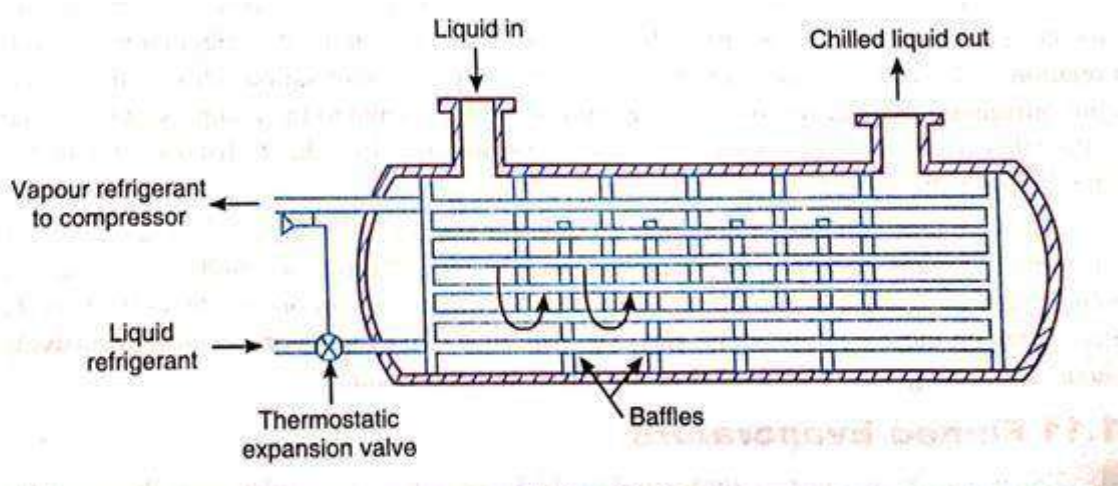


Fig. . Shell and tube evaporator.

These evaporators are generally used to chill water or brine solutions. When it is operated as a dry expansion evaporator, the refrigerant circulates through the tubes and the liquid to be cooled fills the space around the tubes within the shell. The dry expansion shell and tube evaporators are used for refrigerating units of 2 to 250 TR capacity. When it is operated as a flooded evaporator, the water or brine flows through the tubes and the refrigerant circulates around the tubes. The flooded shell and tube evaporators are used for refrigerating units of 10 to 5000 TR capacity.

Shell and Coil Evaporators

The shell and coil evaporators are generally dry expansion evaporators to chill water. The cooling coil is a continuous tube that can be in the form of a single or double spiral. The shell may be sealed or open. The scaled shells are usually found in shell and coil evaporators used to cool drinking water.

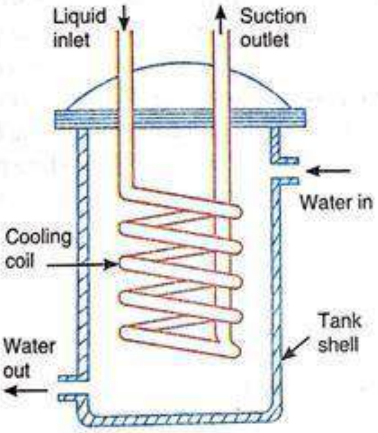


Fig. Shell and coil evaporator.

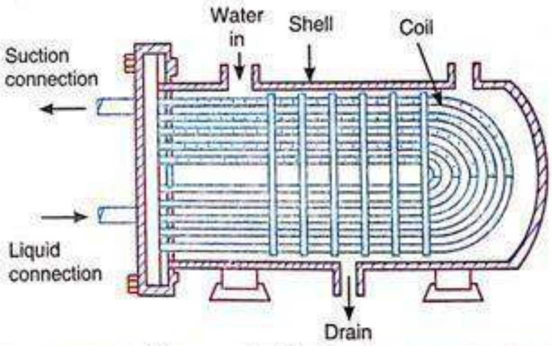


Fig. . Shell and coil evaporator.

The evaporators having flanged shells arc often used to chill water in secondary refrigeration systems. Another type of shell and coil evaporator is shown in Fig. Both types of evaporators are usually used where small capacity (2 to 10 TR) liquid cooling is required. It may be noted that the shell and coil evaporator is restricted to operation above 5°C in order to prevent the freezing problems.

Tube-in-Tube or Double-Tube Evaporators

The tube-in-tube evaporator (or double-tube evaporator) consists of one tube inside another tube. The liquid to be cooled flows through the inner tube while the primary refrigerant or secondary refrigerant (i.e. water, air or brine) circulates in the space between the two tubes. The tube-in-tube evaporator provides high heat transfer rates. However, they require more space than shell and tube evaporators of the same capacity. These evaporators are used for wine cooling and in petroleum industry for chilling of oil.

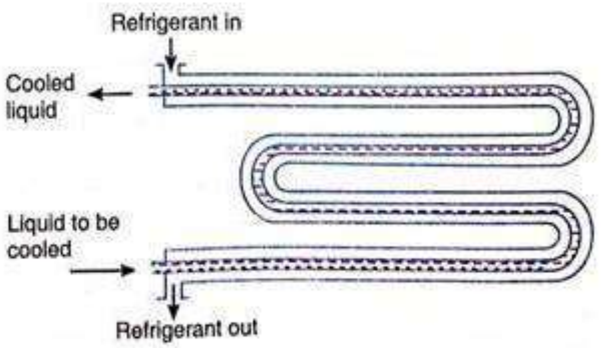


Fig. Tube-in-tube or double-tube evaporator.

SHORT QUESTIONS WITH ANSWER

1. What is the function of rotary compressor? [Possible]

Ans: The niche services for rotary compressors include Freon and ammonia refrigeration, plant air, some wet services, and services with vacuum suction conditions. Other types of compressors cover a majority of the range of uses. Efficiencies or rotary compressors are better than centrifugal and axial but lower than reciprocating. Speed control is the most obvious way to control capacity for rotary compressors, but they are usually direct driven by motors and run at constant speed.

2. Hermetic Sealed Compressors? [Possible]

A hermetic or sealed compressor is one in which both compressor and motor are confined in a single outer welded steel shell. The motor and compressor are directly coupled on the same shaft, with the motor inside the refrigeration circuit. Thus, the need for a shaft seal with the consequent refrigerant leakage problem was eliminated. All the refrigerant pipeline connections to the outer steel shell are by welding or brazing. The electrical conductors to the motor are taken out of the steel shell by sealed terminals made of fused glass.

3. What is the function of condenser and its type? [Possible]

The function of the condenser in a refrigeration system is to transfer heat from the refrigerant to another medium, such as air and/or water. By rejecting heat, the gaseous refrigerant condenses to liquid inside the condenser.

The major types of condensers used are (1) water-cooled, (2) air-cooled, and (3) evaporative. In evaporative condensers, both air and water are used.

Three common types of water-cooled condensers are (1) double pipe, (2) shell and tube), and (3) shell and coil.

4. What is the function of cooling tower and spray pond? [2011 W]

The warm water from the condensers needs to be cooled to the lowest practical temperature before being re-used. The cooling process is carried out in cooling towers or spray ponds after which the water is pumped back to the condensers. In cooling towers or spray ponds the exchange of heat between the warm water and ambient air is by, a. conduction between the fine droplets of water and the surrounding air b. evaporative cooling, which is by far the most effective factor.

5. What are the types of evaporators? [2012]

1. According to the type of construction

(k) Bare tube coil evaporator,
(l) Finned tube evaporator,
(m) Plate evaporator,
(n) Shell and tube evaporator,
(o) Shell and coil evaporator, and
(p) Tube-in-tube evaporator,

2. According to the manner in which liquid refrigerant is fed

(q) Flooded evaporator, and
(r) Dry expansion evaporator

3. According to the mode of heat transfer

(s) Natural convection evaporator, and
(t) Forced convection evaporator

4. According to operating conditions

d. Frosting evaporator,
e. Non-frosting evaporator, and
f. Defrosting evaporator

LONG QUESTIONS

1. With neat sketch explain the working principle of reciprocating compressor? [2012]

2. With neat sketch explain the evaporative type vapour condenser? [2018]

3. With neat sketch explain the working principle of Centrifugal Compressors?

REFRIGERANT FLOW CONTROLS, REFRIGERANTS & APPLICATION OF REFRIGERANTS

Learning Objectives:

EXPANSION VALVES

Capillary tube

Automatic expansion valve

Thermostatic expansion valve

REFRIGERANTS

Classification of refrigerants

Desirable properties of an ideal refrigerant.

Designation of refrigerant.

Thermodynamic Properties of Refrigerants.

Chemical properties of refrigerants.

commonly used refrigerants, R-11, R-12, R-22, R-134a, R-717

Substitute for CFC

Applications of refrigeration

cold storage

dairy refrigeration

ice plant

water cooler

frost free refrigerator

Expansion valve:

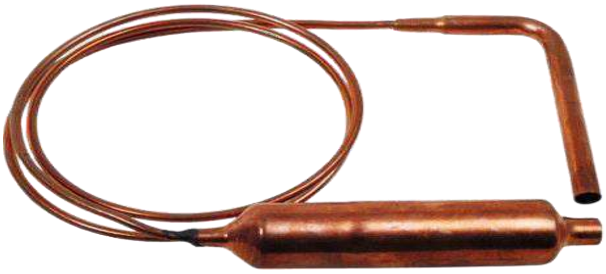
Types of Expansion Device:

Following are the main types of expansion devices used in industrial and commercial refrigeration and air conditioning system.

1. Capillary tube,
2. Hand-operated expansion valve,
3. Automatic or constant pressure expansion valve,
4. Thermostatic expansion valve,
5. Low-side float valve, and
6. High-side float valve.

Capillary Tube

- The capillary tube is used as an expansion device in small capacity hermetic sealed refrigeration units such as in domestic refrigerators, water coolers, room air-conditioners and freezers.
- It is a copper tube of small internal diameter and of varying length depending upon the application.
- The inside diameter of the tube used in refrigeration work is generally about 0.5 mm to 2.25 mm and the length varies from 0.5 m to 5 m.
- It is installed in the liquid line between the condenser and the evaporator
- A fine mesh screen is provided at the inlet of the tube in order to protect it from contaminants.
- A small filter drier is used on some systems to provide additional freeze-up application.
- In its operation, the liquid refrigerant from the condenser enters the capillary tube.

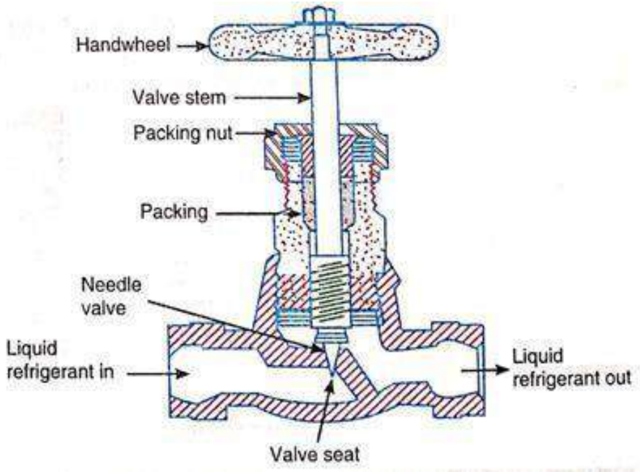


- Due to the frictional resistance offered by a small diameter tube, the pressure drops.
- Since the frictional resistance is directly proportional to the length and inversely proportional to the diameter, therefore longer the capillary tube and smaller its inside diameter, greater is the pressure drop created in the refrigerant flow. In other words, greater pressure difference between the condenser and evaporator

Hand-operated Expansion Valve

- It is the most simple type of expansion valve but it requires an operator to regulate the flow of refrigerant to the evaporator manually.
- The conical-shaped needle valve extends down into the valve port and restricts the flow area through the port.
- When closed, the valve rests on its conical seat.
- The use of hand-operated valve is limited to systems operating under nearly constant loads for long periods of time, such as in ice making plants and cold storages.

- It is not suitable for installations where the intermittently to maintain a constant temperature.

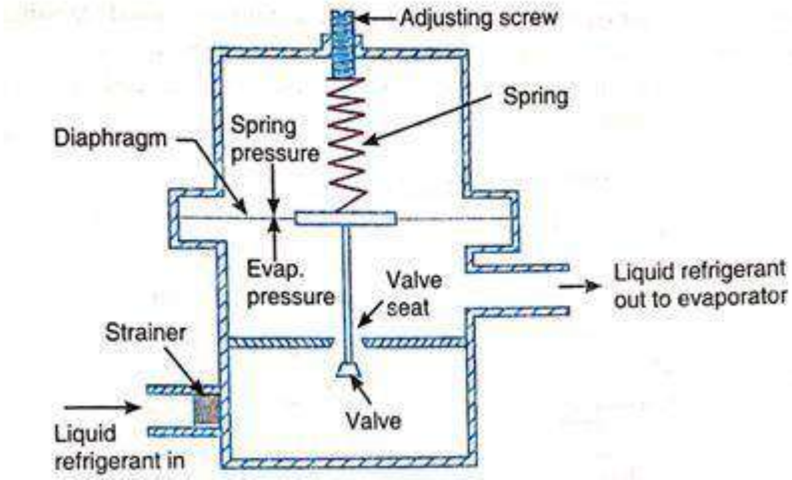


Automatic (or Constant Pressure) Expansion Valve

- The automatic expansion valve is also known as Constant pressure expansion valve, because it maintains constant evaporator pressure regardless of the load on the evaporator. Its main moving force is the evaporator pressure. It is used with dry expansion evaporators where the load is relatively constant.
- It consists of a needle valve and a scat (which forms an orifice), a metallic diaphragm or bellows, spring and an adjusting screw.
- The opening and closing of the valve with respect to the seat depends upon the following two opposing forces acting on the diaphragm:

1. The spring pressure and atmospheric pressure acting on the top of the diaphragm, and

2. The evaporator pressure acting below the diaphragm.

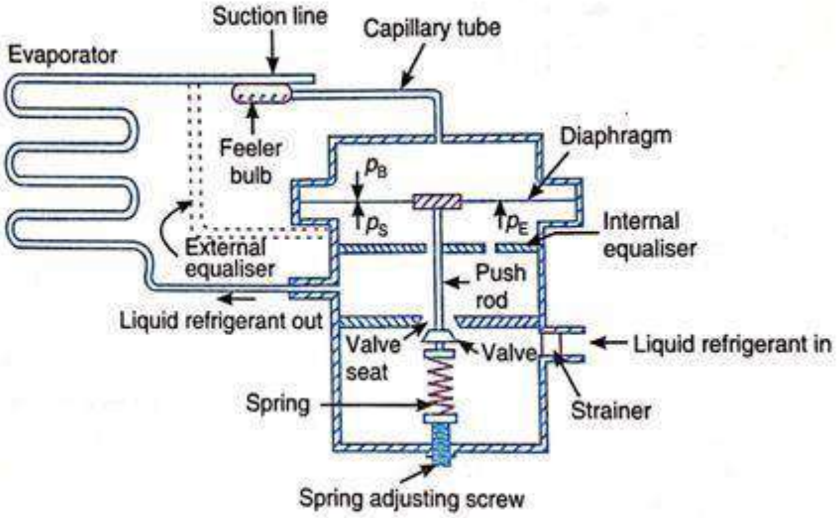


- When the compressor is running, the valve maintains an evaporator pressure in equilibrium with the spring pressure and the atmospheric pressure.

- The spring pressure can be varied by adjusting the tension of the spring with the help of spring adjusting screw.
- Once the spring is adjusted for a desired evaporator pressure, then the valve operates automatically to maintain constant evaporator pressure by controlling the flow of refrigerant to the evaporator.
- When the evaporator pressure falls down, the diaphragm moves downwards to open the valve. This allows more liquid refrigerant to enter into the evaporator and thus increasing the evaporator pressure till the desired evaporator pressure is reached.
- On the other hand, when the evaporator pressure rises, the diaphragm moves upwards to reduce the opening of the valve.
- This decreases the flow of liquid refrigerant to the evaporator which, in turn, lowers the evaporator pressure till the desired evaporator pressure is reached.
- When the compressor stops, the liquid refrigerant continues to flow into the evaporator and increases the pressure in the evaporator. This increase in evaporator pressure causes the diaphragm to move upwards and the valve is closed. It remains closed until the compressor starts again and reduces the pressure in the evaporator.

