Engineering Thermodynamics I

Lecture 13

Refrigeration Cycles

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Lecture learning outcomes:

At the end of this lecture, you will be able to:

i. Explain how refrigeration and heat pumps function to transfer heat from one location to another, enhancing thermal management in various applications.

ii. Identify different types of refrigerants, their properties, environmental impact, and how they facilitate heat transfer in refrigeration systems.

iii. Analyze the theoretical basis of the Carnot refrigeration and heat pump cycles, including efficiency and limitations.

iv. Illustrate the working principles of the vapor-compression refrigeration cycle, its key components, and its role in modern refrigeration systems.

v. Compare real-world vapor-compression refrigeration cycles to ideal models, accounting for inefficiencies such as pressure drops and heat losses.

vi. Use knowledge of refrigeration cycles and heat pumps to assess performance and efficiency in engineering applications.

Content

1. Refrigeration and Heat Pumps

- Refrigeration: A process of transferring heat from a low-temperature region to a high-temperature one to maintain a cooled space at a desired temperature.
- Heat Pump: Operates on the same principle as a refrigerator but is used to supply heat to a space by absorbing heat from a colder source (e.g., outside air or ground).
- **Key Difference**:
  - Refrigerator → Cools a space (primary goal: heat removal).
  - Heat Pump → Heats a space (primary goal: heat addition).

1. Refrigeration and Heat Pumps **Cont…**

The main components of refrigerators and Heat Pumps:

- Compressor – Compresses refrigerant gas, increasing its pressure and temperature.
- Condenser – A heat exchanger where high-pressure refrigerant releases heat to the surroundings (condenses into liquid).
  - In a refrigerator, heat is expelled outside.
  - In a heat pump, heat is delivered indoors.

1. Refrigeration and Heat Pumps Cont…

- Expansion Valve (Throttling Device) – Reduces refrigerant pressure, causing cooling and partial evaporation.
- Evaporator – Absorbs heat from the cooled space (inside fridge or outdoor air for heat pumps), turning refrigerant into low-pressure vapor.
- Refrigerant – to absorb and release heat, allowing for efficient cooling or heating.
- Both Refrigerators and Heat Pumps use a refrigerant, compressor, condenser, evaporator, and expansion device to achieve their respective goals.

1. Refrigeration and Heat Pumps Cont…

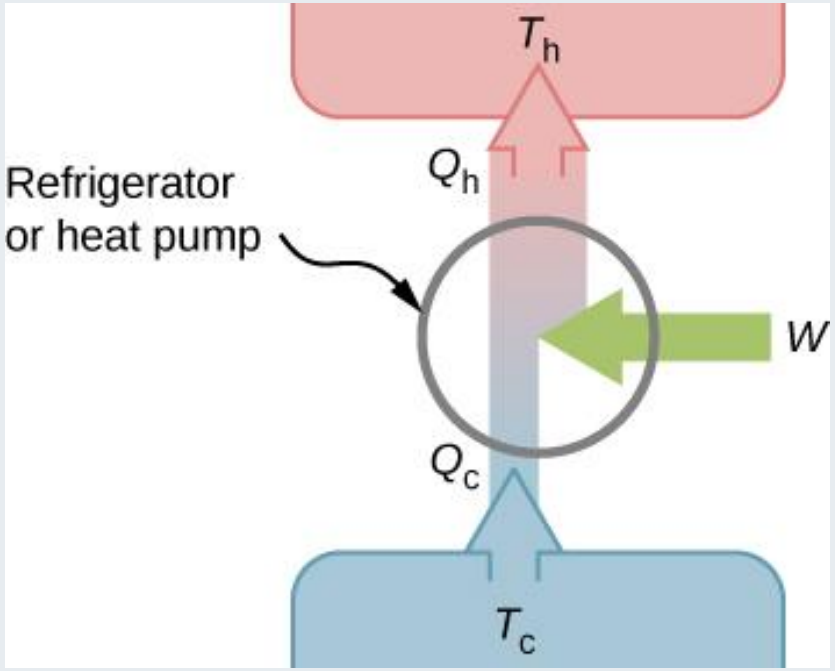

Figure 1: Schematic Representation of a Refrigerator or Heat Pump

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1. Refrigeration and Heat Pumps Cont…

- Both refrigerators and heat pumps are based on the reversed Carnot cycle, a theoretical cycle that is the most efficient way to transfer heat [1].
- The cycle involves transferring heat from a cold source (e.g., the inside of a refrigerator) to a warmer sink (e.g., the surrounding environment).
- The refrigerant is continuously circulated through this cycle, absorbing heat at low temperatures and releasing it at higher temperatures.

