

# Engineering Thermodynamics I

## Lecture 8

### Second Law of Thermodynamics

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# ***Lecture learning outcomes:***

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

- i. Understand the fundamental principles behind refrigerators and heat pumps, including their working mechanisms and energy transfer processes.
- ii. Explore the key statements of the second law of thermodynamics
- iii. Examine the Carnot Cycle and the four stages of the Carnot cycle
- iv. Calculate the efficiency of a Carnot heat engine and understand its operational limitations
- v. Investigate the function of Carnot refrigerators and heat pumps

# Content

1. Refrigerators and Heat Pumps
2. Statements of the Second Law of Thermodynamics
3. The Carnot Cycle
4. The Carnot Heat Engine
5. The Carnot Refrigerator and Heat Pumps

Summary

References

# 1. Refrigerators and Heat Pumps

- A well-known observation from everyday experience is that **heat flows** from regions of **higher temperature** to those of **lower temperature**, or from warmer mediums to cooler ones.
- The reverse process, however, **cannot happen spontaneously**.
- Transferring heat from a colder medium to a hotter one requires specialized devices known as **refrigerators**.
- Refrigerators and heat pumps are devices that transfer heat against its natural flow, from a colder region to a hotter one, by consuming external work [1].

# 1. Refrigerators and Heat Pumps

Cont...

## i. Refrigerators

- Refrigerators, like heat engines, are cyclic devices.
- The working fluid used in the refrigeration cycle is called a **refrigerant**.
- The key components of a refrigerator includes:
  - **Evaporator**: Absorbs heat from the cold space (low-pressure refrigerant).
  - **Compressor**: Increases refrigerant pressure/temperature.
  - **Condenser**: Releases heat to the surroundings.
  - **Expansion Valve**: Lowers pressure, cooling the refrigerant.

# 1. Refrigerators and Heat Pumps

Cont...

- There are different types of refrigeration system:
  - **Vapor-Compression Refrigeration** (most common).
  - **Vapor-Absorption Refrigeration** (uses heat energy instead of mechanical work).
  - **Thermoelectric Cooling** (Peltier effect for small-scale applications).
  - **Cryogenic Refrigeration System** (Used for extremely low temperatures, often in scientific and medical applications)
  - **Magnetic Refrigeration** (emerging technology).

# 1. Refrigerators and Heat Pumps

Cont...

- Refrigerator Components



**Figure 1: Components of a Refrigerator**

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## ii. Heat Pumps

- A heat pump is another device that moves heat from a **low-temperature** medium to a **high-temperature** one.
- Uses **external energy (electricity)** to pump heat from low-temperature to high-temperature spaces.
- It works similarly to a refrigerator but can also provide **heating** by absorbing heat from the outside (air, ground, or water) and releasing it indoors.

# 1. Refrigerators and Heat Pumps

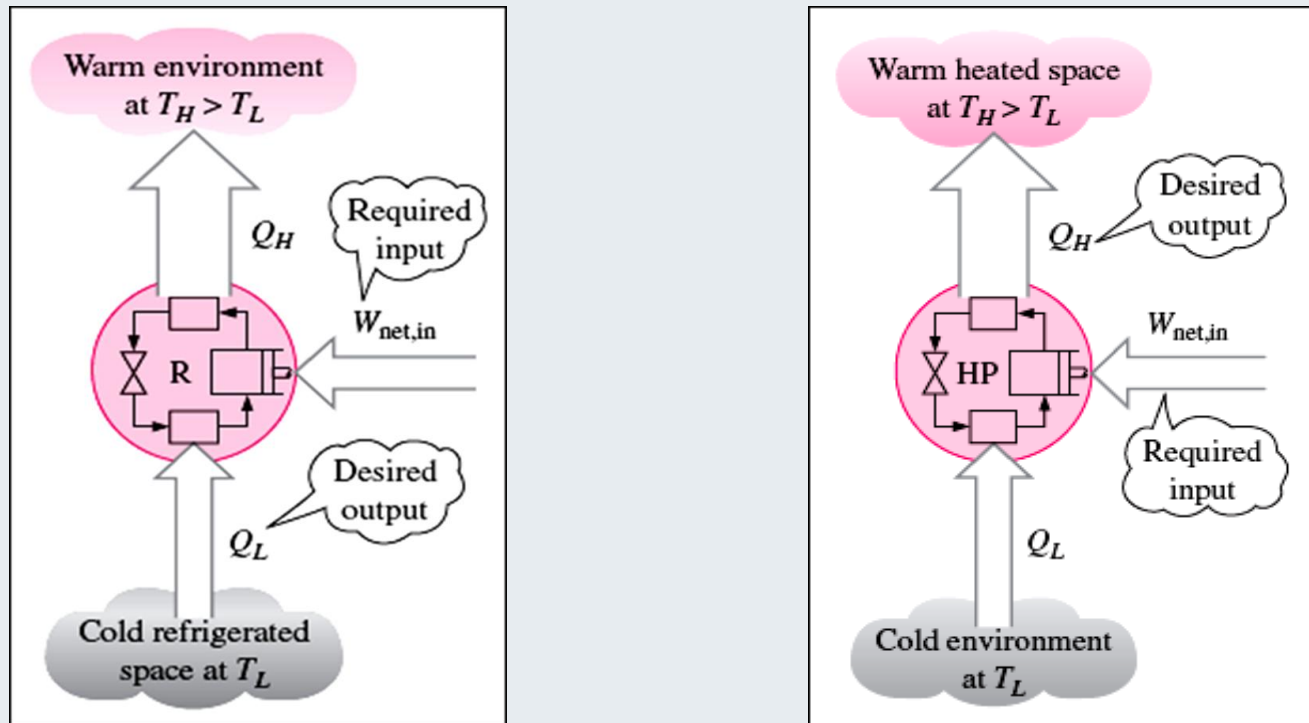
Cont...

