ESO 201A: Thermodynamics

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The Second Law of Thermodynamics: part 4

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Learning objectives

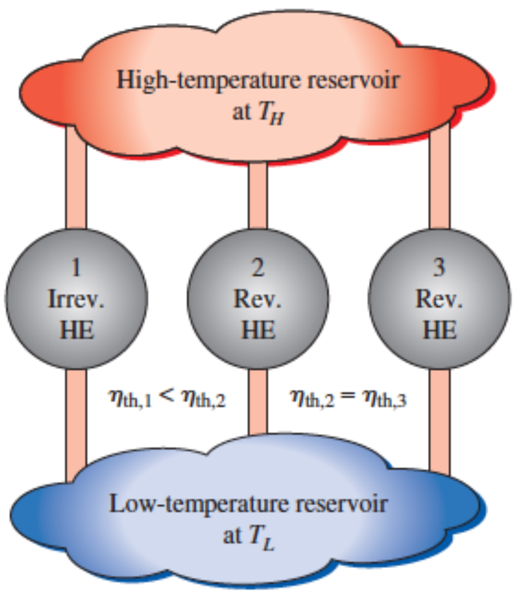
- Introduce the second law of thermodynamics.
- Identify valid processes as those that satisfy both the first and second laws of thermodynamics.
- Discuss thermal energy reservoirs,, heat engines
- Describe the Kelvin–Planck statement of the second law of thermodynamics
- Discuss refrigerators, and heat pumps and describe Clausius statement of the second law of thermodynamics
- Determine the expressions for the thermal efficiencies and coefficients of performance for reversible heat engines, heat pumps, and refrigerators.
- Discuss the concepts of perpetual-motion machines, reversible and irreversible processes
- Describe the Carnot cycle, examine the Carnot principles, idealized Carnot heat engines, refrigerators, and heat pumps.
- Apply the second law to develop the absolute thermodynamic temperature scale.

The Carnot Principles

The Second Law of Thermodynamics puts a limits on the operation of cyclic devices as expressed by KP and Clausius statements

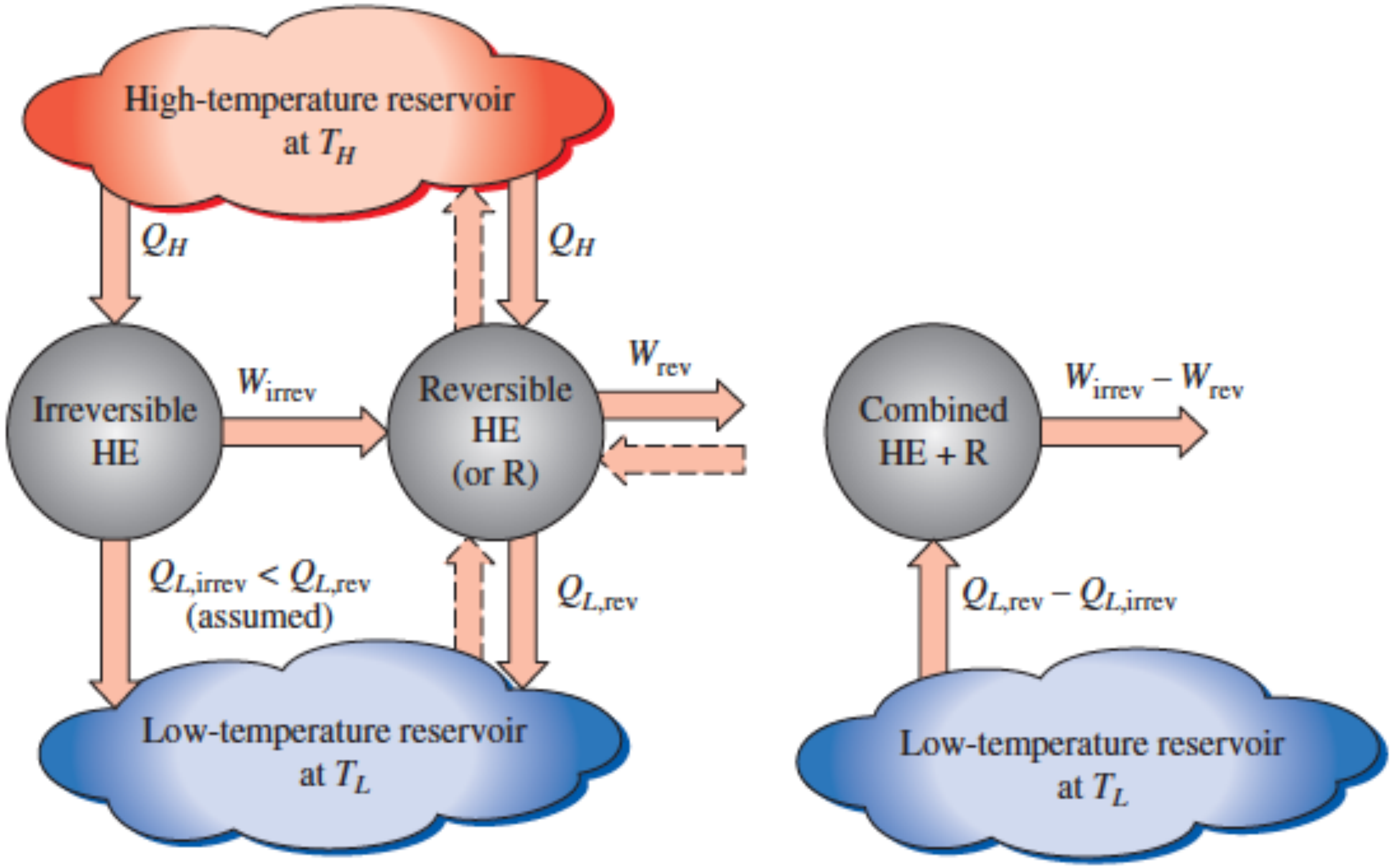
- HE cannot operate by exchanging heat with a single reservoir
- Refrigerator cannot operature without a net energy input from an external source