1. Refrigeration and Heat Pumps Cont….

- The working principle of a Refrigerator:

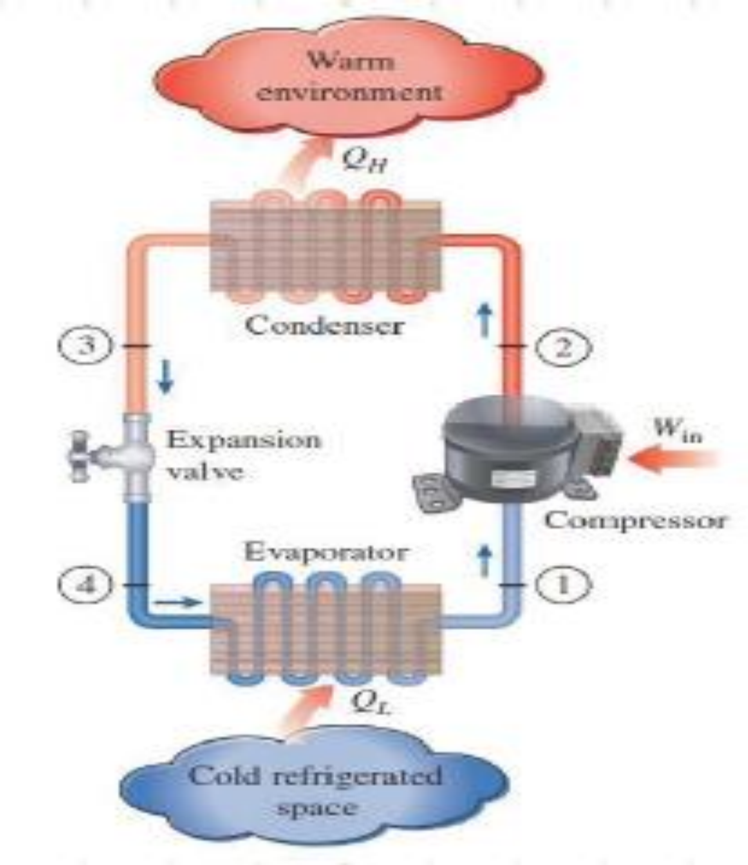

Figure 2: Components of a Refrigerator

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1. Refrigerators and Heat Pumps

Cont…

- The Coefficient of Performance (COP) measures the efficiency of a refrigerator or heat pump by comparing the desired thermal energy transfer to the work input required to achieve it.

$$COP = \frac{Useful\ Thermal\ Energy\ Transferred}{Work\ Input}$$

- For a refrigerator,

$$COP_R = \frac{Heat\ absorbed\ from\ cold\ space\ (Q_L)}{W_{net,in}} = \frac{Q_L}{W_{net,in}}$$

1. Refrigerators and Heat Pumps **Cont…**

- And for a Heat Pump,

$$COP_{HP} = \frac{Heat\ delivered\ to\ warm\ space\ (Q_H)}{W_{net,in}} = \frac{Q_H}{W_{net,in}}$$

- From first law of thermodynamics,

$$(Q_L - Q_H) - (0 - W_{in}) = \Delta U_{cycle} = 0$$

$$W_{in} = W_{net,in} = Q_H - Q_L$$

$$COP_R = \frac{Q_L}{Q_H - Q_L}$$

And, $COP_{HP} = \frac{Q_H}{Q_H - Q_L}$

1. Refrigerators and Heat Pumps Cont…

- Under the same operating conditions the COP_{HP} and COP_R are related by

$$COP_{HP} = COP_R + 1$$

- Higher COP = More efficient heating.
- Heat pumps typically have higher COP than refrigerators because $Q_H = Q_L + W$ (they utilize both absorbed heat and work input).
- Real-world COP values depend on temperature differences

(lower ΔT → higher COP).