- Refrigerators and heat pumps operate on the **same cycle** but differ in their objectives.
  - The objective of a refrigerator is to **maintain the refrigerated space** at a low temperature by removing heat from it.
  - The objective of a heat pump, however, is to **maintain a heated space** at a high temperature.

# 1. Refrigerators and Heat Pumps

Cont...

- Refrigerator and Heat Pump



**Figure 2:** Refrigerator and Heat Pump

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# 1. Refrigerators and Heat Pumps

Cont...

- The performance of a refrigerator or heat pump is quantified by its **coefficient of performance (COP)**.
- Coefficient of Performance (COP) is defined as the ratio of useful thermal energy transferred to the required work input.

$$COP = \frac{\textit{Desired Result}}{\textit{Required Input}}$$

$$COP_R = \frac{Q_L}{W_{net,in}}$$

And,

$$COP_{HP} = \frac{Q_H}{W_{net,in}}$$

# 1. Refrigerators and Heat Pumps

Cont...

- From first law of thermodynamics,

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

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

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

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

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

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

## Example

A household refrigerator has a coefficient of performance (COP) of 1.5 and extracts heat from its refrigerated space at a rate of 75 kJ/min. Determine:

- The electric power consumption of the refrigerator
- The rate of heat transfer to the surrounding air

### Solution:

$$Q_L = 75 \text{ kJ/min}$$

$$COP = 1.5$$

# 1. Refrigerators and Heat Pumps

Cont...

- The coefficient of performance (COP) for a refrigerator is

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{net,in}}$$

- Rearranging for  $\dot{W}$ ,

$$\dot{W}_{net,in} = \frac{\dot{Q}_L}{COP_R} = \frac{75}{1.5} = \mathbf{50 \text{ kJ/min}}$$

- The rate of heat transfer to the surrounding air,  $\dot{Q}_H$

$$\dot{W}_{net,in} = \dot{Q}_H - \dot{Q}_L$$

$$\dot{Q}_H = \dot{W}_{net,in} + \dot{Q}_L = 75 + 50 = \mathbf{125 \text{ kJ/min}}$$

## 2. Statements of the Second Law of Thermodynamics

- The second law of thermodynamics provides fundamental principles governing the direction of heat transfer and the limitations of energy conversion.
- It is expressed through **two main statements**:
  1. **Kelvin-Planck Statement (Heat Engine Perspective)**

This statement defines the constraints of heat engines:

- It states that, '*A heat engine cannot operate in a cycle and produce work without rejecting some heat to a lower-temperature reservoir*' [2].
- That is, a heat engine must exchange heat with a low-temperature sink as well as a high-temperature source to keep operating.
- This means it is **impossible to have a 100% efficient heat engine**, some energy must always be lost to the surroundings.

### 2. Clausius Statement (Refrigerator Perspective)

- This statement applies to refrigerators and heat pumps:
  - It states that, *'Heat cannot spontaneously flow from a colder body to a hotter body without external work being applied'* [2].
  - In other words, a refrigerator requires an **input of work** to transfer heat against its natural direction.
  - Thus, the COP of a refrigerator or heat pump must be less than infinity.  
( $\text{COP} < \infty$ )
- Both statements are **equivalent** because violating one would automatically violate the other.

# 3. The Carnot Cycle

- The Carnot cycle, developed by Sadi Carnot, represents the first **theoretical heat engine** operating through four reversible processes:
  - **Two isothermal** (constant temperature)
  - **Two adiabatic** (no heat transfer) stages
- The **Carnot cycle** is a theoretical thermodynamic cycle that represents the most efficient possible heat engine [1].
- It is an idealized model that sets the upper limit of efficiency for real heat engines, based on the second law of thermodynamics.

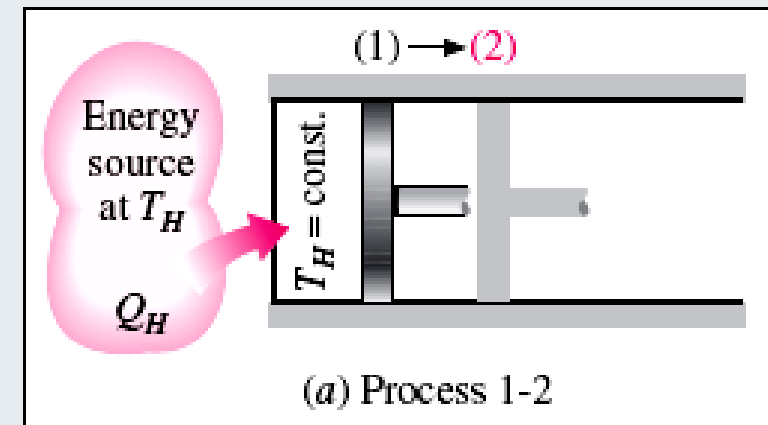
# 3. The Carnot Cycle

Cont...