Carnot Principles



1. The efficiency of an irreversible heat engine (actual HE) is always less than the efficiency of a reversible one operating between the same two reservoirs.
2. The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.

Proof of Carnot Principles



(*a*) A reversible and an irreversible heat engine operating between the same two reservoirs (the reversible heat engine is then reversed to run as a refrigerator)

(*b*) The equivalent combined system

The thermodynamics temperature scale

- Thermodynamic temperature scale-independent of substance
- The second Carnot cycle – all reversible HE operating between the same two reservoir have the same efficiency
- Since reservoirs are at constant T, efficiency of reversible HE:

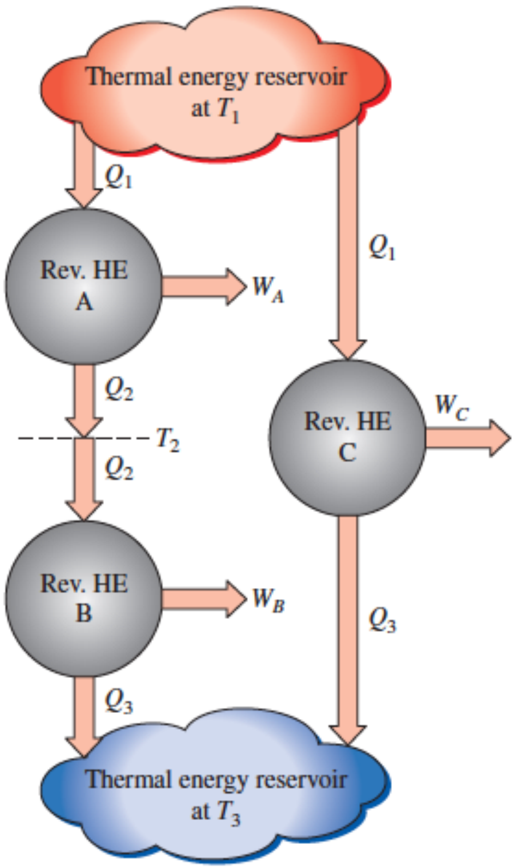
$$\eta_{\text{th,rev}} = g(T_H, T_L)$$

Since

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

Or

$$\frac{Q_H}{Q_L} = f(T_H, T_L)$$



$$\frac{Q_1}{Q_2} = f(T_1, T_2), \quad \frac{Q_2}{Q_3} = f(T_2, T_3), \quad \text{and} \quad \frac{Q_1}{Q_3} = f(T_1, T_3)$$

$$\frac{Q_1}{Q_3} = \frac{Q_1}{Q_2}\frac{Q_2}{Q_3} \qquad \Rightarrow \qquad f(T_1, T_3) = f(T_1, T_2) \cdot f(T_2, T_3)$$