2. Refrigerant

- The refrigerant is a heat carrying medium which during their cycle (i.e. compression, condensation, expansion and evaporation) in the refrigeration system absorbs heat from a low temperature system and discards the heat so absorbed to a higher temperature medium [2].
- The natural ice and mixture of ice and salt were the first refrigerants.
- In 1834, ether, ammonia, sulpur dioxide, methyl chloride and carbon dioxide came into use as refrigerants in compression cycle refrigeration machines [1].
- The suitability of a refrigerant for a certain application is determined by it physical, thermodynamic, chemical properties and by various practical factors.

2. Refrigerant Cont…

- There is no one refrigerant which can be used for all types of application i.e. there is no ideal refrigerant.

Classifications of Refrigerants

- The refrigerants may, broadly, be classified into the following two groups:

1. Primary Refrigerants:- which directly take part in the refrigeration system
   a. Halo- Carbon or organic refrigerants
   b. Azeotrope refrigerants
   c. Inorganic Refrigerants, and
   d. Hydro Carbon refrigerants

2. Refrigerant Cont…

2. Secondary Refrigerants:- refrigerants which are first cooled by primary refrigerants and then used for cooling purposes.

Example:

Brines (A solution of salt in water) are generally used where temperatures are required to be maintained below the freezing point of water i.e. 0℃.

2. Refrigerant Cont…

Designation of refrigerants

- Since a large number of refrigerants have been developed over the years for a wide variety of applications, a numbering system has been adopted to designate various refrigerants.
- From the number, one can get some useful information about the type of refrigerant, its chemical composition, molecular weight etc.
- All the refrigerants are designated by R followed by a

  unique number.

2. Refrigerant **Cont…**

i. Fully saturated, halogenated compounds: These refrigerants are derivatives of alkanes $C_nH_{2n} + 2$ such as methane (CH_4), ethane (C_2H_6). These refrigerants are designated by R_{XYZ},

where:

X+1 indicates the number of Carbon (C) atoms

Y-1 indicates number of Hydrogen (H) atoms, and

Z indicates number of Fluorine (F) atoms

- The balance indicates the number of Chlorine atoms.
- Only 2 digits indicate that the value of X is zero.

2. Refrigerant Cont…

$C_m H_n Cl_p F_q$

And, $n + p + q = 2m + 2$

Where, m= no of Carbon

n= no of Hydrogen

p= no of Chlorine

q= no of Fluorine

X+1 indicates the number of Carbon (C) atoms

Y-1 indicates number of Hydrogen (H) atoms, and

Z indicates number of Fluorine (F) atoms

Example: R 22

X = 0 ⇒ No. of Carbon atoms = 0+1 = 1 ⇒ derivative of methane (CH4)

Y = 2 ⇒ No. of Hydrogen atoms = 2-1 = 1

Z = 2 ⇒ No. of Fluorine atoms = 2

$$1 + p + 2 = 2x1 + 2$$

2. Refrigerant **Cont…**

$n + p + q = 2m + 2$ $1 + p + 2 = 2x1 + 2$

- The balance (number of chlorine) = 4 – no. of (H+F) atoms = 4-1-2 = 1 ⇒ No. of Chlorine atoms = 1

  ∴The chemical formula of $R22 = CHClF_2$

- Similarly it can be shown that the chemical formula of:

  $\mathrm{R12} = CCl_2F_2$

  $\mathrm{R134a} = C_2H_2F_4$

- (Letter a stands for isomer, e.g. molecules having same chemical composition but different atomic arrangement, e.g. R134 and R134a)

2. Refrigerant Cont…

ii. Inorganic refrigerants: they were exclusively used before the introduction of halo-carbon refrigerants.

- They are still in use due to their inherent thermodynamic and physical properties.
- These are designated by number 7 followed by the molecular weight of the refrigerant (rounded-off).