Thermostatic Expansion Valve

- This is also called a constant superheat valve because it maintains a constant superheat of the vapour refrigerant at the end of the evaporator coil, by controlling the flow of liquid refrigerant through the evaporator.
- The thermostatic expansion valve consists of a needle valve and a seat, a metallic diaphragm, spring and an adjusting screw. In addition to this, it has a feeler or thermal bulb which is mounted on the suction line near the outlet of the evaporator coil. The feeler bulb is partly filled with the same liquid refrigerant as used in the refrigeration system.



Working Principle:

- The thermostatic expansion valve consists of a needle valve, a seat, a metallic diaphragm, a spring, adjusting screw and a feeler bulb.
- The opening or closing of valve depends upon following forces acting on the diaphragm:
    - Spring pressure acting on bottom of diaphragm
    - Evaporator pressure acting on bottom of diaphragm
    - Feeler bulb pressure acting on top of diaphragm
- If load on evaporator increases, it causes the liquid refrigerant to boil faster in evaporator coil. Since feeler bulb is installed on the suction line, therefore it is at the same temperature as refrigerant at that point. So temperature of the bulb increases due to early vaporization of refrigerant.
- Thus the feeler bulb pressure increases and gets transmitted through the capillary tube to the diaphragm. The diaphragm moves downwards, opening the valve to admit more liquid refrigerant into the evaporator.
- This continues till pressure equilibrium on diaphragm is reached, at which feeler bulb pressure acting at top of diaphragm is balanced by spring and evaporator pressure acting at bottom of diaphragm.
- When evaporator load decreases, less liquid refrigerant evaporates in the coil, and the excess liquid flows towards the outlet. This cools the feeler bulb and its pressure and temperature decreases.
- This pressure makes the diaphragm move upward, reducing the valve opening and in turn decreasing refrigerant flow to evaporator. These causes decrease in evaporator pressure and again continue till diaphragm pressure equilibrium is reached.

Classification of Refrigerants:

The refrigerants may, broadly, be classified into the following two groups:

1. **Primary refrigerants, and**
2. **Secondary refrigerants.**

The refrigerants which directly take part in the refrigeration system are called primary refrigerants whereas the refrigerants which are first cooled by primary refrigerants and then us& for cooling purposes are known as secondary refrigerants.

Primary Refrigerate: The refrigerant which directly take part in the refrigeration system are called primary refrigerant.

Secondary Refrigerant: The refrigerant which are first cooled by primary refrigerant and then used for cooling purpose are known as secondary refrigerant Example: Brine Solution (Salt + Water)

The primary refrigerants are further classified into the following four groups :

1. Halo-carbon or organic refrigerants,
2. Azeotrope refrigerants,
3. Inorganic refrigerants, and
4. Hydro-carbon refrigerants.

Brine solution is an example of secondary refrigerant. Brine solution is a solution of water and salt. Since salt decreases the freezing point of the water, so it prevents from freezing.

Desirable Properties of an Ideal Refrigerant

A refrigerant is said to be ideal if it has all of the following properties:

1. Low boiling and freezing point,
2. High critical pressure and temperature,
3. High latent heat of vaporization,
4. Low specific heat of liquid, and high specific heat of vapour,
5. Low specific volume of vapour,
6. High thermal conductivity,
7. Non-corrosive to metal,
8. Non-flammable and non-explosive,
9. Non-toxic,
10. Low cost,
11. Easily and regularly available,
12. Easy to liquify at moderate pressure and temperature,
13. Easy of locating leaks by odour or suitable indicator,
14. Mixes well with oil,
15. High coefficient of performance, and
16. Ozone friendly. The standard comparison of refrigerants, as used in the refrigeration industry, is based on an evaporating temperature of — 15°C and a condensing temperature of + 30° C.

Designation System for Refrigerants

- The refrigerants are internationally designated as **R** followed by certain numbers such as R-11, R-12, R-I14 etc.
- A refrigerant followed by a two-digit number indicates that a refrigerant is derived from methane base while three-digit number represents ethane· Base. The number assigned to hydrocarbon and halocarbon refrigerants have a special meaning.
- The first digit on the right is the number of fluorine (F) atoms in the refrigerant.

- The second digit from the right is one more than the hydrogen (H) atoms present.
- The third digit from the right is one less than the number of Carbon(C) atoms, but when this digit is zero, it is omitted.
- The general chemical formula for the refrigerant, either for methane or ethane base, is given by **R (m-1)(n+1) q where** $n + p + q = 2m + 2$

where m = Number of carbon atoms,

n = Number of hydrogen atoms,

p = Number of chlorine atoms, and

q = Number of fluorine atoms.

As discussed above, the number of the refrigerant is given by $R\ (m - 1)(n + 1)\ (q)$.

I. Dichloro-difluoro-methane

Number of chlorine atoms, p = 2

Number of fluorine atoms, q = 2

and number of hydrogen atoms, n = 0

We know that n+p + q = 2m + 2

0 + 2 + 2 = 2m+ 2 or m= 1

That is Number of carbon atoms = 1

Thus, the chemical formula for dichloro-difluoro-methane becomes CCl_2F_2 and the number of refrigerants becomes R (1-1) (0+1)(2) or R-012 *i.e.* R-12.

2. Dichloro- tetrafluoro -ethane

We see that in this refrigerant

Number of chlorine atoms, $p = 2$

Number of fluorine atoms, $q = 4$

and number of hydrogen atoms, n = 0 We know that n + p + q = 2m + 2 0 + 2 + 4 = 2m + 2 i.e. Number of carbon atoms = 2

Or m = 2

Thus, the chemical formula for dichloro-tetrafluoro-ethane becomes $C_2C1_2F_4$ and the number of refrigerants becomes R (2-1) (0+1) (4) or R-114.

3. DiChloro-trifluoro-ethane

Number of chlorine atoms, p = 2

Number of fluorine atoms, q = 3

and number of hydrogen atoms, n = 1

We know that n + p + q = 2m + 2 1 + 2 + 3 = 2m + 2 or m = 2

i.e. Number of carbon atoms = 2

Thus, the chemical formula for dichloro-trifluoro-ethane becomes $CHCl_2CF_3$ and the number of refrigerants becomes R(2 — 1) (1 + 1) (3) or R-123.

The inorganic refrigerants are designated by adding 700 to the molecular mass of the compound. For example, the molecular mass of ammonia is 17, therefore it is designated by R-(700 + 17) or 12-717.

Thermodynamic Properties of Refrigerants

1. Boiling temperature.

The boiling temperature of the refrigerant at atmospheric pressure should be low. If the boiling temperature of the refrigerant is high at atmospheric pressure, the compressor should be operated at high vacuum. The high boiling temperature reduces the capacity and operating cost of the system.

2. Freezing temperature

The freezing temperature of a refrigerant should be well below the operating evaporator temperature. Since the freezing temperature of most of the refrigerants are below - 35°C, therefore this property is taken into consideration only in low temperature operation.

3. Evaporator and condenser pressure.

Both the evaporating (low side) and condensing (high side) pressures should be positive (i.e. above atmospheric) and it should be as near to the atmospheric pressure as possible. The positive pressures are necessary in order to prevent leakage. of air and moisture into the refrigerating system. It also permits easier detection of leaks. Too high evaporating and condensing pressures (above atmospheric) would require stronger refrigerating equipment (i.e. compressor, evaporator and condenser) resulting in higher initial cost.

4. Critical temperature and pressure.

The critical temperature of a refrigerant is the highest temperature at which it can be condensed to a liquid, regardless of a higher pressure. It should be freezing the highest condensing temperature that might be encountered. If the critical temperature of a refrigerant is too-near the desired condensing temperature, the excessive power consumption results.

5. Coefficient of performance and power requirements.

For an ideal refrigerant operating between — 15°C evaporator temperature and 30°C condenser temperature, the theoretical coefficient of performance for the reversed Carnot cycle is 5.74.

6. Latent heat of vaporization.

A refrigerant should have a high latent heat of vaporization at the evaporator temperature. The high latent heat results in high refrigerating effect per kg of refrigerant circulated which reduces the mass of refrigerant to be circulated per tonne of refrigeration. Table 8.10 shows the refrigerating effect for the common refrigerants operating between — 15°C evaporator temperature and 30°C condenser temperature. It also shows the latent heat; mass of refrigerant circulated per tonne of refrigeration and the volume of the liquid refrigerant per tonne of refrigeration.

7. Specific volume.

The specific volume of the refrigerant vapour at evaporator temperature (Le. volume of suction vapour to the compressor) indicates the theoretical displacement of the compressor. The reciprocating compressors are used with refrigerants having high pressures and low volumes of the suction vapour. The centrifugal or turbo compressors are used with refrigerants having low pressures and high volumes of the suction vapour. The rotary compressors are used with refrigerants having intermediate pressures and volumes of the suction vapour.

Chemical Properties of Refrigerants

1. Flammability: We have already discussed that hydro-carbon refrigerants such as ethane, propane etc. are highly flammable. Ammonia is also somewhat flammable and becomes explosive when mixed with air in the ratio of 16 to 25 per cent of gas by volume. The halo-carbon refrigerants are neither flammable nor explosive.

2. Toxicity: The toxicity of refrigerant may be of prime or secondary importance, depending upon the application. Some non-toxic refrigerants (i.e. all fluorocarbon refrigerants) when mixed with certain percentage of air become toxic. The following table shows the relative toxicity of the common refrigerants. based upon the concentration and exposure time required to produce serious results.

3. Solubility of water: Water is only slightly soluble in R-12. At — 18°C, it will hold six parts per million by weight. The solution formed is very slightly corrosive to any of the common metals. The solubility of water with R-22 is more than R-12 by a ratio of 3 to 1. If more water is present than can be dissolved by the refrigerant, the ice will be formed which chokes the expansion valve or capillary tube used for throttling in the system. This may be avoided by the proper dehydration of the refrigerating unit before charging and by the use of silica gel drier of the liquid line. Ammonia is highly soluble in water. Due to this reason, a wetted cloth is put at the point of leak to avoid harm to the persons working in ammonia refrigerating plants.

4. Miscibility: The ability of a refrigerant to mix with oil is called miscibility. This property of refrigerant is considered to be a secondary factor in the selection of a refrigerant. The degree of miscibility depends upon the temperature of the oil and pressure of the refrigerating vapour.

The freon group of refrigerants are highly miscible refrigerants while ammonia, carbon dioxide, Sulphur dioxide and methyl chloride are relatively non-miscible. The non-miscible refrigerants require larger heat transfer surfaces due to poor heat conduction properties of oil. The miscible refrigerants are advantageous from the heat transfer point of view. They give better lubrication as the refrigerant acts as a carrier of oil to the moving parts. The miscible refrigerants also eliminate oil-separation problems and aid in the return of oil from the evaporator.

5. Effect on perishable materials: The refrigerants used in cold storage plant and in domestic refrigerators should be such that in case of leakage, it should have no effect on the perishable materials. The freon group of refrigerants have no effect upon dairy products, meats, vegetables, flowers and furs. There will be no change in colour, taste or texture of the material when exposed to freon. Methyl chloride vapours have no effect upon furs, flowers, eating foods or drinking beverages. Sulphur dioxide destroys flowers, plants and furs, but it does not affect foods. Ammonia dissolves easily in water and becomes alkaline in nature. Since most fruits and vegetables are acidic in nature, therefore ammonia reacts with these products and spoils the taste.

commonly used refrigerants, R-11, R-12, R-22, R-134a, R-717

R-11

R-11 is a colorless and odorless CFC refrigerant that was completely banned from production by 1996 under the Montreal Protocol for depleting the ozone. It is a low-pressure refrigerant that was commonly used in centrifugal chillers and before the 1970's it was used as a propellant for aerosols. The refrigerant is typically stored in orange drums or containers. Chemical Name: Trichlorofluoromethane.

Most Common Replacement: R-123 (HCFC), being phased out in 2020 for the United States and other developed countries.

Refrigerant R12 or Freon 12

Refrigerant R12 or Freon 12 is said to be the most widely used of all the refrigerants being used for different applications. The chemical name of refrigerant R12 is dichlorodifluoromethane and its chemical formula is CCl2F2. The molecular weight of R12 is 120.9 and its boiling point is -21.6-degree F. Since R12 has the molecules of chlorine and fluorine, it is called as chlorofluorocarbon (CFC).

R22

R22, commonly known as "Freon." R22 is an A/C refrigerant — a substance used for cooling in air conditioners— that was once widely used in air conditioning units in homes and businesses alike. But, after years of using R22 in air conditioning units of all sizes, it was discovered that R22 is a dangerous chemical that was significantly contributing to the thinning in the ozone layer.

R134a Refrigerant

R134a is also known as Tetrafluoroethane (CF3CH2F) from the family of HFC refrigerant. With the discovery of the damaging effect of CFCs and HCFCs refrigerants to the ozone layer, the HFC family of refrigerant has been widely used as their replacement. It is now being used as a replacement for R-12 CFC refrigerant in the area of centrifugal, rotary screw, scroll and reciprocating compresssors. It is safe for normal handling as it is non-toxic, non-flammable and non-corrosive.

R717 (Ammonia)

R717 (Ammonia) is refrigerant grade Ammonia (NH3) used in low and medium temperature refrigeration. It is a colourless, pungent, highly toxic gas but is a very efficient refrigerant with zero Global Warming Potential (GWP).

Applications: Industrial Refrigeration

Product Features & Benefits

- Refrigerant can be charged from either the liquid or vapour phase
- Toxic, low-flammability with a safety classification of B2L
- Compressors can be charged with a variety of oils, contact the compressor manufacturer for more information
- Under pressure Ammonia is stored as a liquid
- Moisture content of less than 200ppm

Substitute For CFC

Two of the chemical classes under consideration for replacing CFCs are hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs). HCFCs contribute to the destruction of stratospheric ozone, but to a much lesser extent than CFCs. Use of HCFCs as transitional refrigerants will allow industry to phase out the production of CFCs and will offer environmental benefits over the continued use of CFCs. Because they contain hydrogen, HCFCs break down more easily in the atmosphere than do CFCs. Therefore, HCFCs have less ozone depletion potential, in addition to less global-warming potential.

Cold storage

Generally, cold storage is cooled by refrigerator, using the liquid with low gasification temperature as refrigerant, making it evaporate under the condition of low pressure and mechanical control and absorb the heat in the cold storage, finally to achieve the purpose of cooling. The most commonly used is the compressor refrigerator, mainly made up of compressor, condenser, throttle valve and evaporator, and so on. It can be divided into direct cooling and indirect cooling according to the way of evaporation tube device. The direct cooling installs the evaporator in the cold storage, whereas indirect cooling uses blower to suck the air in the cold storage into the air-cooling device. The advantage of the air cooling is cooling rapidly, uniform temperature etc.

Dairy refrigeration

Dairy is an indispensable part of the global food system and it plays a crucial role in the sustainability of rural areas in particular. It is a well-known fact that the dairy industry actively contributes to the economies of a number of countries. An increasing demand worldwide is noticeably emerging at present, and the industry is globalizing. Milk and dairy products are very essential for human nutrition and development, especially, in children. Although milk is a highly nourishing food, raw fresh milk is highly liable to rot and can be easily spoiled by the growth of microorganisms. Fresh milk is collected from the farm, transported to cooling centers to prevent spoilage, then to processing units to produce other dairy products and finally delivered to the consumers in several ways, as shown in figure 1. The transportation of fresh milk from farms to cooling centers and processing units may take time. Consequently, cooling milk in time becomes major problem associated with raw fresh milk. The milk should be cooled within three to four hours of collecting it from the farm, which otherwise leads to spoilage. Thus, refrigeration plays a vital role in dairy industry.

Ice plant

The function of an ice plant or ice factory is to make or form ice in large quantity and in large size. The ice making process is quite similar to the one we observe in a domestic refrigerator. The only difference lies in the ice making the stage. In the freezer compartment, the tray with water when it comes in contact with very low-temperature environment, becomes ice but in an ice plant which is a huge commercial factory, it uses separate ice making or ice freezing circuit. The cold is produced in one circuit and it is transferred to the water cans by another circuit.

Ammonia: It is the primary refrigerant which takes heat from brine. This ammonia changes phase while moving in the circuit

Brine: It is the secondary refrigerant which takes heat from the water and produces ice.

Water cooler

Water coolers usually use a condenser/evaporator type cooling system with a compressor to change the refrigerant state from gas to liquid. Older water coolers, some of which are still in use, used Freon, or R-12 refrigerant to cool the water. This refrigerant has been replaced by what are considered less harmful refrigerants like R-134a, and possibly R-22 depending on when and by whom they were built. Refrigerants are used depending on their boiling point (lower for freezers and ice machines, higher, but still cold for refrigeration units and air conditioning systems), so these are two that fit the temperature range suitable for water coolers.