## Processes of Carnot Cycle

Process 1-2 (Reversible Isothermal Expansion)  $T_H$  constant

- The gas initially at temperature  $T_H$  has its cylinder head maintained in thermal contact with a heat reservoir at the same temperature  $T_H$ .
- During slow expansion, the gas performs work on its surroundings, which would normally cause its temperature to decrease.

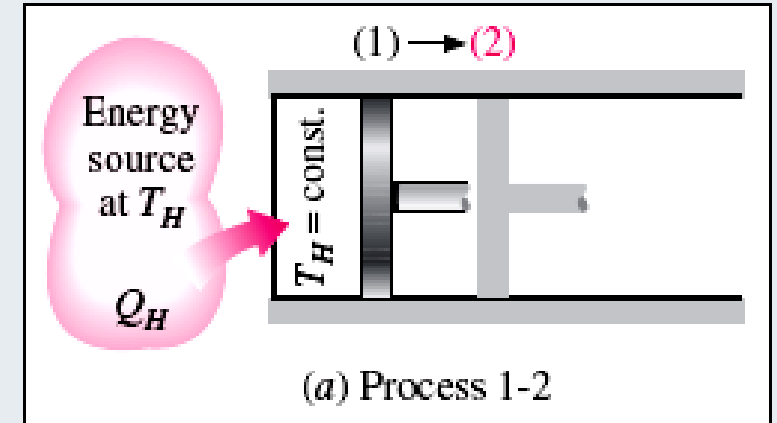


# 3. The Carnot Cycle

Cont...

Process 1-2 (Reversible Isothermal Expansion)  $T_H$  constant

- However, whenever the gas temperature drops infinitesimally (by  $dT$ ), an immediate heat transfer occurs from the reservoir to the gas, restoring its temperature to  $T_H$ .
- This mechanism maintains isothermal conditions throughout the expansion process.

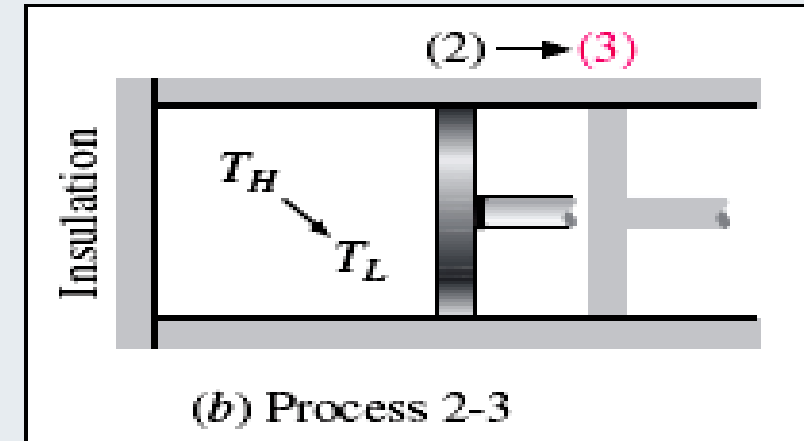


# 3. The Carnot Cycle

Cont...

Process 2-3 (Reversible Adiabatic Expansion)\_T drops from  $T_H$  to  $T_L$

- At state 2, the thermal reservoir in contact with the cylinder head is removed and replaced with insulation, rendering the system adiabatic.
- The gas then undergoes a slow expansion, performing work on the surroundings, until its temperature decreases from  $T_H$  to  $T_L$  (reaching state 3).

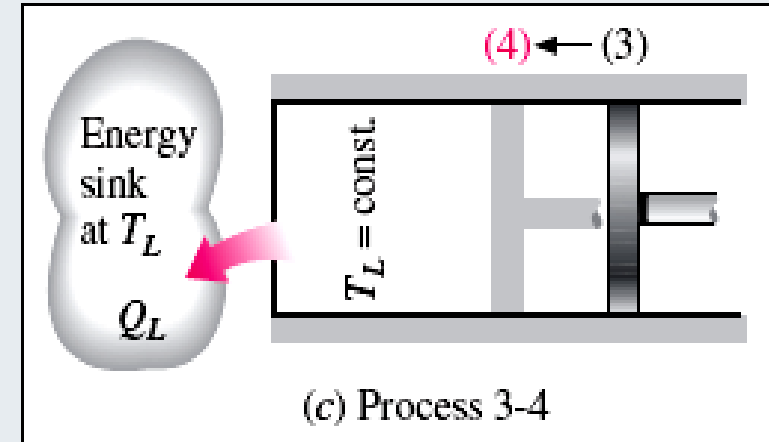


# 3. The Carnot Cycle

Cont...

Process 3-4 (Reversible Isothermal Compression)  $T_L$  constant

- At state 3, the insulation on the cylinder head is removed, and the cylinder is placed in contact with a thermal sink at temperature  $T_L$ .
- An external force then compresses the gas, performing work on it.