Example:

- Ammonia: Molecular weight is 17; R 717
- Carbon dioxide: Molecular weight is 44; R 744
- Water: Molecular weight is 18, R 718

2. Refrigerant Cont…

iii. Mixtures:

- Azeotropic (stable mixtures of refrigerants) are designated by 500 series

Example:

- R 500: Mixture of R 12 (73.8 %) and R 152a (26.2%)
- R 502: Mixture of R 22 (48.8 %) and R 115 (51.2%)
- R503: Mixture of R 23 (40.1 %) and R 13 (59.9%)
- R507A: Mixture of R 125 (50%) and R 143a (50%)

2. Refrigerant Cont…

- Zeotropic refrigerants (e.g. non-azeotropic mixtures) are designated by 400 series.

Example:

- R404A : Mixture of R 125 (44%), R 143a (52%) and R 134a (4%)
- R407A : Mixture of R 32 (20%), R 125 (40%) and R 134a (40%)
- R407B : Mixture of R 32 (10%), R 125 (70%) and R 134a (20%)
- R410A : Mixture of R 32 (50%) and R 125 (50%)

2. Refrigerant **Cont…**

iv. Hydrocarbon Refrigerants: Successfully used in industrial and commercial installations.

- They possess satisfactory thermodynamic properties but are highly flammable and explosive.

Example:

- Propane (C_3H_8): R 290
- n-butane (C_4H_{10}): R 600
- iso-butane (C_4H_{10}): R 600a

2. Refrigerant Cont…

Criteria for refrigerant selection

The desirable characteristics for a widely used refrigerant include:

- Environmental acceptability
- Chemical stability
- Materials compatibility
- Refrigeration-cycle performance
- Adherence to nonflammable and nontoxic guidelines
- Boiling point

3. Reversed Carnot Refrigerator and Heat Pump

- Recall that the Carnot cycle is a theoretical thermodynamic cycle that provides the maximum possible efficiency for a heat engine operating between two temperature reservoirs.
- While real-world devices cannot achieve this ideal performance, the Carnot model helps engineers optimize designs and compare efficiencies.
- When reversed, it becomes the Carnot refrigerator or Carnot heat pump, serving as an ideal benchmark for refrigeration and heating systems.
- The applications of refrigerators and heat pumps are:
  - Refrigerators: Household cooling, industrial refrigeration.
  - Heat Pumps**:** Space heating, geothermal systems, HVAC

3. Reversed Carnot Refrigerator and Heat Pump **Cont…**

- The cycle consists of four reversible processes (two isothermal and two adiabatic):

Process 1-2: Isentropic (Adiabatic) Compression

- Refrigerant is compressed, increasing temperature from T_L to T_H.
- No heat transfer occurs (work is done on the system).

Process 2-3: Isothermal Heat Rejection (Condensation)

- Refrigerant rejects heat (Q_H) to the hot reservoir at constant temperature (T_H).
- Entropy decreases while pressure remains high.

3. Reversed Carnot Refrigerator and Heat Pump Cont…

Process 3-4: Isentropic (Adiabatic) Expansion

- Refrigerant expands, reducing temperature from T_H to T_L.
- No heat transfer occurs (work is extracted).

Process 4-1: Isothermal Heat Absorption (Evaporation)

- Refrigerant absorbs heat (Q_L) from the cold reservoir at constant temperature (T_L).
- Entropy increases while pressure drops.

3. Reversed Carnot Refrigerator and Heat Pump Cont…

Coefficient of Performance (COP)

The efficiency of a reversed Carnot cycle is measured by its COP.

Carnot Refrigerator COP

$$COP_R = \frac{Heat\ absorbed\ from\ cold\ space\ (Q_L)}{W_{net,in}} = \frac{Q_L}{W_{net,in}}$$

From Carnot principles, we know that

$$\frac{Q_H}{Q_L} = \frac{T_H}{T_L} \quad \text{and} \quad W_{net,in} = Q_H - Q_L \text{, Therefore,}$$

$$COP_R = \frac{Q_L}{W_{net,in}} = \frac{Q_L}{Q_H - Q_L} = \frac{T_L}{T_H - T_L}$$

3. Reversed Carnot Refrigerator and Heat Pump **Cont…**

- The COP of a Heat Pump is:

$$COP_{HP} = \frac{Q_H}{W_{net,in}} = \frac{Q_H}{Q_H - Q_L} = \frac{T_H}{T_H - T_L}$$

- COP decreases as the temperature difference $(T_H - T_L)$ increases.
- COP of a heat pump is always greater than that of a refrigerator by 1 (since COP_{HP}=$COP_R + 1$).
- Real systems have lower COP due to irreversibilities (friction, heat losses).