Frost free refrigerator

This frost forms when water vapor hits the cold coils. The water vapor condenses -- turns to liquid water. Think of the water beading up on a glass of iced tea on a summer day -- that is an example of water vapor in the air condensing. The same thing happens on the ice-cold freezer coils, except that when the water condenses onto the coils it immediately freezes.

A frost-free freezer has three basic parts:

A timer

A heating coil

A temperature sensor

Every six hours or so, the timer turns on the heating coil. The heating coil is wrapped among the freezer coils. The heater melts the ice off the coils. When all of the ice is gone, the temperature sensor senses the temperature rising above 32 degrees F (0 degrees C) and turns off the heater. Heating the coils every six hours takes energy, and it also cycles the food in the freezer through temperature changes. Most large chest freezers therefore require manual defrosting instead -- the food lasts longer and the freezer uses less power.

SHORT QUESTION WITH ANSWER :

1. Define refrigerant ? [2009s, 2020w]

Ans : Refrigerant is a heat carrying medium used in refrigeration system which absorb heat in evaporator chamber and reject it in condenser.

2. State any four important properties of Freon-12 [2009 BP]

Ans : Non Flammable, Non Toxic, Colorless, Has no smell

3. State four important properties of refrigerant. [2007s]

1. Low boiling and freezing point,
2. High critical pressure and temperature,
3. High latent heat of vaporisation,
4. Low specific heat of liquid, and high specific heat of vapour,
5. Low specific volume of vapour,
6. High thermal conductivity,
7. Non-corrosive to metal

4. What is the use of refrigerant ? [2006s]

Ans : A refrigerant is chemical compound that is used as the heat carrier, which changes from gas to liquid and then back to gas in the refrigeration cycle. Refrigerants are used primarily in refrigerators/freezers, air-conditioning, and fire suppression systems.

5. Define primary and secondary refrigerant. [2012, 2020w]

Ans :

Primary Refrigerate : The refrigerant which directly take part in the refrigeration system are called primary refrigerant.

Secondary Refrigerant : The refrigerant which are first cooled by primary refrigerant and then used for cooling purpose are known as secondary refrigerant Example : Brine Solution (Salt + Water)

6. Write the chemical formula for R11 and R113, R 21, R22, R 13

refrigerant	**chemical**	**name**
R11	$CCl3F$	**trichloro-fluoro-methane**
R12	$CCl2F2$	dichloro-difluoro-methane
R13	$CClF3$	chloro-trifluoro-methane
R21	$CHCl_2F$	Dichlorofluoromethane
R22	$CHClF_2$	**Difluorochloromethane**
R113	$Cl_2FC\text{-}CClF_2$	**trichlorotrifluoroethane**

7. What are the physical properties of refrigerant ? [2020w]

Ans :

- Stability and inertness
- Corrosive
- Viscocity
- Thermal conductivity
- Dielectric strength
- Leakage tendency
- Cost

LONG QUESTIONS

1. State the desirable properties of ideal refrigerant. [2010s, 2009s, 2011w, 2012w, 2014w, 2020w]

2. Explain the working principle of thermostatic expansion valve ?

3. Explain the working principle of Automatic (or Constant Pressure) Expansion Valve ?

4. _. Explain the working principle of hand operated Expansion Valve ?

PSYCHROMETRICS & COMFORRT AIR CONDITIONING SYSTEM

6. 1 Psychrometric Terms

Though there are many psychrometric terms, yet the following are important from the subject point of view :

1. Dry air.

The pure dry air is a mixture of a number of gases such as nitrogen, oxygen, carbon dioxide, hydrogen, argon, neon, helium etc. But the nitrogen and oxygen have the major portion of the combination. The molecular mass of dry air is taken as 28.966 and the gas constant of air (R a) is equal to 0.287 kJ/kg K or 287 J/kg K. The molecular mass of water vapour is taken as 18.016 and the gas constant for water vapour (Ra) is equal to 0.461 kJ/kg K or 461.J/kg K.

2. Moist air.

It is a mixture of dry air and water vapour. The amount of water vapour present in the air depends upon the absolute pressure and temperature of the mixture. 3. Saturated air. It is a mixture of dry air and water vapour, when the air has diffused the maximum amount of water vapour into it. The water vapours, usually, occur in the form of superheated steam as an invisible gas.

4. Degree of saturation.

It is the ratio of actual mass of water vapour in a unit mass of dry air to the mass of water vapour in the same mass of dry air when it is saturated at the same temperature.

5. Humidity.

It is the mass of water vapour present in 1 kg of dry air, and is generally expressed in terms of gram per kg of dry air (g / kg of dry air). It is also called specific humidity or humidity ratio.

6. Absolute humidity.

It is the mass of water vapour present in 1 m3 of dry air, and is generally expressed in terms of gram per cubic metre of dry air (g /m3 of dry air)• It is also expressed in terms of grains per cubic metre of dry air. Mathematically, one kg of water vapour is equal to 15 430 grains.

7. Relative humidity.

It is the ratio of actual mass of water vapour in a given volume of moist air to the mass of water vapour in the same volume of saturated air at the same temperature and pressure. It is briefly written as R_H.

8. Dry bulb temperature.

It is the temperature of air recorded by a thermometer, when it is not affected by the moisture present in the air. The dry bulb temperature (briefly written as DBT) is generally denoted by td or t_{db}.

9. Wet bulb temperature.

It is the temperature of air recorded by a thermometer, when its bulb is surrounded by a wet cloth exposed to the air. Such a thermometer is called 'wet bulb thermometer. The wet bulb temperature (briefly written as WBT) is generally denoted by tw, or t_{wb}.

10. Wet bulb depression.

It is the difference between dry bulb temperature and wet bulb temperature at any point. The wet bulb depression indicates relative humidity of the air.

11. Dew point temperature.

It is the temperature of air recorded by a thermometer, when the moisture (water vapour), present in it begins to condense. In other words, the dew point temperature is the temperature corresponding to the partial pressure of water vapour (Pv).

12. Dew point depression.

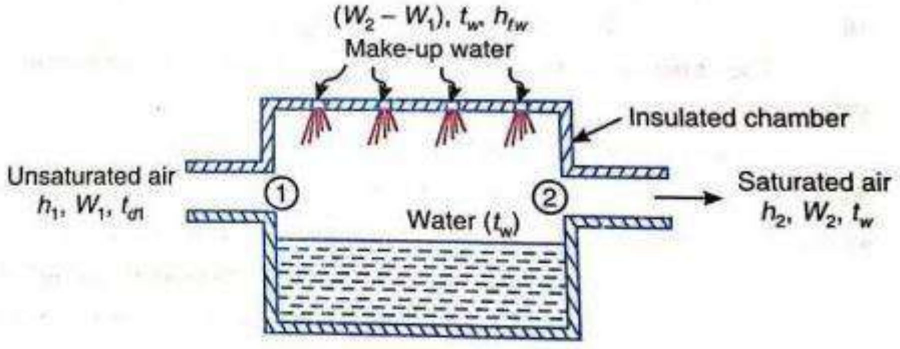
It is the difference between the dry bulb temperature and dew point temperature of air.

6. 2 Thermodynamic Wet Bulb Temperature or Adiabatic Saturation Temperature

The thermodynamic wet bulb temperature or adiabatic saturation temperature is the temperature at which the air can be brought to saturation state, adiabatically, by the evaporation of water into the flowing air.

The equipment used for the adiabatic saturation of air, in its simplest form, consists of an insulated chamber containing adequate quantity of water. There is also an arrangement for extra water (known as make-up water) to flow into the chamber from its top.

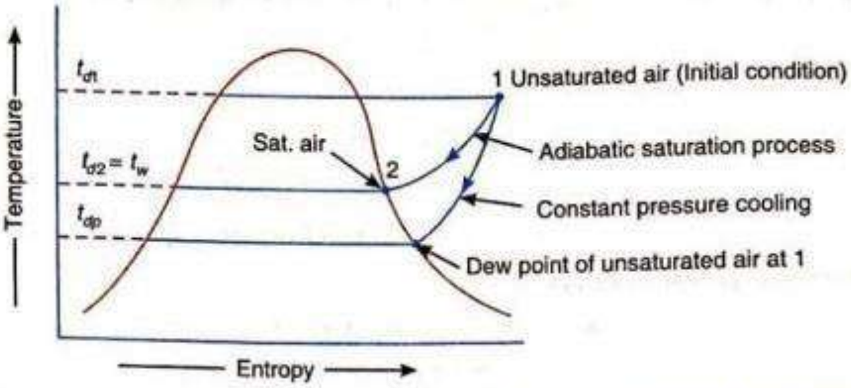
Let the unsaturated air enters the chamber at section 1. As the air passes through the chamber over a long sheet of water, the water evaporates which is carried with the flowing stream of air, and the specific humidity of the air increases.



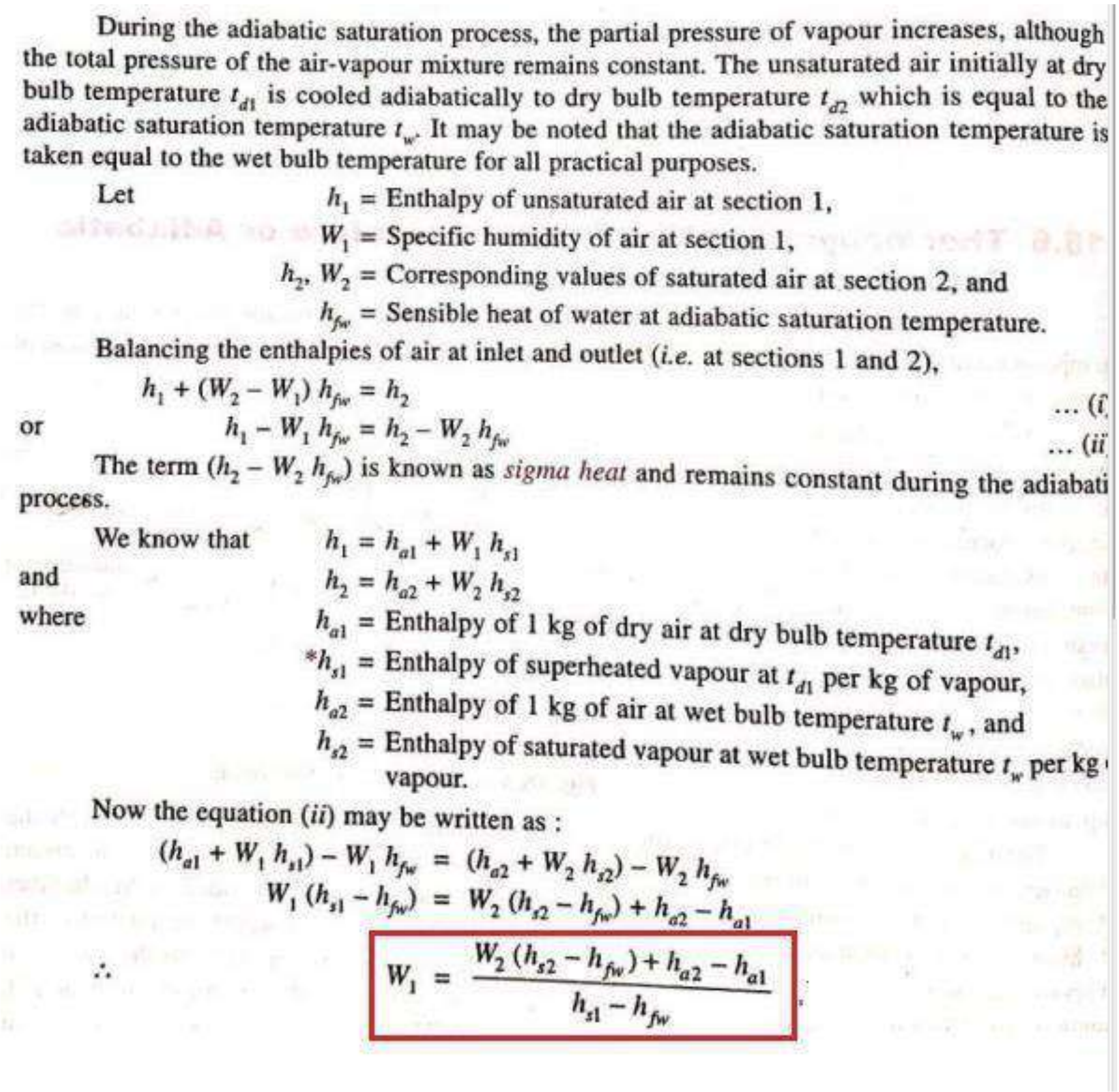
. Adiabatic saturation of air.

The make-up water is added to the chamber at this temperature to make the water level constant. Both the air and water are cooled as the evaporation takes place. This process continues until the energy transferred from the air to the water is equal to the energy required to vaporise the water. When steady conditions are reached, the air flowing at section 2 is saturated with water vapour. The temperature of the saturated air at section -2 is known as thermodynamic wet bulb temperature or adiabatic saturation temperature.

The adiabatic saturation process can be represented on *T-s* diagram as shown by the curve 1-2



T-s diagram for adiabatic saturation process.



During the adiabatic saturation process, the partial pressure of vapour increases, although the total pressure of the air-vapour mixture remains constant. The unsaturated air initially at dry bulb temperature t_{d1} is cooled adiabatically to dry bulb temperature t_{d2} which is equal to the adiabatic saturation temperature t_w. It may be noted that the adiabatic saturation temperature is taken equal to the wet bulb temperature for all practical purposes.

Let h_1 = Enthalpy of unsaturated air at section 1,
W_1 = Specific humidity of air at section 1,
h_2, W_2 = Corresponding values of saturated air at section 2, and
h_{fw} = Sensible heat of water at adiabatic saturation temperature.

Balancing the enthalpies of air at inlet and outlet (*i.e.* at sections 1 and 2),

$$h_1 + (W_2 - W_1)\, h_{fw} = h_2 \qquad \text{... (}i$$

or

$$h_1 - W_1\, h_{fw} = h_2 - W_2\, h_{fw} \qquad \text{... (}ii$$

The term $(h_2 - W_2\, h_{fw})$ is known as *sigma heat* and remains constant during the adiabati process.

We know that $h_1 = h_{a1} + W_1\, h_{s1}$

and $h_2 = h_{a2} + W_2\, h_{s2}$

where h_{a1} = Enthalpy of 1 kg of dry air at dry bulb temperature t_{d1},
*h_{s1} = Enthalpy of superheated vapour at t_{d1} per kg of vapour,
h_{a2} = Enthalpy of 1 kg of air at wet bulb temperature t_w, and
h_{s2} = Enthalpy of saturated vapour at wet bulb temperature t_w per kg vapour.