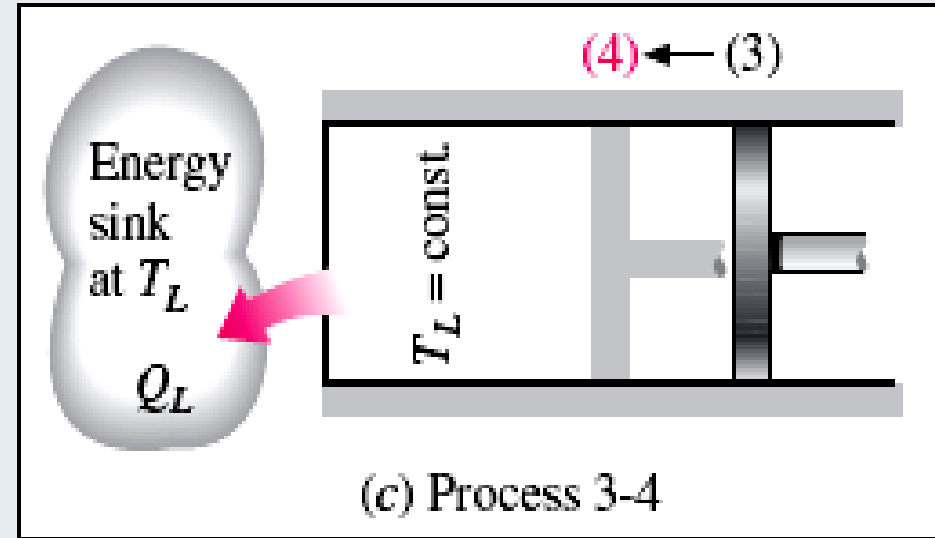


# 3. The Carnot Cycle

Cont...

## Reversible Isothermal Compression

- Although the gas temperature tends to increase during compression, any infinitesimal rise  $dT$  is immediately offset by heat transfer to the sink, maintaining the gas at a constant temperature  $T_L$ .



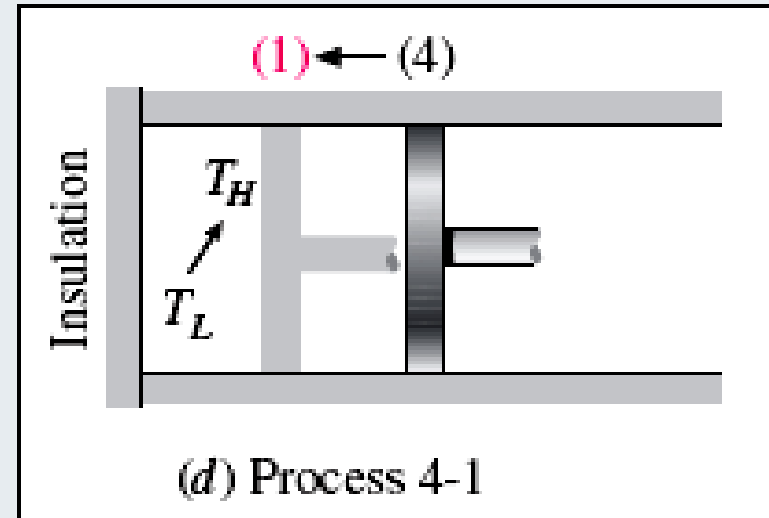
# 3. The Carnot Cycle

Cont...

## Process 4-1 (Reversible Adiabatic

Compression)\_T rises from  $T_L$  to  $T_H$ )

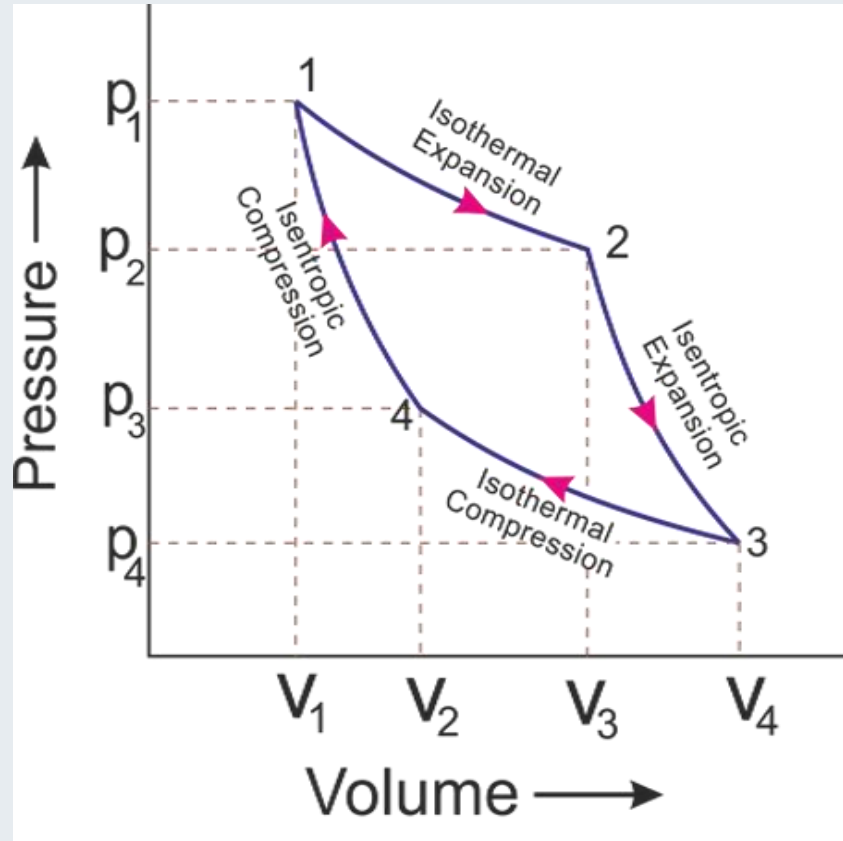
- At state 4, the low-temperature reservoir is removed, and the cylinder head is re-insulated.
- The gas then undergoes reversible adiabatic compression, causing its temperature to rise from  $T_L$  to  $T_H$ .
- This process returns the system to its initial state (state 1), completing the cycle.