3. Reversed Carnot Refrigerator and Heat Pump Cont…

- What are the practical limitations of a reversed Carnot Refrigerator and heat pump?

While the Carnot cycle sets the theoretical maximum efficiency, real refrigerators and heat pumps face challenges:

- Isothermal processes require infinite time (real processes are not perfectly reversible).
- Adiabatic processes are difficult to achieve (heat losses occur).
- Real refrigerants have non-ideal properties (phase changes, pressure drops).

3. Reversed Carnot Refrigerator and Heat Pump Cont…

- The Reversed Carnot Refrigerator and Heat Pump provides the highest possible COP for refrigeration and heat pump systems [3].
- However, it is not a suitable model for refrigeration cycles since processes 2-3 and 4-1 are not practical because;
- Process 2-3 involves the compression of a liquid–vapor mixture, which requires a compressor that will handle two phases, and process 4-1 involves the expansion of high-moisture-content refrigerant in a turbine.

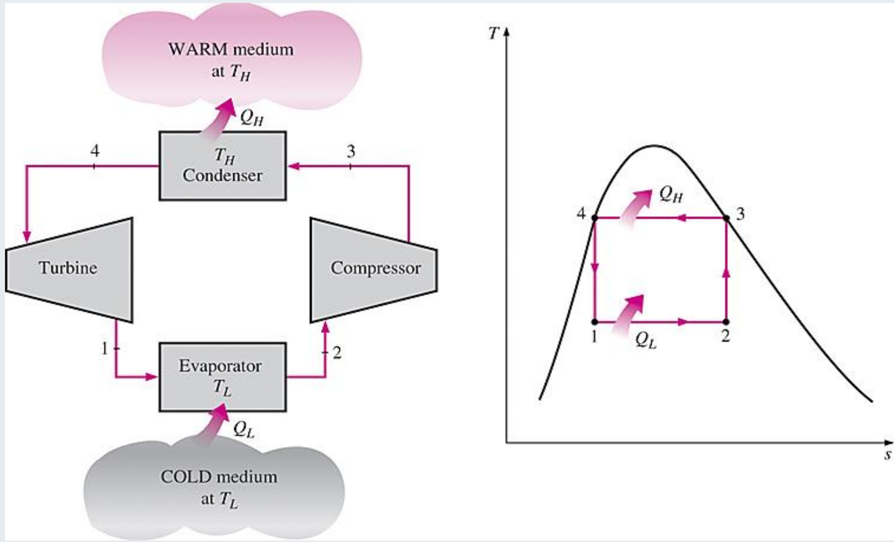

Figure 3: Schematic and T-s diagram of Reversed Carnot Refrigerator

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4. The Vapor- Compression Refrigeration Cycle

- The vapor-compression refrigeration cycle (VCR) is the ideal model for refrigeration systems.
- Unlike the reversed Carnot cycle, the refrigerant is vaporized completely before it is compressed and the turbine is replaced with a throttling device.
- The vapor compression refrigeration cycle is the most widely used refrigeration system in [4]:
  - Domestic refrigerators and freezers
  - Air conditioning systems
  - Industrial refrigeration (food processing, chemical plants)
  - Heat pumps for space heating

4. The Vapor- Compression Refrigeration Cycle Cont…

- It operates by circulating a refrigerant through four main components, undergoing phase changes to transfer heat from a low-temperature region to a high-temperature region [5].
- Vapor Compression Refrigeration cycle uses a volatile refrigerant that alternates between liquid and vapor states.
- It is more practical than Carnot cycle while following similar thermodynamic principles.