Now the equation (*ii*) may be written as :

$$(h_{a1} + W_1\, h_{s1}) - W_1\, h_{fw} = (h_{a2} + W_2\, h_{s2}) - W_2\, h_{fw}$$

$$W_1\,(h_{s1} - h_{fw}) = W_2\,(h_{s2} - h_{fw}) + h_{a2} - h_{a1}$$

$$\therefore \qquad \boxed{W_1 = \frac{W_2\,(h_{s2} - h_{fw}) + h_{a2} - h_{a1}}{h_{s1} - h_{fw}}}$$

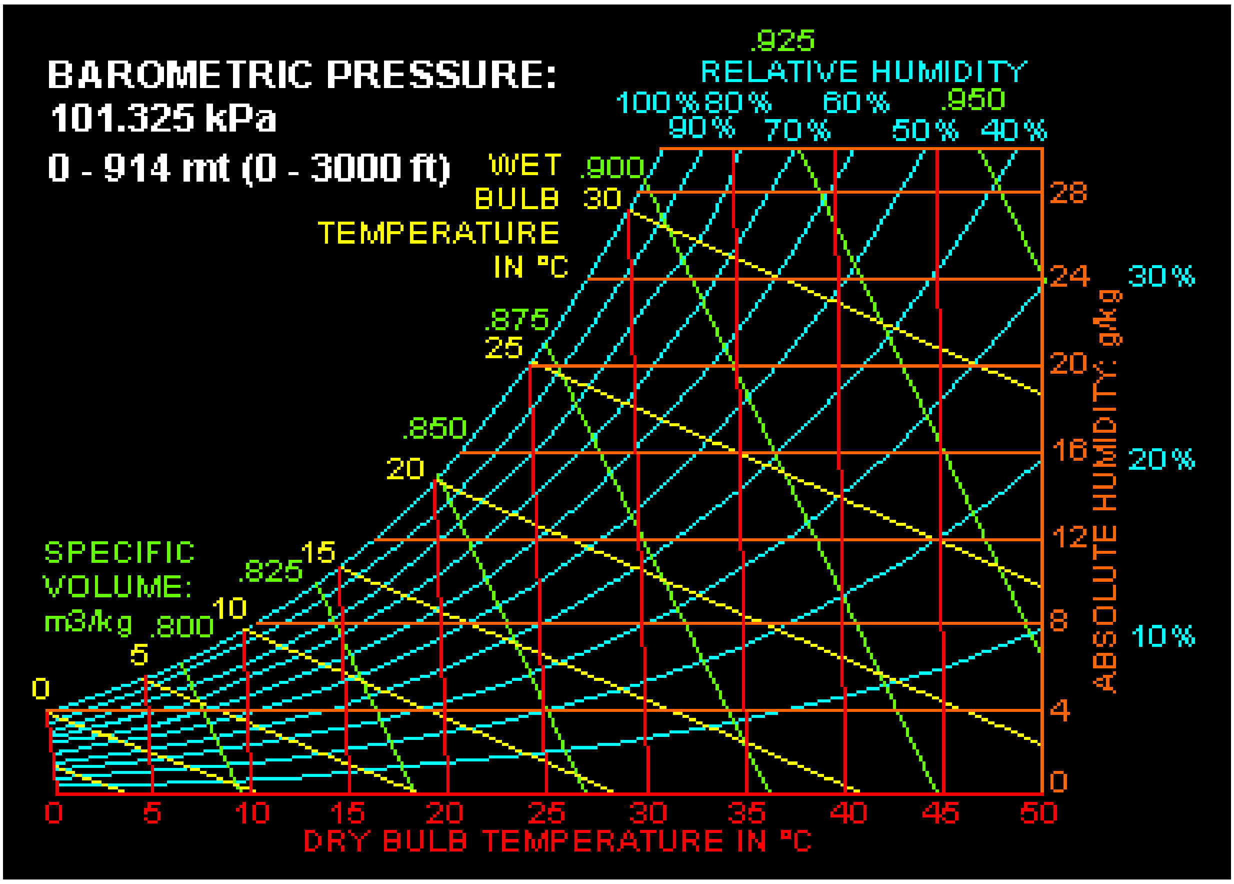
Psychrometric Chart :

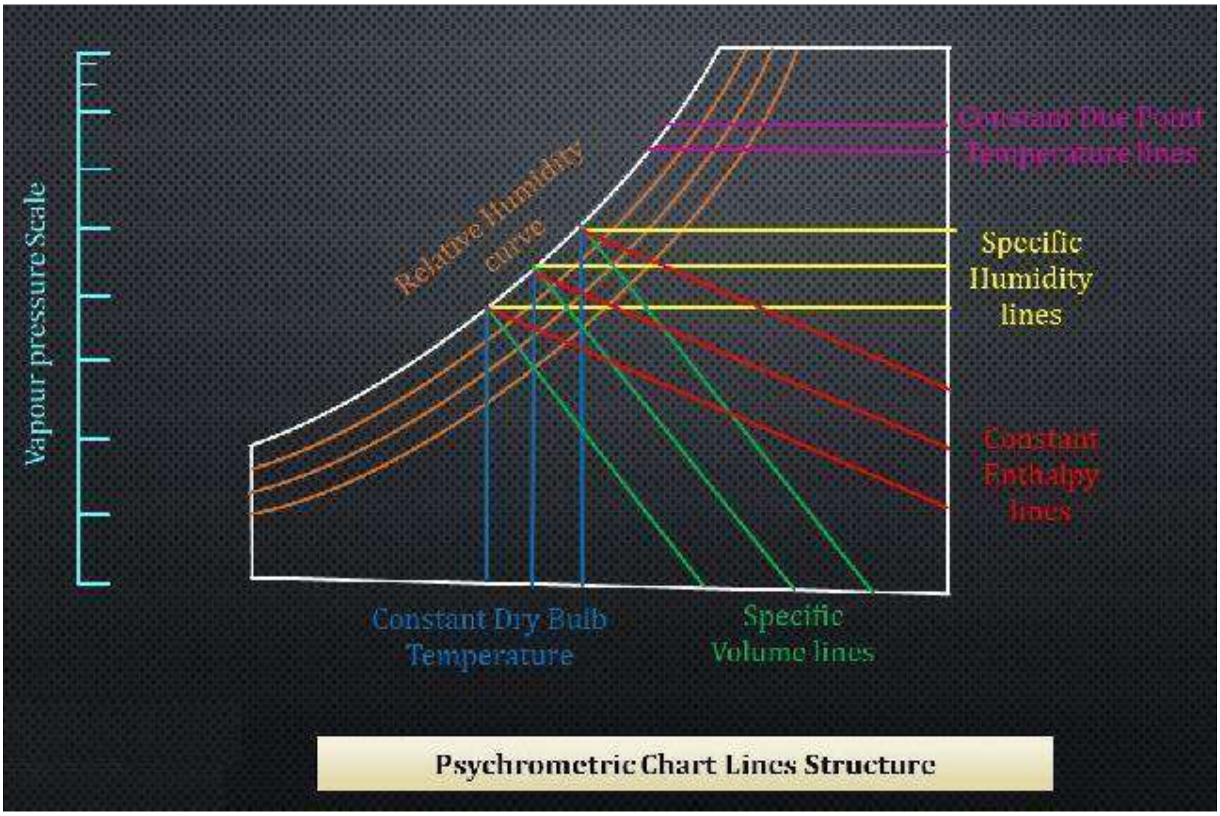
It is the graphical representation of various thermodynamic properties of moist air. The pyschrometric chart is very useful for finding out the properties of air and eliminate a lot of calculations. The psychrometric chart is normally drawn for standard atmosphere pressure of 760 mm of Hg.

Example : 1

For a sample of air having 22 degree DBT, relative humidity 30% at barometric pressure of 760 mm of Hg.

Calculate 1. Vapour pressure 2. Humidity ratio 3. Vapour density and 64. Enthalpy Verify your result by psychro metric chart.





Psychrometric Chart Lines Structure

1. *Vapour pressure*

Let p_v = Vapour pressure.

From steam tables, we find that the saturation pressure of vapour corresponding to dry bulb temperature of 22° C is

$$p_s = 0.026\,42 \text{ bar}$$

We know that relative humidity (ϕ),

$$0.3 = \frac{p_v}{p_s} = \frac{p_v}{0.026\,42}$$

$$\therefore \quad p_v = 0.3 \times 0.026\,42 = 0.007\,926 \text{ bar} \quad \textbf{Ans.}$$

2. *Humidity ratio*

We know that humidity ratio,

$$W = \frac{0.622\,p_v}{p_b - p_v} = \frac{0.622 \times 0.007\,926}{1.013\,08 - 0.007\,926}$$

$$= 0.0049 \text{ kg/kg of dry air} \quad \textbf{Ans.}$$

3. *Vapour density*

We know that vapour density,

$$\rho_v = \frac{W\,(p_b - p_v)}{R_a\,T_d} = \frac{0.0049\,(1.013\,08 - 0.007\,926)\,10^5}{287\,(273 + 22)}$$

$$= 0.005\,82 \text{ kg/m}^3 \text{ of dry air} \quad \textbf{Ans.}$$

4. *Enthalpy*

From steam tables, we find that saturation temperature or dew point temperature corresponding to a pressure of $p_v = 0.007\,926$ bar is

$$t_{dp} = 3.8° \text{ C}$$

and latent heat of vaporisation of water at dew point temperature of 3.8° C is

$$h_{fgdp} = 2492.6 \text{ kJ/kg}$$

We know that enthalpy,

$$h = 1.022\,t_d + W\,(h_{fgdp} + 2.3\,t_{dp})$$

$$= 1.022 \times 22 + 0.0049\,(2492.6 + 2.3 \times 3.8)$$

$$= 22.484 + 12.256 = 34.74 \text{ kJ/kg of dry air} \quad \textbf{Ans.}$$

Verification from psychrometric chart

The initial condition of air *i.e.* 22° C dry bulb temperature and 30% relative humidity is marked on the psychrometric chart at point *A* as shown in Fig. 16.15.

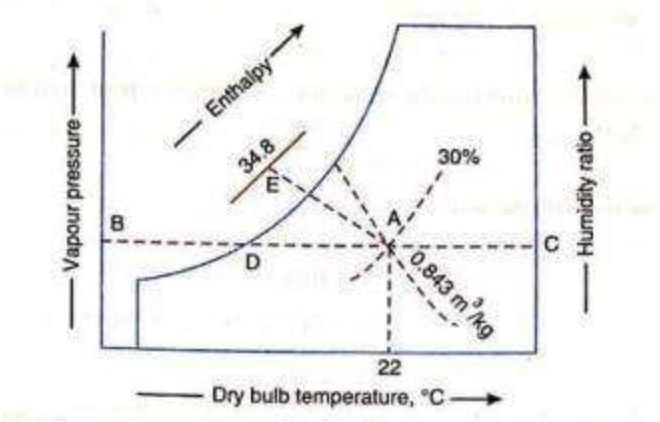
From point *A*, draw a horizontal line meeting the vapour pressure line at point *B* and humidity ratio line at *C*. From the psychrometric chart, we find that vapour pressure at point *B*,

$$p_v = 5.94 \text{ mm of Hg}$$

$$= 5.94 \times 133.3 = 791.8 \text{ N/m}^2 = 0.007\,918 \text{ bar} \quad \textbf{Ans.}$$

and humidity ratio at point *C*,

$$W = 5 \text{ g/kg of dry air} = 0.005 \text{ kg/kg of dry air} \quad \textbf{Ans.}$$



We also find from the psychrometric chart that the specific volume at point A is 0.843 m^3/kg of dry air.

Vapour density. $Þ_v = W/Þ_a = 0.005/0.843 = 0.0058$ kg/m^3 of dry air

Ans. Now from point A. draw a line parallel to the wet bulb temperature line meeting the enthalpy line at point E. Now the enthalpy of air as read from the chart is 34.8 kJ/kg of dry air.

Psychrometric Processes

The various psychrometric processes involved in air conditioning to vary the psychrometric properties of air according to the requirement are as follows :

1. Sensible heating,
2. Sensible cooling.
3. Humidification and dehumidification,
4. Cooling and adiabatic humidification.
5. Cooling and humidification by water injection,
6. Heating and humidification.
7. Humidification by steam injection,
8. Adiabatic chemical dehumidification.
9. Adiabatic mixing of air streams.

Sensible Heating

The heating of air without any change in its specific humidity, is known as sensible heating. Let air at temperature t_{d1}, passes over a heating coil of temperature t_{d3}. It may be noted that the temperature of air leaving the heating coil (t_{d2}) will be less than t_{d3}. The process of sensible heating, on the psychrometric chart, is shown by a horizontal line 1-2 extending from left to right. The point 3 represents the surface temperature of the heating coil.

The heat absorbed by the air during sensible heating may be obtained from the psychrometric chart by the enthalpy difference (h_2-h_1). It may be noted that the specific humidity during the sensible heating remains constant (i.e. $W_1 = W_2$) . The dry bulb temperature increases from

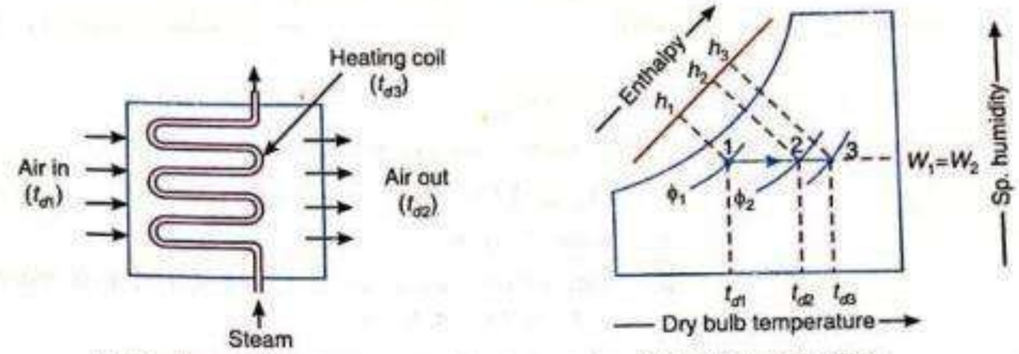
t_{d1}, to t_{d2} and relative humidity reduces from Ø1 to Ø2. The amount of heat added during sensible heating may also be obtained from the relation

Heat added.

$$\begin{aligned} q &= h_2 - h_1 \\ &= c_{pa}(t_{d2} - t_{d1}) + W\, c_{ps}(t_{d2} - t_{d1}) \\ &= (c_{pa} + W\, c_{ps})(t_{d2} - t_{d1}) = c_{pm}(t_{d2} - t_{d1}) \end{aligned}$$

The term $(c_{pa} + W\, c_{ps})$ is called *humid specific heat* (c_{pm}) and its value is taken as 1.022 kJ /kg K.

∴ Heat added, $q = 1.022\,(t_{d2} - t_{d1})$ kJ/kg



(*a*) Psychrometric process.

(*b*) Psychrometric chart.

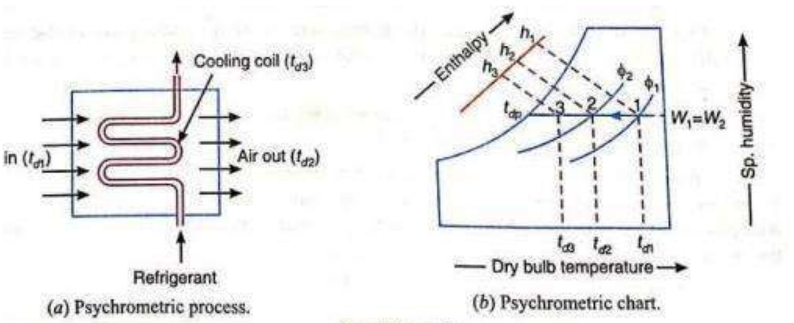
Sensible heating.

Notes : 1. For sensible heating, steam or hot water is passed through the heating coil. The heating coil may be electric resistance coil.

2. The sensible heating of moist air can be done to any desired temperature.

Sensible cooling:

The cooling of air, without any change in its specific humidity, is known as sensible cooling. Let air at temperature t_{d1} passes over a cooling coil of temperature t_{d3} . It may be noted that the temperature of air leaving the cooling coil (t_{d2}) will be more than t_{d3}. The process of sensible cooling, on the psychrometric chart, is shown by a horizontal line 1-2 extending from right to left. The point 3 represents the surface temperature of the cooling coil. The heat rejected by air during sensible cooling may be obtained from the psychometric chart by the enthalpy difference ($h_1 - h_2$). It may be noted that the specific humidity during the sensible cooling remains constant (i.e. W_1=W_2). The dry bulb temperature reduces from t_{d1} to t_{d2} and relative humidity increases from (Ø1 to Ø1). The amount of heat rejected during sensible cooling may also be obtained from the relation:



(*a*) Psychrometric process.

(*b*) Psychrometric chart.

Sensible cooling.

Heat rejected, $q = h_1 - h_2$

$$= c_{pa}(t_{d1} - t_{d2}) + W\,c_{ps}(t_{d1} - t_{d2})$$

$$= (c_{pa} + W\,c_{ps})(t_{d1} - t_{d2}) = c_{pm}(t_{d1} - t_{d2})$$

The term $(c_{pa} + W\,c_{ps})$ is called *humid specific heat* (c_{pm}) and its value is taken as 1.022 kJ /kg K.

$\therefore$ Heat rejected, $q = 1.022\,(t_{d1} - t_{d2})$ kJ/kg

For air conditioning purposes, the sensible heat per minute is given as

$$SH = m_a\,c_{pm}\,\Delta t = v\,\rho\,c_{pm}\,\Delta t \text{ kJ/min} \qquad \ldots (\because\; m = v\,\rho)$$

where v = Rate of dry air flowing in m^3/min,

ρ = Density of moist air at 20° C and 50% relative humidity $= 1.2\ \text{kg/m}^3$ of dry air,

c_{pm} = Humid specific heat = 1.022 kJ /kg K, and

$\Delta t = t_{d1} - t_{d2}$ = Difference of dry bulb temperatures between the entering and leaving conditions of air in ° C.