# 3. The Carnot Cycle

Cont...

## The P-v Diagram of a Carnot Cycle



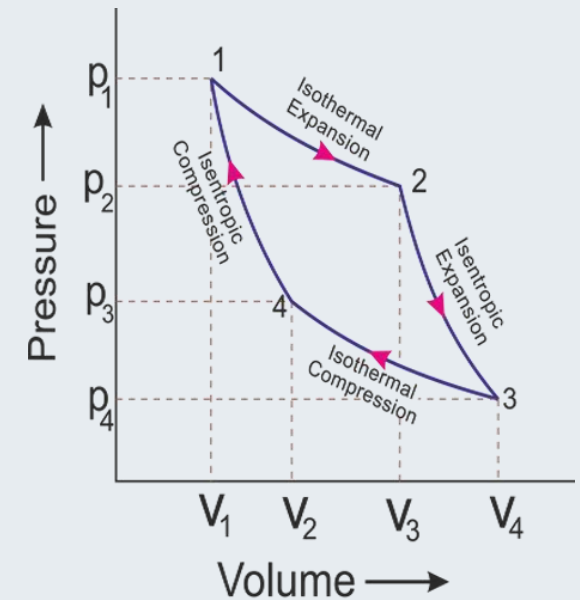
**Figure 3:** P-V diagram of a Carnot Cycle

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# 3. The Carnot Cycle

Cont...

- On a  $P$ - $V$  diagram, the area beneath a process curve corresponds to the boundary work for quasi-equilibrium (internally reversible) processes. In this cycle:
  - The area under curve 1-2-3 represents the work output during expansion (done *by* the gas).
  - The area under curve 3-4-1 represents the work input during compression (done *on* the gas).
  - The enclosed area (1-2-3-4-1) equals the net work output of the cycle, the difference between work produced and work consumed.



# 4. The Carnot Heat Engines

- The Carnot heat engine is a theoretical model of an ideal heat engine that operates with the **maximum possible efficiency engine** possible between **two given temperatures** [3].
- It's based on **reversible processes**, and its efficiency is solely determined by the temperatures of the hot and cold reservoirs.
- Though no physical engine can ever be truly Carnot-perfect, engineers use its principles to **improve the efficiency** of real-world thermal engines, such as those in power plants and automobiles.

# 4. The Carnot Heat Engine

Cont...

## Key characteristics of Carnot Heat Engine:

- The engine operates in a cyclic process consisting of four stages: **two isothermal** (constant-temperature) processes and **two adiabatic** (no heat exchange) processes.
- The efficiency of a Carnot engine depends solely on the **temperatures** of the **heat source** ( $T_H$ ) and the **heat sink** ( $T_L$ ), and is given by:

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

And,  $\frac{Q_L}{Q_H} = \frac{T_L}{T_H}$  Therefore,

$$\eta_{th,carnot} = 1 - \frac{T_L}{T_H}$$

# 4. The Carnot Heat Engine

Cont...

## Key Characteristics of Carnot Heat Engines:

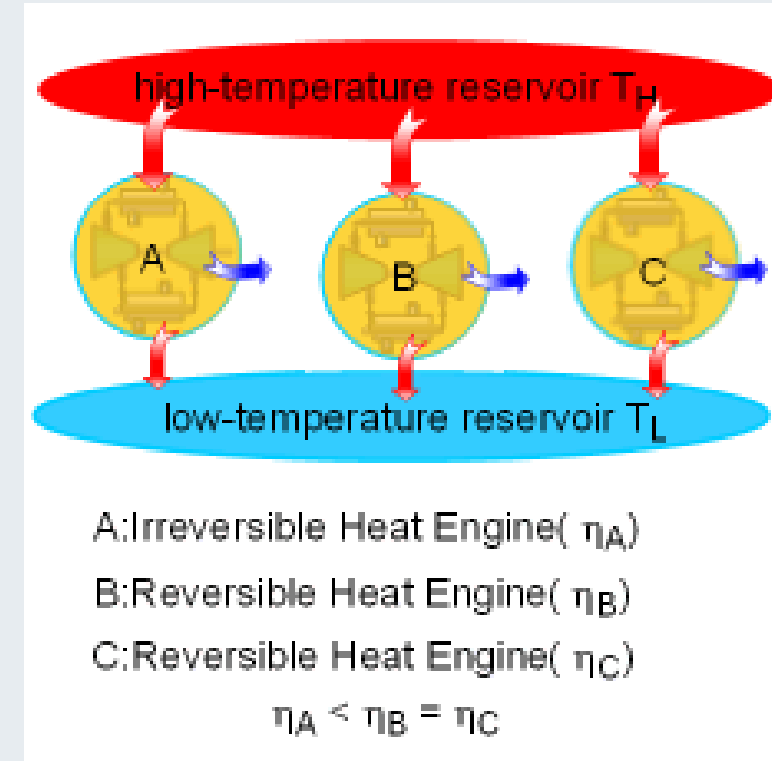
- The engine assumes perfect insulation and frictionless operation, which means **no energy is lost** due to inefficiencies like heat dissipation or mechanical friction.
- Since real heat engines always have inefficiencies, the Carnot engine represents the upper limit of efficiency that any engine can strive to achieve.