4. The Vapor- Compression Refrigeration Cycle

Cont…

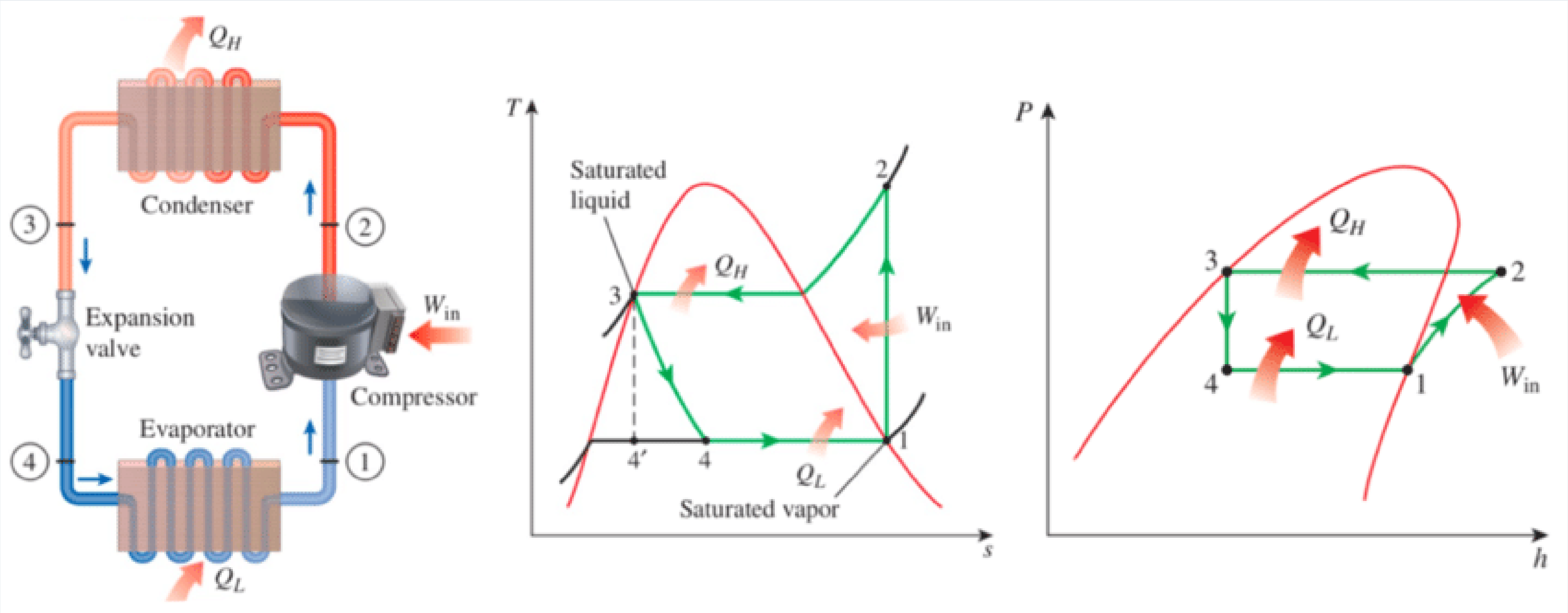

Figure 4: Schematic diagram, T-s diagram and P-h diagram of an Ideal Vapor-Compression Refrigeration cycle

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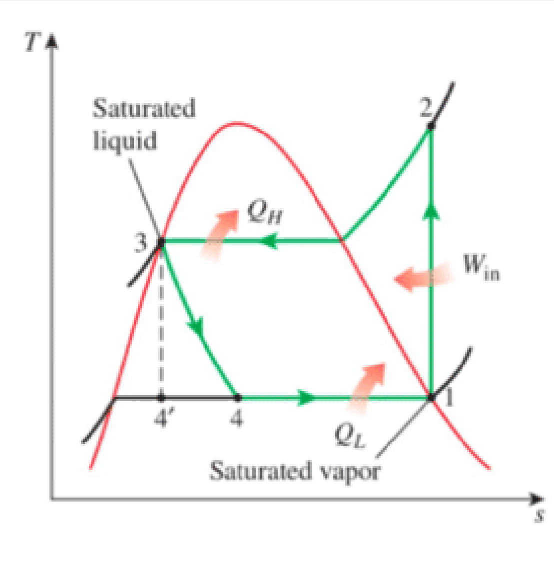
4. The Vapor- Compression Refrigeration Cycle Cont…



The cycle consists of four main processes on P-h (Pressure-Enthalpy) and T-s (Temperature-Entropy) diagrams:

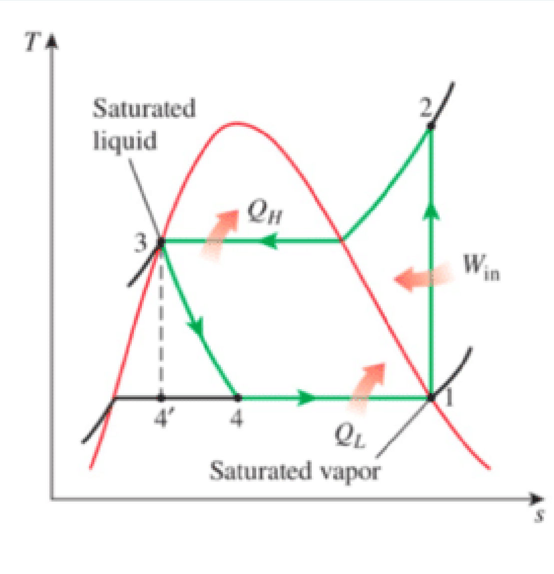
Process 1-2: Isentropic Compression in a compressor

- Work input to the system (W_{in})
- Entropy remains constant (ideal case)

Process 2-3: Isobaric Heat Rejection in a condenser

- Heat rejected (Q_H) in condenser
- Refrigerant changes from vapor to liquid

4.The Vapor- Compression Refrigeration Cycle Cont…



Process 3-4: Isenthalpic Expansion in an expansion device

- Pressure and temperature drop
- Quality (vapor fraction) increases

Process 4-1: Isobaric Heat Absorption in an evaporator

- Heat absorbed (Q_L) in evaporator
- Refrigerant changes from liquid-vapor mix to saturated vapor

5. Real Vapor- Compression Refrigeration Cycle

- The Real Vapor-Compression Refrigeration Cycle differs from the ideal cycle due to various practical inefficiencies and irreversibilities that occur in actual systems.
- Understanding these deviations is crucial for proper system design, performance analysis, and troubleshooting.

The major deviations from ideal cycles are:

1. Compression Process

- Actual compression is not isentropic and the effects are:
  - Higher discharge temperature
  - Increased work input
  - Lower volumetric efficiency

5. Real Vapor- Compression Refrigeration Cycle **Cont…**

2. Pressure Drops

Occur in:

- Suction and discharge lines
- Condenser and evaporator
- Filter-driers

The consequences of pressure drops are:

- Reduced system capacity
- Increased compression ratio
- Lower COP

5. Real Vapor- Compression Refrigeration Cycle Cont…

3. Heat Transfer Limitations

Finite temperature differences required:

- Condenser: $Tcondenser > Tambient$
- Evaporator: $Tevaporator < Tcooled\ space$

The Impacts are:

- Reduces effective temperature lift
- Decreases COP

5. Real Vapor- Compression Refrigeration Cycle Cont…

4. Subcooling and Superheating

Desirable subcooling:

- Prevents flash gas formation
- Increases refrigerating effect

Necessary superheating:

- Ensures dry compression
- Prevents liquid slugging

5. Real Vapor- Compression Refrigeration Cycle **Cont…**

Pre-Caution For Domestic Refrigerators

1. Open the refrigerator door the fewest times possible
2. Cool the hot foods to room temperature first before putting them into the refrigerator
3. Clean the condenser coils
4. Check the door gasket for air leaks
5. Avoid unnecessarily low temperature settings
6. Avoid excessive ice build-up on the interior surfaces of the evaporator
7. Do not block the air flow passages to and from the condenser coils

Summary

- Refrigerant is a working fluid that absorbs and releases heat during phase changes in refrigeration and heat pump systems.
- Reversed Carnot Refrigerator and Heat Pump are idealized thermodynamic cycles demonstrating the highest theoretical efficiency for cooling and heating applications.
- The Vapor-Compression Refrigeration Cycle is a widely used refrigeration method involving four main components where the refrigerant undergoes phase changes to transfer heat effectively.
- Real Vapor-Compression Refrigeration Cycle is a practical version of the ideal cycle, accounting for inefficiencies such as pressure drops, irreversibilities.
- Coefficient of Performance (COP) is a measure of efficiency

  for refrigeration and heat pump systems, defined as the

  ratio of desired output (cooling or heating) to energy input.

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Thank you !