Substituting the values of ρ and c_{pm} in the above expression, we get

$$SH = v \times 1.2 \times 1.022 \times \Delta t = 1.2264\,v \times \Delta t \text{ kJ/min}$$

$$= \frac{1.2264\,v \times \Delta t}{60} = 0.020\,44\,v \times \Delta t \text{ kJ/s or kW}$$

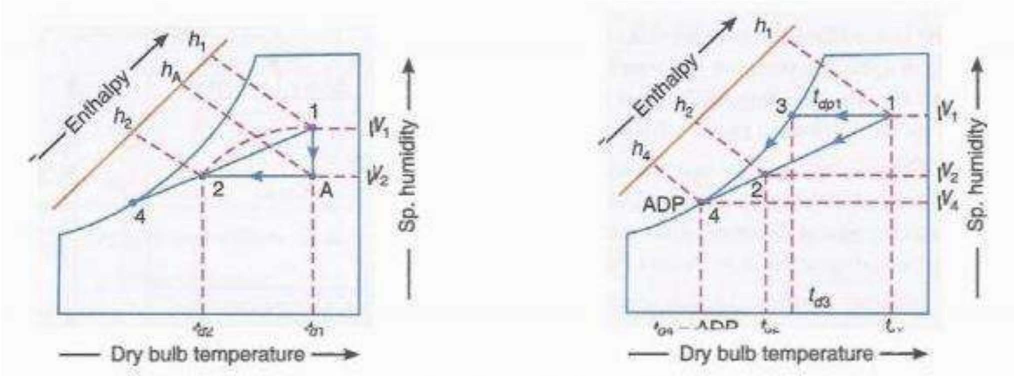
$$\ldots (\because\; 1 \text{ kJ/s} = 1 \text{ kW})$$

Notes : 1. For sensible cooling, the cooling coil may have refrigerant, cooling water or cool gas flowing through it.

2. The sensible cooling can be done only up to the dew point temperature (t_{dp}) as shown in Fig. 16.17 (*b*). The cooling below this temperature will result in the condensation of moisture.

Cooling and Dehumidification

This process is generally used in summer air conditioning to cool and dehumidify the air. The air is passed over a cooling coil or through a cold-water spray. In this process, the dry bulb temperature as well as the specific humidity of air decreases. The final relative humidity of the air is generally higher than that of the entering air. The dehumidification of air is only possible when the effective surface temperature of the cooling coil (t_{d4}) is less than the dew point temperature of the air entering coil (t_{dp1}). The effective surface temperature of the coil is known as apparatus dew point briefly written as ADP). The cooling and dehumidification process is shown in fig.



(a) Cooling and dehumidification. (b)

Let t_{d1} = Dry bulb temperature of air entering the coil,

t_{dp1} = Dew point temperature of the entering air = t_{d3}, and

t_{d4} = Effective surface temperature or *ADP* of the coil.

Under ideal conditions, the dry bulb temperature of the air leaving the cooling coil (*i.e.* t_{d4}) should be equal to the surface temperature of the cooling coil (*i.e. ADP*), but it is never possible due to inefficiency of the cooling coil. Therefore, the resulting condition of air coming out of the coil is shown by a point 2 on the straight line joining the points 1 and 4. The by-pass factor in this case is given by

$$BPF = \frac{t_{d2} - t_{d4}}{t_{d1} - t_{d4}} = \frac{t_{d2} - ADP}{t_{d1} - ADP}$$

Also
$$BPF = \frac{W_2 - W_4}{W_1 - W_4} = \frac{h_2 - h_4}{h_1 - h_4}$$

Actually, the cooling and dehumidification process follows the path as shown by a dotted curve in Fig. (*a*), but for the calculation of psychrometric properties, only end points are important. Thus the cooling and dehumidification process shown by a line 1-2 may be assumed to have followed a path 1-*A* (*i.e.* dehumidification) and *A*-2 (*i.e.* cooling) as shown in Fig. 16.29 (*a*). We see that the total heat removed from the air during the cooling and dehumidification process is

$$q = h_1 - h_2 = (h_1 - h_A) + (h_A - h_2) = LH + SH$$

where $LH = h_1 - h_A$ = Latent heat removed due to condensation of vapour of the reduced moisture content ($W_1 - W_2$), and

$SH = h_A - h_2$ = Sensible heat removed.

We know that sensible heat factor,

$$SHF = \frac{\text{Sensible heat}}{\text{Total heat}} = \frac{SH}{LH + SH} = \frac{h_A - h_2}{h_1 - h_2}$$

Example 1 *In a cooling application, moist air enters a refrigeration coil at the rate of 100 kg of dry air per minute at 35° C and 50% RH. The apparatus dew point of coil is 5° C and by-pass factor is 0.15. Determine the outlet state of moist air and cooling capacity of coil in TR.*

Solution. Given : $m_a = 100$ kg/min ; $t_{d1} = 35°$ C ; $\phi_1 = 50\%$; $ADP = 5°$ C ; $BPF = 0.15$

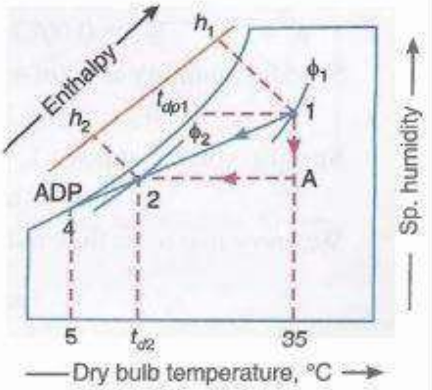
Outlet state of moist air

Let t_{d2} and ϕ_2 = Temperature and relative humidity of air leaving the cooling coil.

First of all, mark the initial condition of air, *i.e.* 35° C dry bulb temperature and 50% relative humidity on the psychrometric chart at point 1, as shown in Fig. 16.30. From the psychrometric chart, we find that the dew point temperature of the entering air at point 1,

$$t_{dp1} = 23° \text{ C}$$

Since the coil or apparatus dew point (*ADP*) is less than the dew point temperature of entering air, therefore it is a process of cooling and dehumidification.



We know that by-pass factor,

$$BPF = \frac{t_{d2} - t_{d4}}{t_{d1} - t_{d4}} = \frac{t_{d2} - ADP}{t_{d1} - ADP}$$

$$0.15 = \frac{t_{d2} - 5}{35 - 5} = \frac{t_{d2} - 5}{30}$$

$$\therefore \quad t_{d2} = 0.15 \times 30 + 5 = 9.5° \text{ C} \quad \textbf{Ans.}$$

From the psychrometric chart, we find that the relative humidity corresponding to a dry bulb temperature (t_{d2}) of 9.5° C on the line 1-4 is $\phi_2 = 99\%$. **Ans.**

Cooling capacity of the coil

The resulting condition of the air coming out of the coil is shown by point 2, on the line joining the points 1 and 4, as shown in Fig. 16.30. The line 1-2 represents the cooling and dehumidification process which may be assumed to have followed the path 1-*A* (*i.e.* dehumidification) and *A*-2 (*i.e.* cooling). Now from the psychrometric chart, we find that enthalpy of entering air at point 1,

$$h_1 = 81 \text{ kJ/kg of dry air}$$

and enthalpy of air at point 2,

$$h_2 = 28 \text{ kJ/kg of dry air}$$

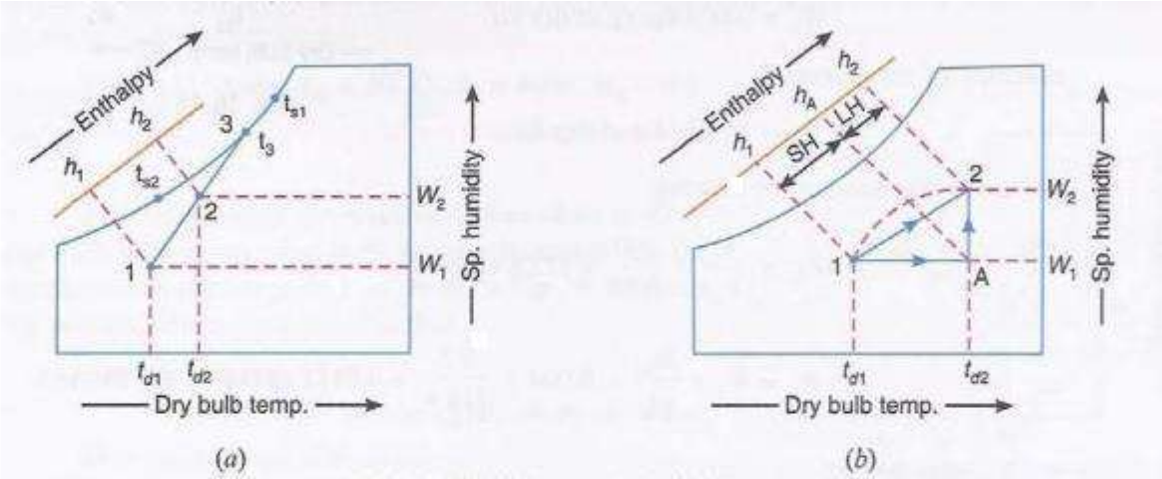
We know that cooling capacity of the coil

$$= m_a (h_1 - h_2) = 100\,(81 - 28) = 5300 \text{ kJ/min}$$

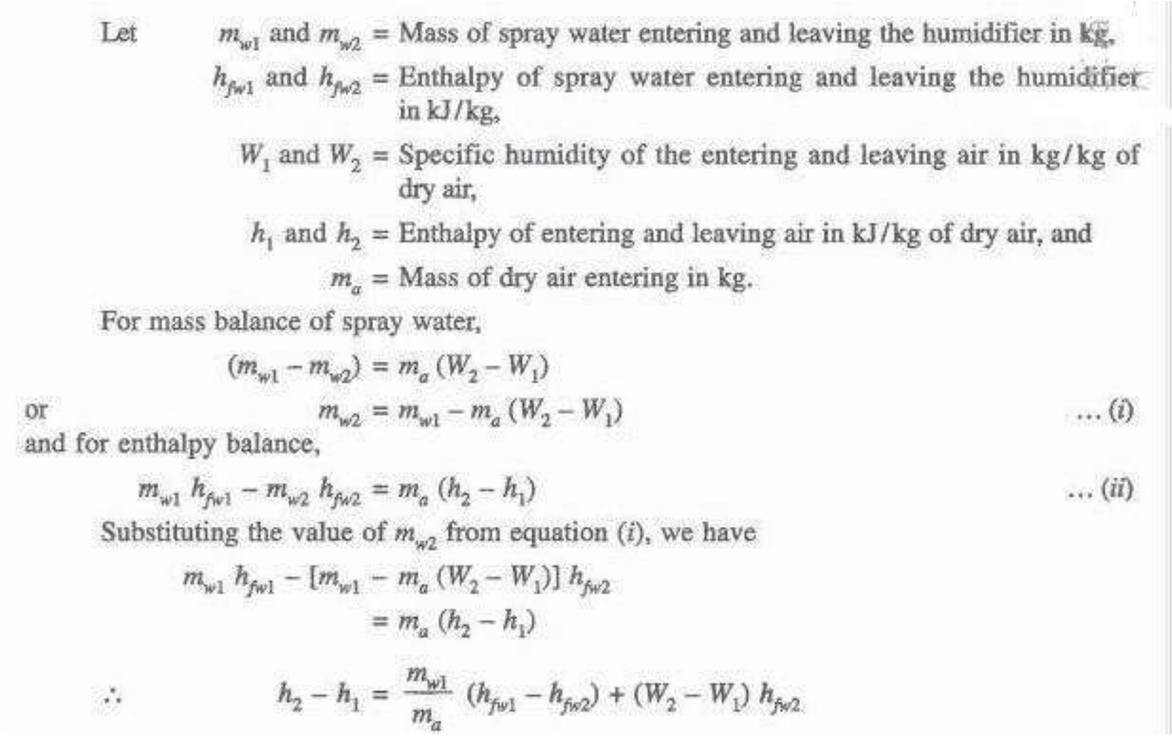
$$= 5300/210 = 25.24 \text{ TR} \quad \textbf{Ans.} \qquad \ldots (\because \ 1 \text{ TR} = 210 \text{ kJ/min})$$

Heating and Humidification

This process is generally used in winter air conditioning to warm and humidify the air. It is the reverse process of cooling and dehumidification. When air is passed through a humidifier having spray water temperature higher than the dry bulb temperature of the entering air, the unsaturated air will reach the condition of saturation and thus the air becomes hot. The heat of vaporisation of water is absorbed from the spray water itself and hence it gets cooled. In this way, the air becomes heated and humidified. The process of heating and humidification is shown by line 1-2 on the psychrometric chart as shown in Fig. The air enters at condition 1 and leaves at condition 2. In this process, the dry bulb temperature as well as specific humidity of air increases. The final relative humidity of the air can be lower or higher than that of the entering air.



(a) (b)



Let m_{w1} and m_{w2} = Mass of spray water entering and leaving the humidifier in kg,

h_{fw1} and h_{fw2} = Enthalpy of spray water entering and leaving the humidifier in kJ/kg,

W_1 and W_2 = Specific humidity of the entering and leaving air in kg/kg of dry air,

h_1 and h_2 = Enthalpy of entering and leaving air in kJ/kg of dry air, and

m_a = Mass of dry air entering in kg.

For mass balance of spray water,

$$(m_{w1} - m_{w2}) = m_a (W_2 - W_1)$$

or

$$m_{w2} = m_{w1} - m_a (W_2 - W_1) \qquad \dots (i)$$

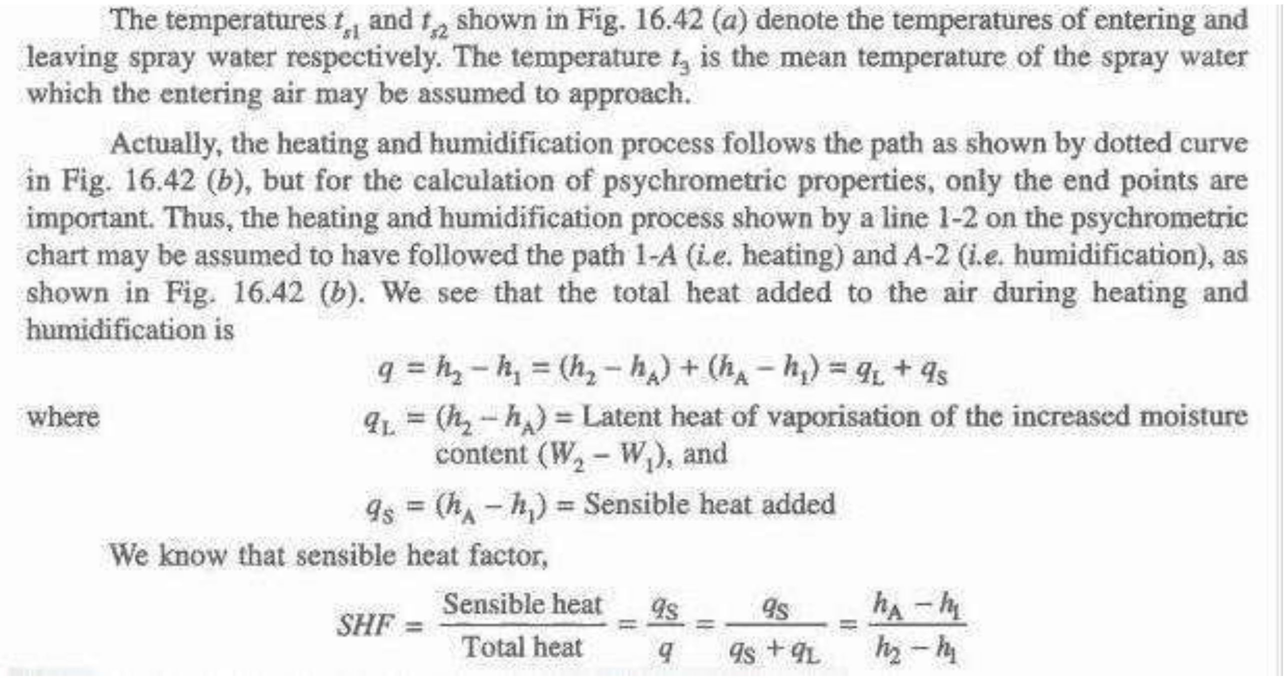
and for enthalpy balance,

$$m_{w1}\, h_{fw1} - m_{w2}\, h_{fw2} = m_a (h_2 - h_1) \qquad \dots (ii)$$

Substituting the value of m_{w2} from equation (*i*), we have

$$m_{w1}\, h_{fw1} - [m_{w1} - m_a (W_2 - W_1)]\, h_{fw2} = m_a (h_2 - h_1)$$

$$\therefore \quad h_2 - h_1 = \frac{m_{w1}}{m_a} (h_{fw1} - h_{fw2}) + (W_2 - W_1)\, h_{fw2}$$



The temperatures t_{s1} and t_{s2} shown in Fig. 16.42 (*a*) denote the temperatures of entering and leaving spray water respectively. The temperature t_3 is the mean temperature of the spray water which the entering air may be assumed to approach.