# 4. The Carnot Heat Engine

Cont...

## Carnot Principles

- Considering heat engines operating between two fixed-temperature reservoirs (where  $T_H > T_L$ ), we derive two key conclusions regarding thermal efficiency, these are known as the **Carnot Principles**:



**Figure 4:** Carnot principles

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# 4. The Carnot Heat Engine

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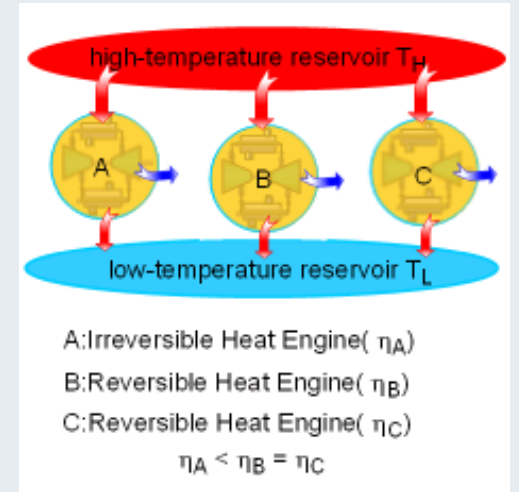
## Carnot Principles

- Principle 1 (Irreversible vs. Reversible Efficiency):

*"The efficiency of any irreversible heat engine is always less than that of a reversible engine operating between the same two temperature reservoirs [1]."*

- Principle 2 (Universality of Reversible Efficiency):

*"All reversible heat engines operating between the same two constant-temperature reservoirs achieve identical efficiencies [1]."*



# 4. The Carnot Heat Engine

Cont...

## Example

- A Carnot heat engine operates between a high-temperature reservoir at  $T_H=500\text{K}$  and a low-temperature reservoir at  $T_L=300\text{ K}$ . The engine absorbs  $Q_H=1000\text{kJ}$  of heat from the high-temperature source during each cycle.

Calculate:

- The thermal efficiency of the Carnot heat engine.
- The amount of work output per cycle.
- The amount of heat rejected to the cold reservoir.

# 4. The Carnot Heat Engine

Cont...

## Solution:

- The efficiency of a Carnot heat engine is given by:

$$\eta_{th,carnot} = 1 - \frac{T_L}{T_H}$$

$$\eta_{th,carnot} = 1 - \frac{300}{500} = \mathbf{0.4 \text{ or } 40\%}$$

- The useful work output of the engine is:

$$W = \eta_{th} \times Q_H$$

$$W = 0.4 \times 1000 = \mathbf{400 \text{ kJ}}$$

- The heat rejected to the cold reservoir,

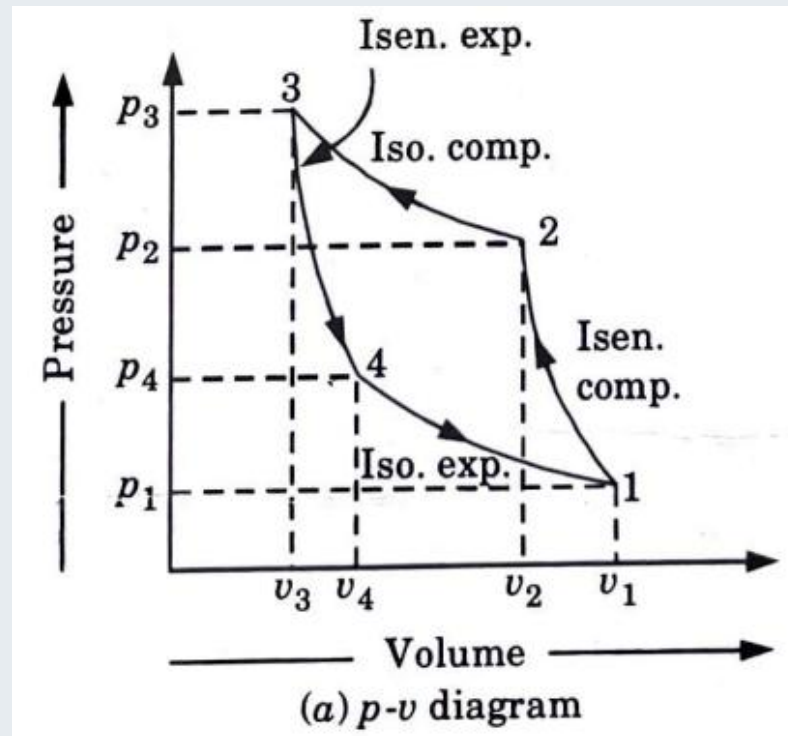
$$Q_L = Q_H - W = 1000 - 400 = \mathbf{600 \text{ kJ}}$$

# 5. The Carnot Refrigerator and Heat Pump

- A **Carnot refrigerator** and a **Carnot heat pump** are theoretical thermodynamic devices that operate on the **reversed Carnot cycle**, which consists of two isothermal and two adiabatic (isentropic) processes [4].
- They are essentially **the same device**, differing only in their objective:
  - refrigerators aim to remove heat from a **cold reservoir**, while
  - heat pumps aim to transfer heat to a **warm reservoir**.
- It's a theoretical model, and real-world refrigerators and heat pumps **do not perfectly follow** this cycle, but they can be designed to operate close to it.