Actually, the heating and humidification process follows the path as shown by dotted curve in Fig. 16.42 (*b*), but for the calculation of psychrometric properties, only the end points are important. Thus, the heating and humidification process shown by a line 1-2 on the psychrometric chart may be assumed to have followed the path 1-*A* (*i.e.* heating) and *A*-2 (*i.e.* humidification), as shown in Fig. 16.42 (*b*). We see that the total heat added to the air during heating and humidification is

$$q = h_2 - h_1 = (h_2 - h_A) + (h_A - h_1) = q_L + q_S$$

where $q_L = (h_2 - h_A)$ = Latent heat of vaporisation of the increased moisture content $(W_2 - W_1)$, and

$q_S = (h_A - h_1)$ = Sensible heat added

We know that sensible heat factor,

$$SHF = \frac{\text{Sensible heat}}{\text{Total heat}} = \frac{q_S}{q} = \frac{q_S}{q_S + q_L} = \frac{h_A - h_1}{h_2 - h_1}$$

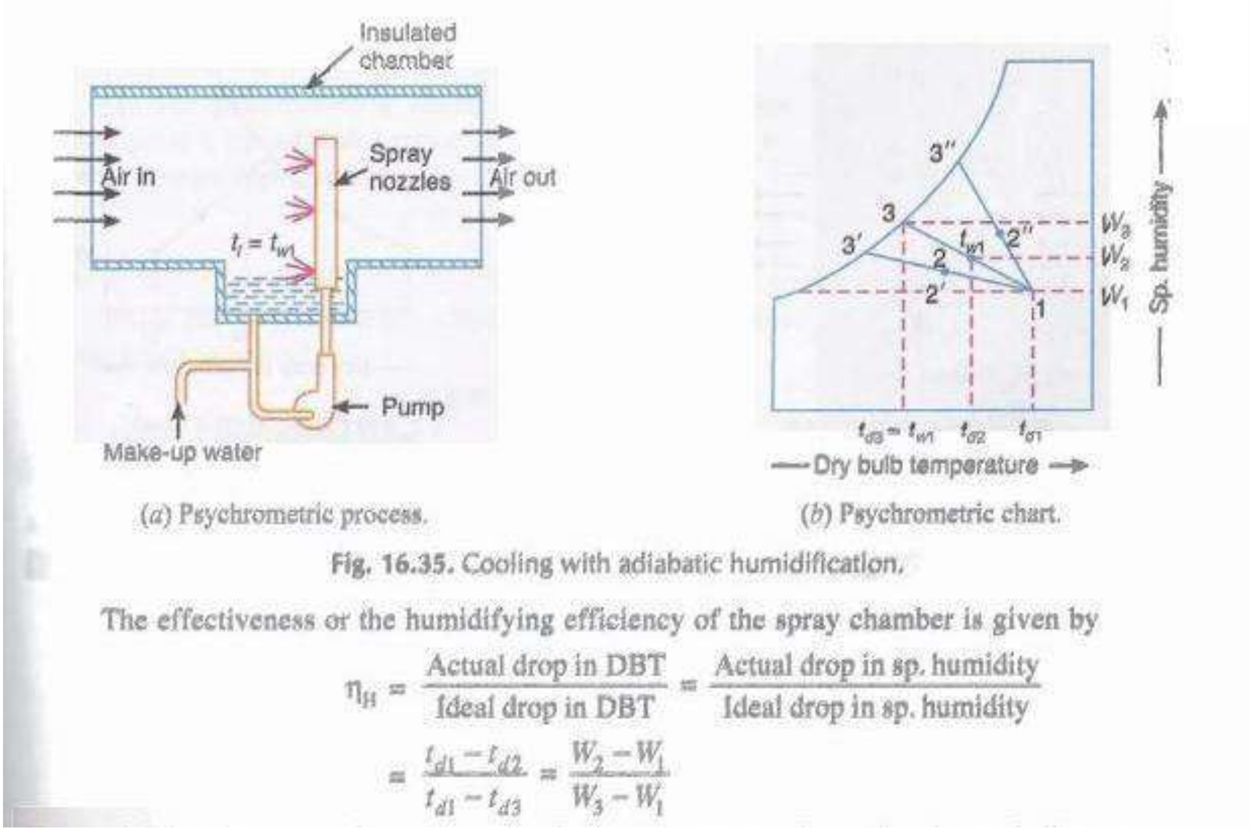
Cooling with Adiabatic Humidification

When the air is passed through an insulated chamber, having sprays of water (known as air washer) maintained at a temperature (t_1) higher than the dew point temperature of entering air (t_{dp1}), but lower than its dry bulb temperature (t_{d1}) of entering air or equal to the wet bulb temperature of the entering air (t_{w1}). then the air is said to be cooled and humidified.

Since no heat is supplied or rejected from the spray water as the same water is re-circulated again and again, therefore, in this case, a condition of adiabatic saturation will be reached. The temperature of spray water will reach the thermodynamic wet bulb temperature of the air entering the spray water.

This process is shown by line 1-3 on the psychrometric chart as shown in Fig (b), and follows the path along the constant wet bulb temperature line or constant enthalpy line. In an ideal case i.e. when the humidification is perfect (or the humidifying efficiency of the spray chamber is 100%), the final condition of the air will be at point 3 (Le. at temperature ta and relative humidity 100%).

In actual practice, perfect humidification is never achieved. Therefore, the final condition of air at outlet is represented by point 2 on the line 1-3, as shown in Fig. (b).



(*a*) Psychrometric process. (*b*) Psychrometric chart.

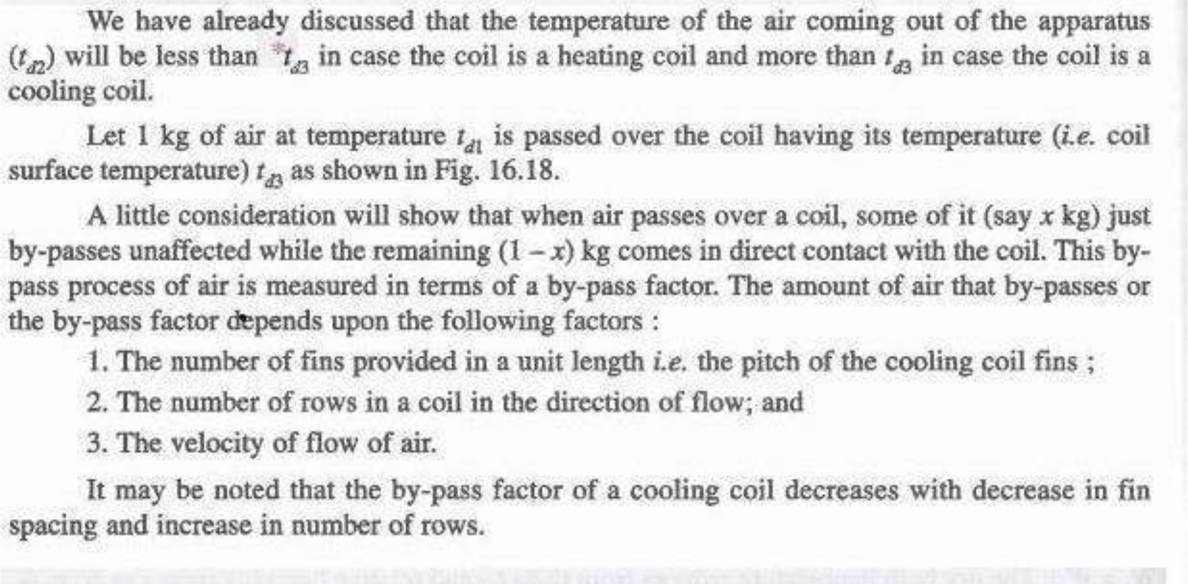
Fig. 16.35. Cooling with adiabatic humidification.

The effectiveness or the humidifying efficiency of the spray chamber is given by

$$\eta_H = \frac{\text{Actual drop in DBT}}{\text{Ideal drop in DBT}} = \frac{\text{Actual drop in sp. humidity}}{\text{Ideal drop in sp. humidity}}$$

$$= \frac{t_{d1} - t_{d2}}{t_{d1} - t_{d3}} = \frac{W_2 - W_1}{W_3 - W_1}$$

SHF, BPF

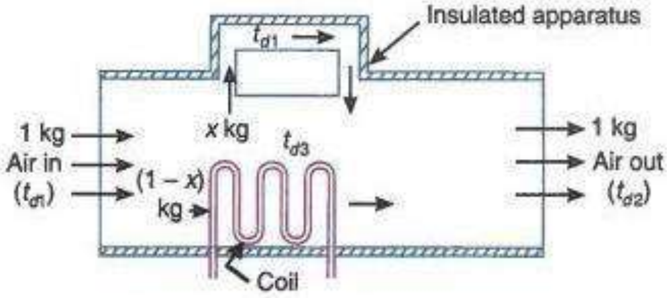

We have already discussed that the temperature of the air coming out of the apparatus (t_{d2}) will be less than *t_{d3} in case the coil is a heating coil and more than t_{d3} in case the coil is a cooling coil.

Let 1 kg of air at temperature t_{d1} is passed over the coil having its temperature (*i.e.* coil surface temperature) t_{d3} as shown in Fig. 16.18.

A little consideration will show that when air passes over a coil, some of it (say x kg) just by-passes unaffected while the remaining $(1 - x)$ kg comes in direct contact with the coil. This by-pass process of air is measured in terms of a by-pass factor. The amount of air that by-passes or the by-pass factor depends upon the following factors :

1. The number of fins provided in a unit length *i.e.* the pitch of the cooling coil fins ;
2. The number of rows in a coil in the direction of flow; and
3. The velocity of flow of air.

It may be noted that the by-pass factor of a cooling coil decreases with decrease in fin spacing and increase in number of rows.



. By-pass factor.

Balancing the enthalpies, we get

$$x\,c_{pm}\,t_{d1} + (1 - x)\,c_{pm}\,t_{d3} = 1 \times c_{pm}\,t_{d2} \qquad \text{... (where } c_{pm} = \text{Specific humid heat)}$$

or
$$x\,(t_{d3} - t_{d1}) = t_{d3} - t_{d2}$$

$$\therefore \qquad x = \frac{t_{d3} - t_{d2}}{t_{d3} - t_{d1}}$$

where x is called the *by-pass factor* of the coil and is generally written as *BPF*. Therefore, by-pass factor for heating coil,

$$BPF = \frac{t_{d3} - t_{d2}}{t_{d3} - t_{d1}}$$

Similarly, *by-pass factor for cooling coil,

$$BPF = \frac{t_{d2} - t_{d3}}{t_{d1} - t_{d3}}$$

The by-pass factor for heating or cooling coil may also be obtained as discussed below :

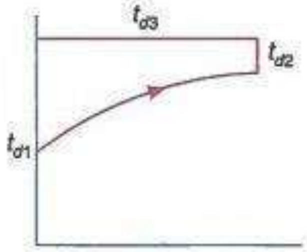
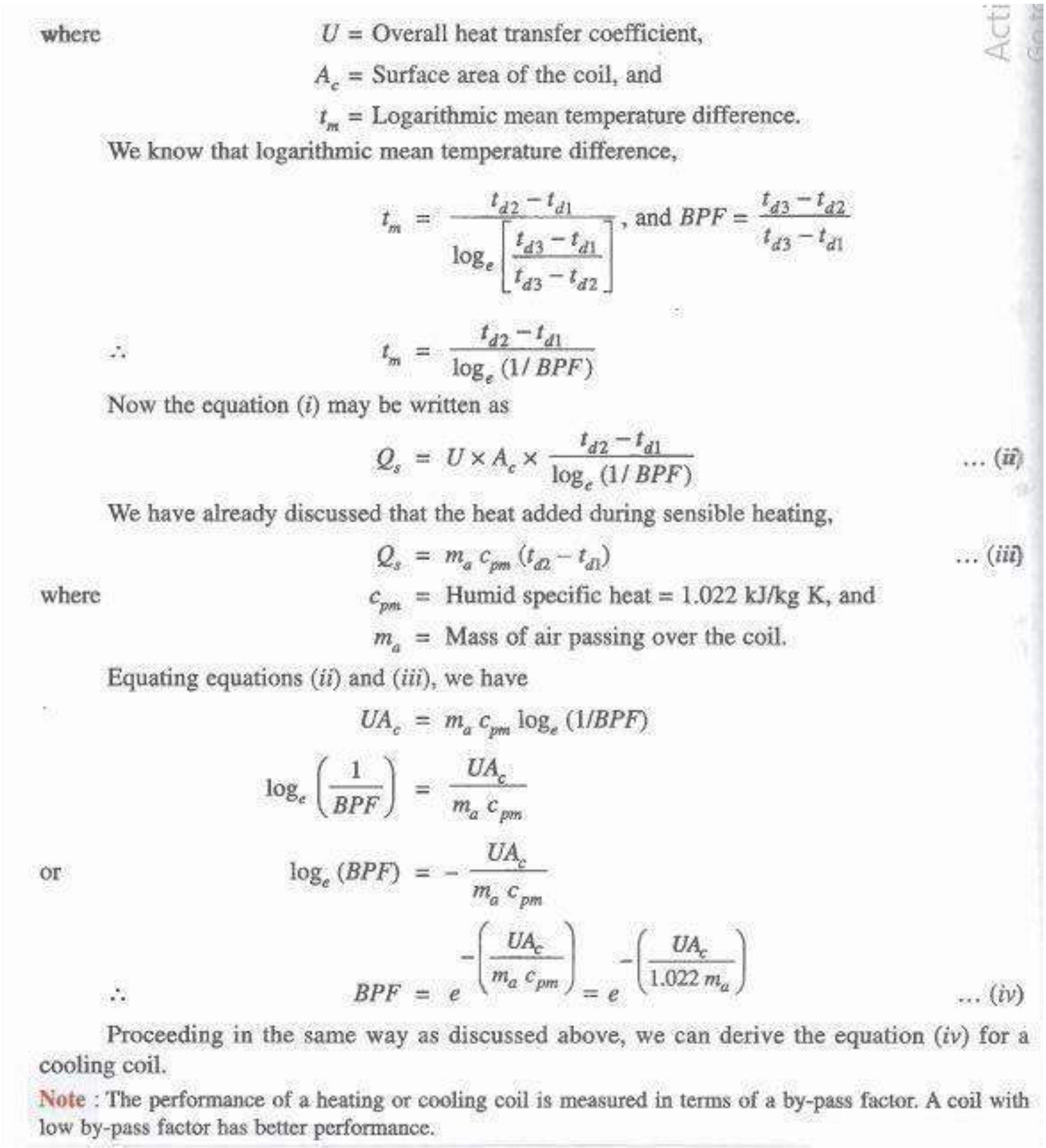


Fig. 16.19

Let the air passes over a heating coil. Since the temperature distribution of air passing through the heating coil is as shown in Fig. 16.19, therefore sensible heat given out by the coil,

$$Q_s = U\,A_c\,t_m \qquad \text{... }(i)$$



where U = Overall heat transfer coefficient,

A_c = Surface area of the coil, and

t_m = Logarithmic mean temperature difference.

We know that logarithmic mean temperature difference,

$$t_m = \frac{t_{d2} - t_{d1}}{\log_e \left[\frac{t_{d3} - t_{d1}}{t_{d3} - t_{d2}}\right]}, \text{ and } BPF = \frac{t_{d3} - t_{d2}}{t_{d3} - t_{d1}}$$

$$\therefore \quad t_m = \frac{t_{d2} - t_{d1}}{\log_e (1/BPF)}$$

Now the equation (*i*) may be written as

$$Q_s = U \times A_c \times \frac{t_{d2} - t_{d1}}{\log_e (1/BPF)} \quad \ldots (ii)$$

We have already discussed that the heat added during sensible heating,

$$Q_s = m_a \, c_{pm} (t_{d2} - t_{d1}) \quad \ldots (iii)$$

where c_{pm} = Humid specific heat = 1.022 kJ/kg K, and

m_a = Mass of air passing over the coil.

Equating equations (*ii*) and (*iii*), we have

$$UA_c = m_a \, c_{pm} \log_e (1/BPF)$$

$$\log_e \left(\frac{1}{BPF}\right) = \frac{UA_c}{m_a \, c_{pm}}$$

or

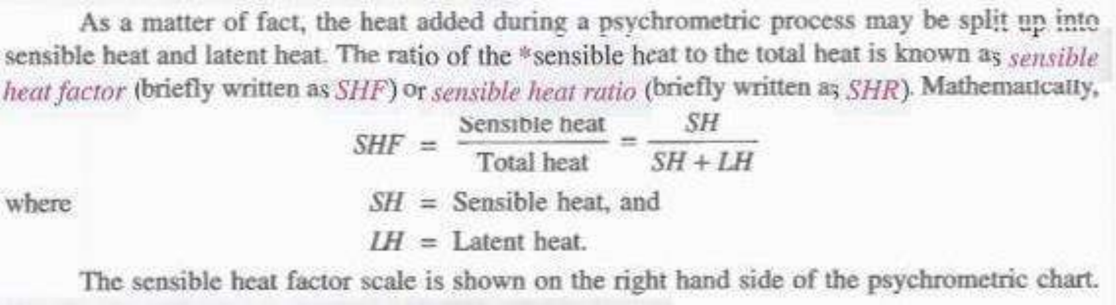
$$\log_e (BPF) = -\frac{UA_c}{m_a \, c_{pm}}$$

$$\therefore \quad BPF = e^{-\left(\frac{UA_c}{m_a \, c_{pm}}\right)} = e^{-\left(\frac{UA_c}{1.022 \, m_a}\right)} \quad \ldots (iv)$$

Proceeding in the same way as discussed above, we can derive the equation (*iv*) for a cooling coil.

Note : The performance of a heating or cooling coil is measured in terms of a by-pass factor. A coil with low by-pass factor has better performance.

Sensible Heat Factor (SHF)



As a matter of fact, the heat added during a psychrometric process may be split up into sensible heat and latent heat. The ratio of the *sensible heat to the total heat is known as *sensible heat factor* (briefly written as *SHF*) or *sensible heat ratio* (briefly written as *SHR*). Mathematically,

$$SHF = \frac{\text{Sensible heat}}{\text{Total heat}} = \frac{SH}{SH + LH}$$

where SH = Sensible heat, and

LH = Latent heat.

The sensible heat factor scale is shown on the right hand side of the psychrometric chart.

Adiabatic Mixing

When two quantities of air having different enthalpies and different specific humidities are mixed, the final condition of the air mixture depends upon the masses involved, and on the enthalpy and specific humidity of each of the constituent masses which enter the mixture.

Now consider two air streams 1 and 2 mixing adiabatically as shown in Fig. .

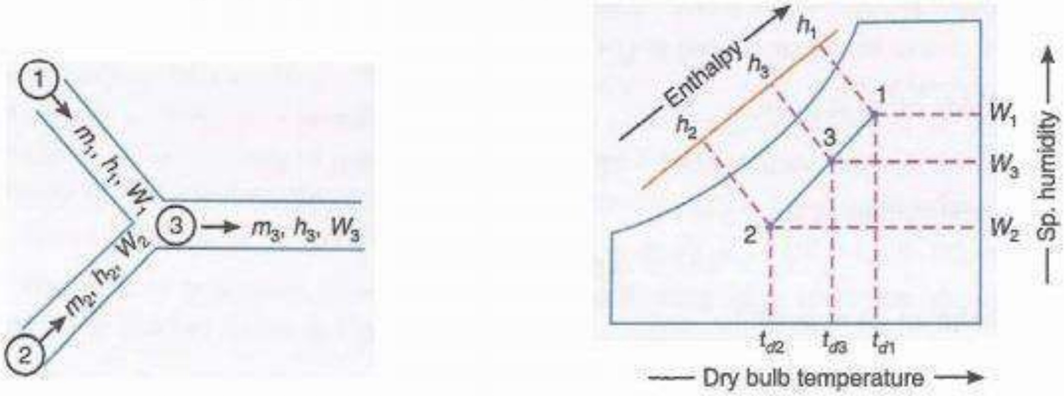
Let m_1 = Mass of air entering at 1,

h_1 = Enthalpy of air entering at 1,

W_1 = Specific humidity of air entering at 1,

m_2, h_2, W_2 = Corresponding values of air entering at 2, and

m_3, h_3, W_3 = Corresponding values of the mixture leaving at 3.



(a) (b)

Fig. .. Adiabatic mixing of two air streams.

Assuming no loss of enthalpy and specific humidity during the air mixing process, we have for the mass balance,

$$m_1 + m_2 = m_3 \qquad \ldots (i)$$

For the energy balance,

$$m_1 h_1 + m_2 h_2 = m_3 h_3 \qquad \ldots (ii)$$

and for the mass balance of water vapour,

$$m_1 W_1 + m_2 W_2 = m_3 W_3 \qquad \ldots (iii)$$

Substituting the value of m_3 from equation (*i*) in equation (*ii*),

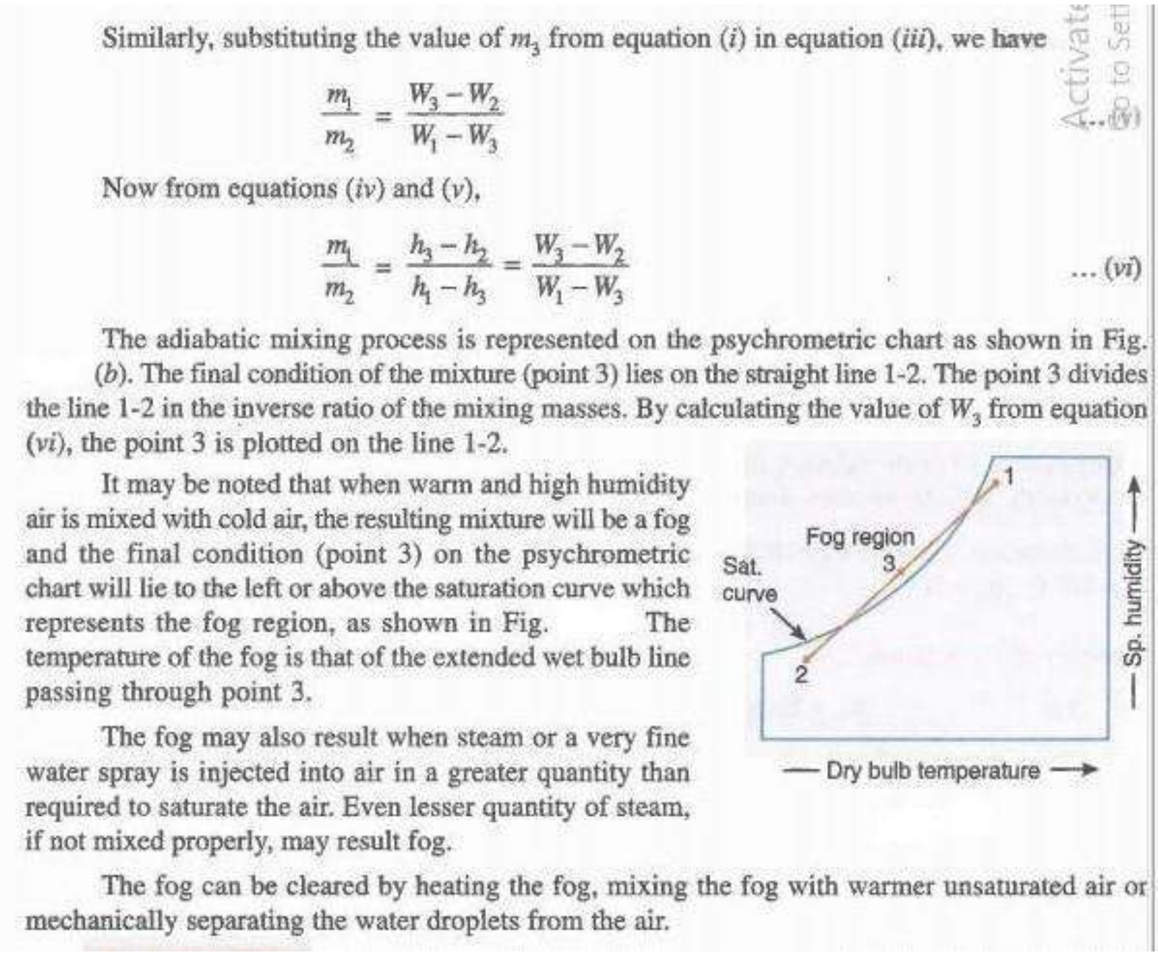
$$m_1 h_1 + m_2 h_2 = (m_1 + m_2) h_3 = m_1 h_3 + m_2 h_3$$

or

$$m_1 h_1 - m_1 h_3 = m_2 h_3 - m_2 h_2$$

$$m_1 (h_1 - h_3) = m_2 (h_3 - h_2)$$

$$\therefore \quad \frac{m_1}{m_2} = \frac{h_3 - h_2}{h_1 - h_3} \qquad \ldots (iv)$$



Similarly, substituting the value of m_3 from equation (*i*) in equation (*iii*), we have

$$\frac{m_1}{m_2} = \frac{W_3 - W_2}{W_1 - W_3} \quad \dots (v)$$

Now from equations (*iv*) and (*v*),

$$\frac{m_1}{m_2} = \frac{h_3 - h_2}{h_1 - h_3} = \frac{W_3 - W_2}{W_1 - W_3} \quad \dots (vi)$$

The adiabatic mixing process is represented on the psychrometric chart as shown in Fig. (*b*). The final condition of the mixture (point 3) lies on the straight line 1-2. The point 3 divides the line 1-2 in the inverse ratio of the mixing masses. By calculating the value of W_3 from equation (*vi*), the point 3 is plotted on the line 1-2.

It may be noted that when warm and high humidity air is mixed with cold air, the resulting mixture will be a fog and the final condition (point 3) on the psychrometric chart will lie to the left or above the saturation curve which represents the fog region, as shown in Fig. The temperature of the fog is that of the extended wet bulb line passing through point 3.

The fog may also result when steam or a very fine water spray is injected into air in a greater quantity than required to saturate the air. Even lesser quantity of steam, if not mixed properly, may result fog.

The fog can be cleared by heating the fog, mixing the fog with warmer unsaturated air or mechanically separating the water droplets from the air.

Numerical on above : Numerical are provided at the end of the chapters.

Effective temperature and comfort chart

The degree of warmth or cold felt by a human body depends mainly on the following three factors: 1. Dry bulb temperature, 2. Relative humidity, and 3. Air velocity. In order to evaluate the combined effect of these factors, the term effective temperature is employed. It is defined as that index which corelates the combined effects of air temperature, relative humidity and air velocity on the human body. The numerical value of effective temperature is made equal to the temperature of still (i.e. 5 to 8 tit/min air velocity) saturated air, which produces the same sensation of warmth or coolness as produced under the given conditions.

The practical application of the concept of effective temperature is presented by the comfort chart, as shown in Fig.. This chart is the result of research made on different kinds of people subjected to wide range of environmental temperature, relative humidity and air movement by the American Society of Heating, Refrigeration and Air conditioning Engineers (ASHRAE). It is applicable to reasonably still air (5 to 8 m/min air velocity) to situations where the occupants are seated at rest or doing light work and to spaces whose enclosing surfaces are at a mean temperature equal to the air-dry bulb temperature. In the comfort chart, as shown in Fig., the dry bulb temperature is taken as abscissa and the wet bulb temperature as ordinates. The relative humidity lines are replotted from the psychrometric chart.

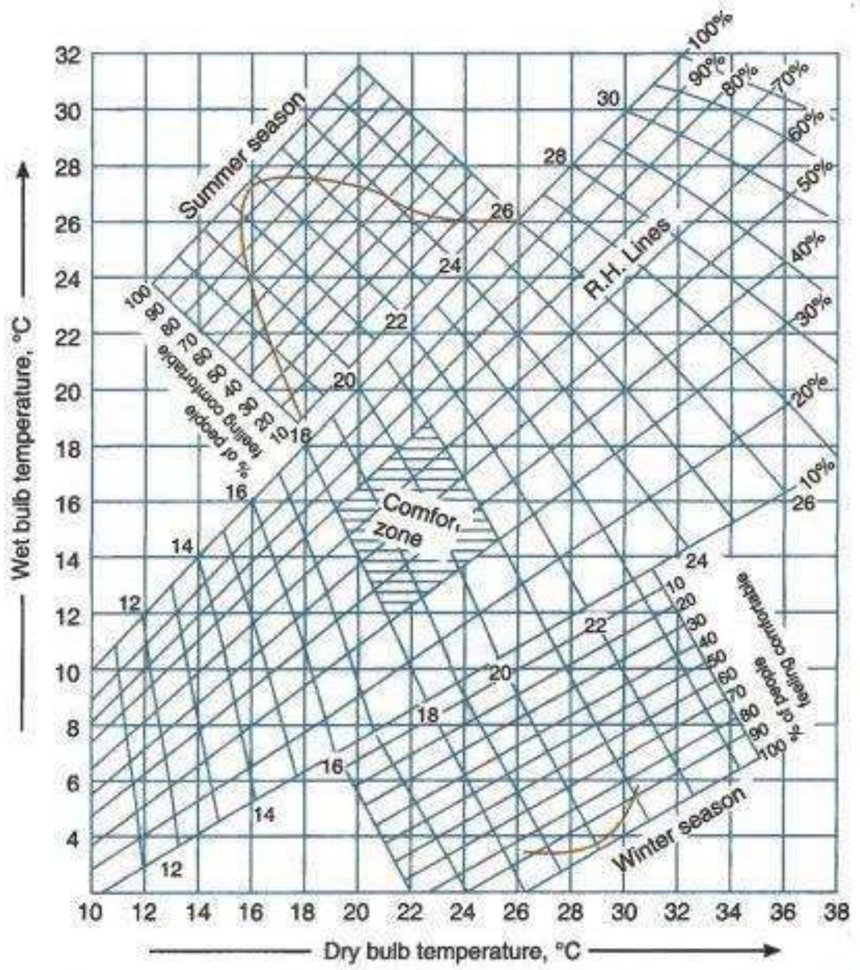
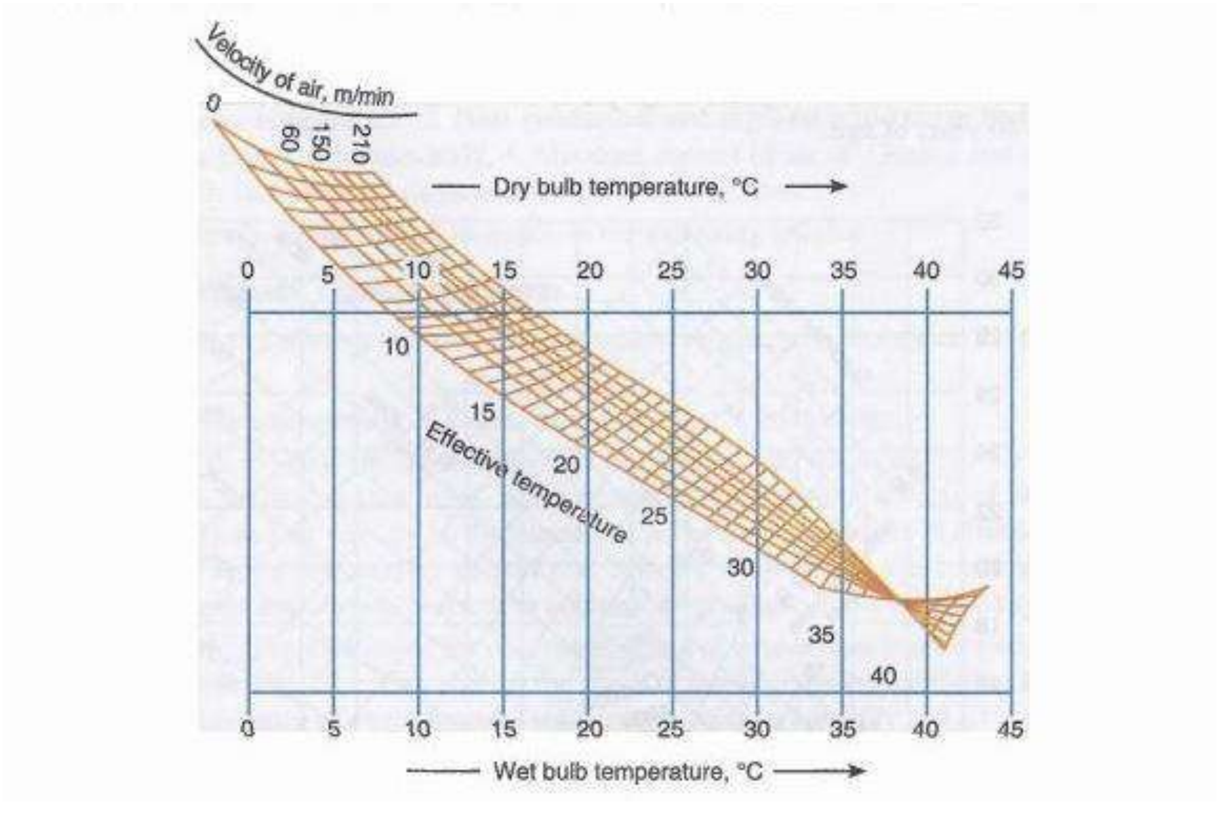


Fig. Comfort chart for still air (air velocities from 5 to 8 m/min)

However, all points located on a given effective temperature line do not indicate conditions of equal comfort or discomfort. The extremely high or low relative humidities may produce conditions of discomfort regardless of the existent effective temperature. The moist desirable relative humidity range lies between 30 and 70 per cent. When the relative humidity is much below 30 per cent, the mucous membranes and the skin surface become too dry for comfort and health. On the other hand, if the relative humidity is above 70 per cent, there is a tendency for a clammy or sticky sensation to develop. The curves at the top and bottom, as shown in Fig. 17.1, indicate the percentages of person participating in tests, who found various effective temperatures satisfactory for comfort. The comfort chart shows the range for both summer and winter condition within which a condition of comfort exists for most people. For summer conditions, the chart indicates that a maximum of 98 percent people felt comfortable for an effective temperature of 21.6°C . For winter conditions, chart indicates that an effective temperature of 20°C was desired by 97.7 percent people. It has been found that for comfort, women require 0.5°C higher effective temperature than men. AU men and women above 40 years of age prefer 0.5°C higher effective temperature than the persons below 40 years of age.