# 5. The Carnot Refrigerator and Heat Pump

- The P-v diagram of a Carnot Refrigerator and Heat Pump



**Figure 4:** P-v diagram of a Carnot Refrigerator

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# 5. The Carnot Refrigerator and Heat Pump

Cont...

- The Carnot cycle represents the **maximum possible efficiency** for a refrigerator or heat pump operating between two given temperatures [5].
- The Coefficient of Performance of **Refrigerators** can be determined:

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

$$COP_R = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

For a Carnot Refrigerator,  $\frac{Q_H}{Q_L} = \frac{T_H}{T_L}$

$$\text{Therefore, } COP_{R,Carnot} = \frac{1}{\frac{T_H}{T_L} - 1}$$

# 5. The Carnot Refrigerator and Heat Pump

Cont...

Similarly,

The Coefficient of Performance of **Heat Pumps** can be determined:

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

$$COP_{HP} = \frac{\frac{Q_H}{Q_L}}{\frac{Q_H}{Q_L} - 1}$$

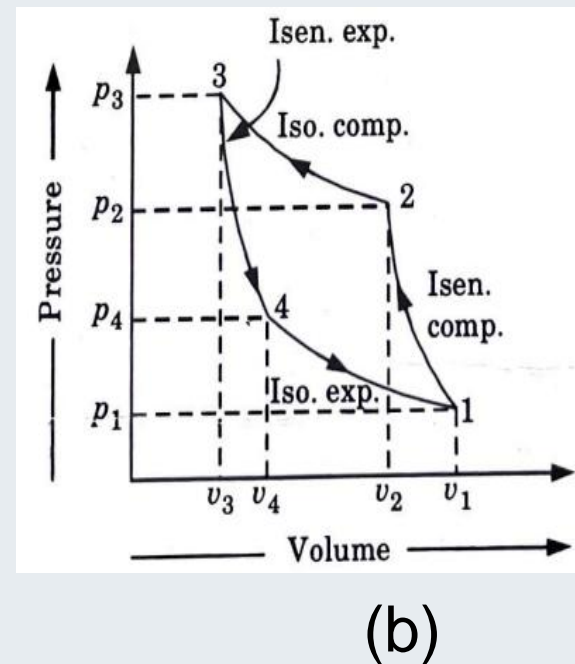
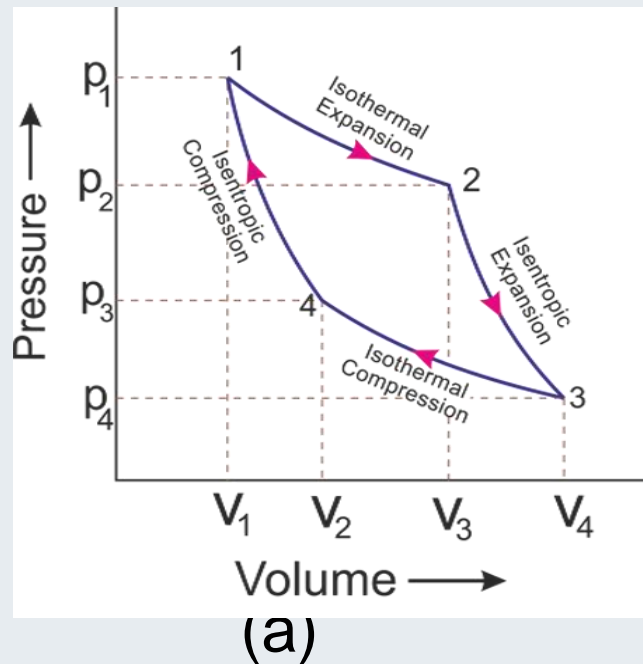
For a Carnot Heat Pump,  $\frac{Q_H}{Q_L} = \frac{T_H}{T_L}$

Therefore,  $COP_{HP,Carnot} = \frac{\frac{T_H}{T_L}}{\frac{T_H}{T_L} - 1}$

# 5. The Carnot Refrigerator and Heat Pump

Cont...

- You may have observed that the power cycle operates in the clockwise direction when plotted on a process diagram (a).
- The Carnot cycle may be reversed, in which it operates as a refrigerator.
- The refrigeration cycle operates in the counter clockwise direction (b).



# 5. The Carnot Refrigerator and Heat Pump

Cont...

## Example 1:

A refrigerator operates between a cold region at  $T_C = 5^\circ\text{C}$  and a warm region at  $T_H = 30^\circ\text{C}$ . The refrigerator extracts 1500 kJ of heat from the cold space per cycle.

Calculate:

- The coefficient of performance (COP) of the refrigerator.
- The equivalent heat pump COP.
- The amount of work input required per cycle.

# 5. The Carnot Refrigerator and Heat Pump

Cont...

## Solution:

$$T_C = 5^\circ\text{C} + 273 = 278 \text{ K}$$

$$T_H = 30^\circ\text{C} + 273 = 303 \text{ K}$$

The coefficient of performance (COP) for a refrigerator is given by:

$$COP_R = \frac{Q_L}{W_{net,in}}$$

Using the Carnot efficiency,

$$COP_{R,Carnot} = \frac{1}{\frac{T_H}{T_L} - 1} = \frac{1}{\frac{303}{278} - 1} = \mathbf{11.12}$$

# 5. The Carnot Refrigerator and Heat Pump

Cont...