It may be noted that the comfort chart, as shown in Fig. does not take into account the variations in comfort conditions when there are wide variations in the mean radiant temperature (MRT). In the range of 26.5°C, a rise of 0.5°C in mean radiant temperature above the mom dry bulb temperature raises the effective temperature by 0.5°C. The effect of mean radiant temperature on comfort is less pronounced at high temperatures than at low temperatures. The comfort conditions for persons at work vary with the rate of work and the amount of clothing worn. In general, the greater the degree of activity, the lower the effective temperature necessary for comfort. Fig. shows the variation in effective temperature with different air velocities. We see that for the atmospheric conditions of 24°C dry bulb temperature and 16°C wet bulb temperature correspond to about 21°C with nominally still air (velocity 6 m /min) and it is about 17°C at an air velocity of 210 m / min. The same effective temperature is observed at higher dry bulb and wet bulb temperatures with higher velocities. The case is reversed after 37.8°C as in that case higher velocities will increase sensible heat flow from air to body and will decrease comfort. The same effective temperature means same feeling of warmth, but it does not mean same comfort.



SHORT QUESTIONS WITH ANSWER

1. What is dew point temperature? [2010s, 2009s, 2006s]

The dew point is the temperature at which air is saturated with water vapor, which is the gaseous state of water. When air has reached the dew-point temperature at a particular pressure, the water vapor in the air is in equilibrium with liquid water, meaning water vapor is condensing at the same rate at which liquid water is evaporating.

2. Define relative humidity? [2010s, 2009s, 2006BP]

Ans : It is the ratio of actual mass of water vapour in a given volume of moist air to the mass of water vapour in the same volume of saturated air at the same temperature and pressure. It is briefly written as RH.

3. What is the difference between dry bulb and wet bulb temperature? [2009s, 2009BP, 2007S, 2006S, 2011, 2020]

Dry bulb temperature: It is the temperature of air recorded by a thermometer, when it is not affected by the moisture present in the air. The dry bulb temperature (briefly written as DBT) is generally denoted by td or t_{db}

Wet bulb temperature: It is the temperature of air recorded by a thermometer, when its bulb is surrounded by a wet cloth exposed to the air. Such a thermometer is called 'wet bulb thermometer. The wet bulb temperature (briefly written as WBT) is generally denoted by tw, or t_{wb}.

4. Define relative humidity and humidity ratio? [2007S, 2006S, 2011]

Relative humidity: It is the ratio of actual mass of water vapour in a given volume of moist air to the mass of water vapour in the same volume of saturated air at the same temperature and pressure. It is briefly written as RH.

Humidity ratio: It is the mass of water vapour present in 1 kg of dry air, and is generally expressed in terms of gram per kg of dry air (g / kg of dry air). It is also called specific humidity or humidity ratio

5. Define humidity ratio, relative humidity DBT andWBT ? [2012]

Answer is mentioned above

6. What is saturated air? [2011]

Saturated air is air that holds water vapor at its highest level. Air is composed of moisture or water vapor, regardless of the amount of pressure and temperature levels. Excess moisture leads to the formation of saturated air as brought about by the conversion of moisture into dew.

7. What is apparatus dew point temperature? [2009S]

Apparatus Dew Point (ADP) is the effective surface temperature of the cooling coil. It is also the temperature at a fixed flow rate at which both sensible and latent heat gains are removed (from the conditioned space) at the required rates. It is also often called as the 'Coil Temperature.

8. What is sensible heat factor? [2014W]

Sensible heat factor is the ratio of sensible heat and Total heat. Sensible heat is the heat which increases or decreases the temperature of the body. Latent heat is the heat which increases the specific humidity without increasing or decreasing the temperature of the body.

9. Define specific humidity? [2014W]

Specific humidity, mass of water vapour in a unit mass of moist air, usually expressed as grams of vapour per kilogram of air, or, in air conditioning, as grains per pound. The specific humidity is an extremely useful quantity in meteorology.

LONG QUESTIONS:

1. With the help of Psychrometric chart explain the sensible cooling and sensible heating? [2020]

2. Describe cooling and dehumidification process of air and show the ADP in psychrometric chart. [2014]

3. Describe slings psychrometer? [2010]

Air Conditioning System

Learning Objectives:

Factors affecting comfort air conditioning.

Equipment used in an air-conditioning.

Classification of air-conditioning system

Winter Air Conditioning System

Summer air-conditioning system.

Numerical on above

Introduction:

The air conditioning is that branch of engineering science which deals with the study of partitioning of air that is supplying and maintaining desirable internal atmospheric conditions for human comfort, irrespective of external conditions.

Factors affecting comfort air conditioning:

The four important factors for comfort air conditioning are discussed as below

1. Temperature of air.

in Air Conditioning the control of temperature means the maintain of any desirable temperature within an enclosed space even though the temperature of the outside air is above or below the desired room temperature. This is accomplished either by the addition or removal of heat from the enclosed space as and when demanded. It may be noted that a human being feels comfortable when the air is at 21°C with 56% relative humidity.

2. Humidity of air.

The control of humidity of air means the decreasing or increasing of moisture contents of air during summer or winter respectively in order to produce comfortable and healthy conditions. The control of humidity is not only necessary for human comfort but it also increases the efficiency of the workers. In general, for summer air conditioning, the relative humidity should not be less than 60% whereas for winter air conditioning it should not be more than 40%.

3. Purity of air.

It is an important factor for the comfort of a human body. It has been noticed that people do not feel comfortable when breathing contaminated air, even if it is within acceptable temperature and humidity ranges. It is thus obvious that proper filtration, cleaning and purification of air is essential to keep it free from dust and other impurities.

4. Motion of air.

The motion or circulation of air is another important factor which should be controlled, in order to keep constant temperature throughout the conditioned space. It is, therefore, necessary that there should be equi-distribution of air throughout the space to be air conditioned.

Equipment's Used in an Air Conditioning System

Following are the main equipment's or parts used in an air conditioning system

1. **Circulation fan.** The main function of this fan is to move air to and from the room.
2. **Air conditioning unit.** It is a unit which consists of cooling and dehumidifying processes for summer air conditioning or heating and humidification processes for winter air conditioning.
3. **Supply duct.** It directs the conditioned air from the circulating fan to the space to be air conditioned at proper point.
4. **Supply outlets.** These are grills which distribute the conditioned air evenly in the room.
5. **Return outlets.** These are the openings in a room surface which allow the room air to enter the return duct.
6. **Filters.** The main function of the filters is to remove dust, dirt and other harmful bacteria from the air.

Classification of Air Conditioning Systems

The air conditioning systems may be broadly classified as follows:

1. According to the purpose

(a) Comfort air conditioning system, and

(b) Industrial air conditioning system.

2. According to season of the year

(a) Winter air conditioning system,

(b) Summer air conditioning system, and

(c) Year-round air conditioning system.

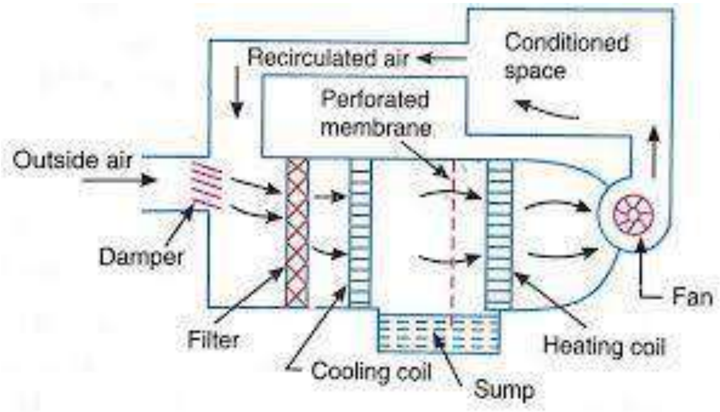
3. according to the arrangement of equipment

a Unitary air conditioning system and

b Central air conditioning system

A. Comfort air conditioning system:

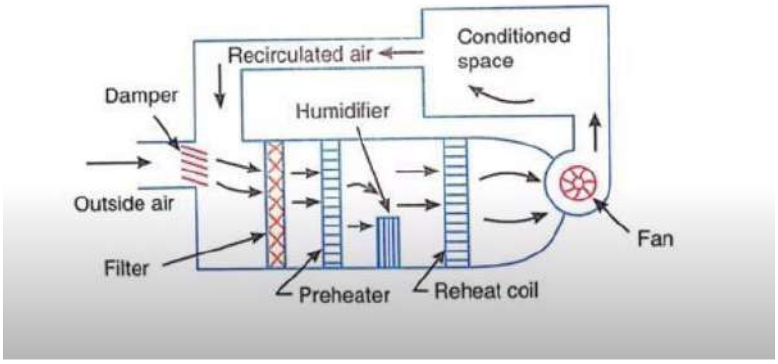
in comfort air conditioning the air is brought to the required dry bulb temperature and relative humidity for the human health comfort and efficiency if sufficient data of required condition is not given then it is assumed to be 21-degree Celsius driver temperature and 50% relative humidity the sensible heat factor is generally kept at following for residence aur private off = 0.9, for restaurant or busy office = 0.8, Auditorium or cinema hall = 0.7, Ball room dance hall = 0.6



The comfort air conditioning may be adapted for homes office top restaurants theatres Hospital School etc

B. Industrial air conditioning system:

It is an important system of air conditioning these days in which the inside dry bulb temperature and relative humidity of the air is kept constant for proper working of the machines and for the proper Research and manufacturing processes. Some of the sophisticated electronic and other machines need a particular dry bulb temperature and relative humidity. Sometimes these machines are required a particular method of psychrometric processes. This type of air conditioning system is used in textile mill, paper mill, machine parts manufacturing plant , Tool Room, photo processing plants etc.



Winter air-conditioning system:

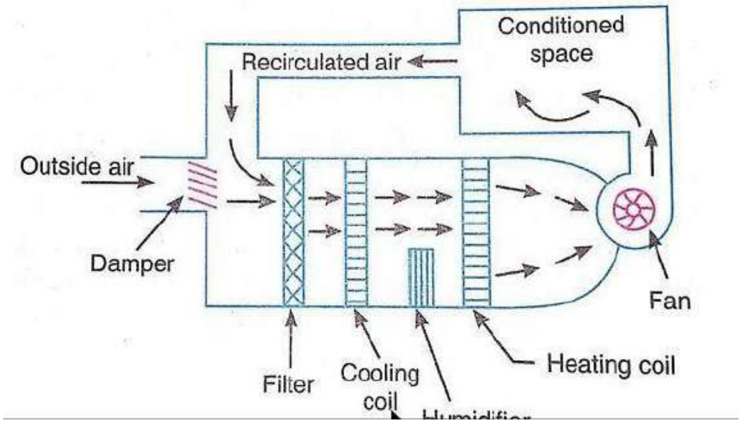
Winter air conditioning system in winter air conditioning the air is heated which is generally accompanied by humidification. the schematic arrangement of the system is shown in the figure. The outside air flows through a damper and mixtures up with recirculated air which is obtained from the conditioned space. The mixed air passes through a filter to remove dirt, dust, and other impurities. The air now passes through a preheated coil in order to prevent the possible freezing of water and to control the evaporation of water in the humidifier. After, the air is made to pass through a reheat coil to bring the air to the designed dry bulb temperature.

Summer Air Conditioning System:

It is the most important type of air conditioning, in which the air is cooled and generally dehumidified. The schematic arrangement of a typical summer air conditioning system is shown figure. The outside air flows through the damper, and mixes up with recirculated air (which is obtained from the conditioned space). The mixed air passes through a filter to remove dirt, dust and other impurities. The air now passes through a cooling coil. The coil has a temperature much below the required dry bulb temperature of the air in the conditioned space. The cooled air passes through a perforated membrane and loses its moisture in the condensed form which is collected in a sump. After that, the air is made to pass through a heating coil which heats up the air slightly. This is done to bring the air to the designed dry bulb temperature and relative humidity. Now the conditioned air is supplied to the conditioned space by a fan. From the conditioned space, a part of the used air is exhausted to the atmosphere by the exhaust fans or ventilators. The remaining part of the used air (known as recirculated air) is again conditioned as shown in Fig. 18.5. The outside air is sucked and made to mix with the recirculated air in order to make up for the loss of conditioned (or used) air through exhaust fans or ventilation from the conditioned space.

Year-Round Air Conditioning System

The year-round air conditioning system should have equipment for both the summer and winter air conditioning. The schematic arrangement of a modem summer year-round air conditioning system is shown in Figure.



The outside air flows through the damper and mixes up with the recirculated air (which is obtained from the conditioned space). The mixed air passes through a filter to remove dirt, dust and other impurities. In summer air conditioning, the cooling coil operates to cool the air to the desired value. The dehumidification is obtained by operating the cooling coil the dew point temperature (apparatus dew point). In winter, the cooling the heating coil operates to heat the air. The spray type humidifier is season to humidify the air.

SHORT QUESTION WITH ANSWER

1. What is the function of air filter in Air conditioning? [2011]

Ans : The air in the HVAC system passes through the air filter. The filter's job is to catch particulates and pollutants such as dust, mold, pet dander and fungal spores. The mesh that is the main namesake of the filter that air passes through becomes denser, thus catching these materials and not hindering the flow of air. If you don't change your air filter as frequently as you should, the air can't pass through as easily, as well as more and more particulars have the chance of getting through the mesh, thus harming indoor air quality.

2. Name four importance of Air conditioning? [2007 S, 2020W]

1. It's literally a life saver
2. Better air quality
3. Fewer insects and parasites
4. Improved work force efficiency
5. Prevents electronic devices from overheating

3. What is the use of Air filter and blower in air conditioning? [2020W]

The filter's job is to catch particulates and pollutants such as dust, mold, pet dander and fungal spores.

An air conditioner uses blowers to transfer the warm air away from any space and replace it with cold air. It also maximizes airflow for better circulation and machine function. But contrary to popular belief, an air conditioner blower comes in different forms and sizes, depending on the air conditioning system itself. The four most commonly used types are the propeller fan, centrifugal fan, vane-axial fan and the tube-axial fan.

LONG QUESTIONS :

1. With neat diagram explain the working principle of summer air conditioning system ? [2006,2014 2018]

2. Describe the different components of air distribution system a and ducting? [2010]

3. Explain detail specification of room air conditioning? [2006]

4. Give classification of air conditioning system?

5. Explain the working of a desert cooler?

6. Explain in detail about the summer air conditioning and winter air conditioning system?

7. With neat sketch explain the thermostatic expansion valve?