- The work input can be determined by rearranging the COP equation:

$$W = \frac{Q_L}{COP_R} = \frac{1500 \text{ kJ}}{11.12} = \mathbf{134.9 \text{ kJ}}$$

- The COP of Heat Pump can be:

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

$$COP_{HP} = 11.12 + 1 = \mathbf{12.12}$$

- For the same amount of work input, the heat pump can deliver:

$$Q_H = COP_{HP} \times W$$

$$Q_H = 12.12 \times 134.9 = \mathbf{1635 \text{ kJ}}$$

# 5. The Carnot Refrigerator and Heat Pump

Cont...

## Example 2:

A Carnot heat engine receives heat from a high-temperature reservoir at  $900^{\circ}\text{C}$ , absorbing energy at a rate of 800 kJ per minute. It then releases waste heat to the surrounding air at  $27^{\circ}\text{C}$ . The engine's entire work output is utilized to operate a Carnot refrigerator, which draws heat from a refrigerated space maintained at  $-5^{\circ}\text{C}$  and transfers it to the same ambient air at  $27^{\circ}\text{C}$ .

Determine:

- The maximum rate at which heat can be removed from the refrigerated space.
- The total rate at which heat is rejected to the ambient air.

# 5. The Carnot Refrigerator and Heat Pump

Cont...

## Solution:

- The maximum thermal efficiency,

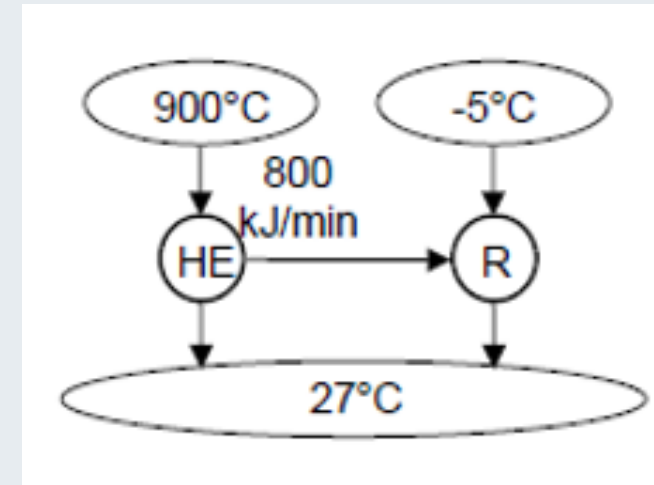
$$\eta_{th,max} = 1 - \frac{T_L}{T_H} = 1 - \frac{300\text{ K}}{1173\text{ K}} = 0.744$$

- The maximum power output of the heat engine:

$$\dot{W}_{net,out} = \eta_{th} \dot{Q}_H = (0.744)(800\text{ kJ}/\text{min})$$

$$\dot{W}_{net,out} = 595.2\text{ kJ}/\text{min}$$

- Therefore, the power input to the refrigerator is also  $\dot{W}_{net,in} = 595.2\text{ kJ}/\text{min}$



# 5. The Carnot Refrigerator and Heat Pump

Cont...

- The maximum rate of heat removal from the refrigerated space will be:

$$COP_{R,carnot} = \frac{1}{\frac{T_H}{T_L} - 1} = \frac{1}{\frac{(27 + 273)}{(-5 + 273)} - 1} = 8.37$$

- The rate of heat removal from the refrigerated space becomes:

$$\dot{Q}_{L,R} = (COP_{R,carnot})(\dot{W}_{net,in})$$

$$\dot{Q}_{L,R} = (8.37)(595.2 \text{ kJ}/\text{min}) = \mathbf{4982 \text{ kJ}/\text{min}}$$

# 5. The Carnot Refrigerator and Heat Pump

Cont...

- The total rate of heat rejection to the ambient air is the sum of the heat rejected by the heat engine ( $\dot{Q}_{L,HE}$ ) and the heat discarded by the refrigerator ( $\dot{Q}_{H,R}$ )

$$\dot{Q}_{L,HE} = \dot{Q}_{H,HE} - \dot{W}_{net,out}$$

$$\dot{Q}_{L,HE} = 800 - 595.2 = 204.8 \text{ kJ/min}$$

$$\dot{Q}_{H,R} = \dot{Q}_{L,R} + \dot{W}_{net,in}$$

$$\dot{Q}_{H,R} = 4982 + 595.2 = 5577.2 \text{ kJ/min}$$

$$\dot{Q}_{ambient} = \dot{Q}_{L,HE} + \dot{Q}_{H,R}$$

$$\dot{Q}_{ambient} = 204.8 + 5577.2 = \mathbf{5782 \text{ kJ/min}}$$

# Summary

- Refrigerators and Heat Pumps are devices that transfer heat against the natural flow, using work input to move heat from a colder region to a warmer one. Performance is measured using the coefficient of performance (COP).
- Second Law of Thermodynamics states that energy transfers tend toward increasing entropy, and no process is 100% efficient in converting heat into work.
- Carnot Cycle is an idealized cycle consisting of two isothermal and two adiabatic processes, providing the theoretical maximum efficiency for heat engines.
- Carnot Heat Engine operates on the Carnot cycle, achieving the highest possible efficiency, with performance dependent solely on the temperature of the heat reservoirs.
- Carnot Refrigerator and Heat Pump operate on the reversed Carnot cycle; the Carnot refrigerator maximizes cooling efficiency, while the Carnot heat pump maximizes heating efficiency.

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Thank you !