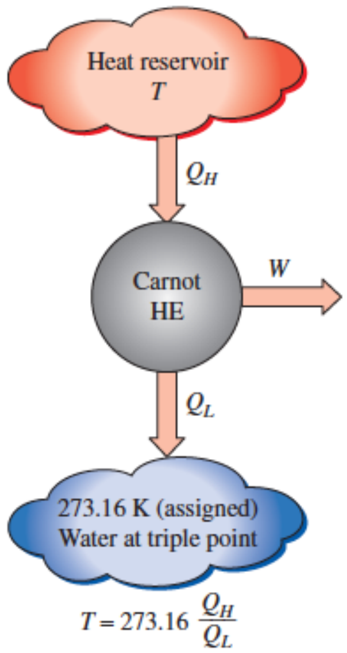
LHS funciton of T=> RHS should be function of T and independent of T_2

The thermodynamics temperature scale

Condition is satisfied if the function *f* has the following form

$$f(T_1, T_2) = \frac{\phi(T_1)}{\phi(T_2)} \quad \text{and} \quad f(T_2, T_3) = \frac{\phi(T_2)}{\phi(T_3)}$$

$$\frac{Q_1}{Q_3} = f(T_1, T_3) = \frac{\phi(T_1)}{\phi(T_3)}$$



For reversible HE, operating between T_H and T_L

$$\frac{Q_H}{Q_L} = \frac{\phi(T_H)}{\phi(T_L)}$$

Lord Kelvin proposed $\phi(T)=T$

$$\left(\frac{Q_H}{Q_L}\right)_{\text{rev}} = \frac{T_H}{T_L}$$

T here is absolute

Kelvin scale, with magnitude of *kelvin =1/273.16 of the temperature between absolute zero and triple point temperature of water*

$$T(^\circ\text{C}) = T(\text{K}) - 273.15$$

The Carnot HE

The hypothetical HE that operates on the reversible Carnot cycle is called Carnot HE

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

For any HE (reversible/irreversible)

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

Efficiency of Carnot engine: Carnot efficiency

Highest efficiency of a HE operating between the two thermal energy reservoirs at temperature T_L and T_H

$$\eta_{th} \begin{cases} < \ \eta_{th,rev} & \text{irreversible heat engine} \\ = \ \eta_{th,rev} & \text{reversible heat engine} \\ > \ \eta_{th,rev} & \text{impossible heat engine} \end{cases}$$

Comparison of real process with the reversible process

The Carnot HE

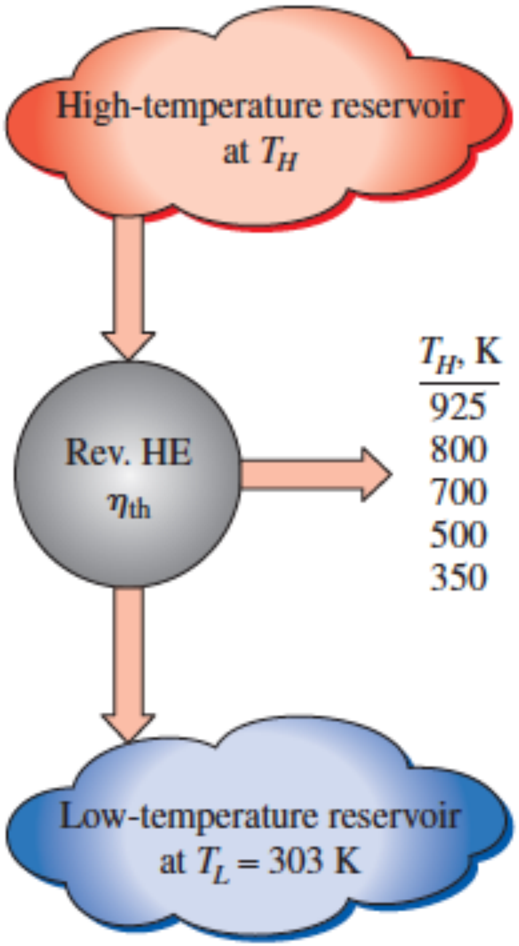
Steam power plant: T_H=1000K, T_L =300K
Max efficiency =70%
Actual efficiency 40% is not.
Efficiency of Carnot HE increase with increase in T_H, or decrease in T_L

Thermal efficiency of actual HE can be maximized by supplying heat to the engine at maximum T(limited by material strength) and rejecting heat from engine at the lowest possible temperature (limited by cooling medium)

Example

A Carnot heat engine receives 650 kJ of heat from a source of unknown temperature and rejects 250 kJ of it to a sink at 24^{o}C. Determine (a) the temperature of the source and (b) the thermal efficiency of the heat engine

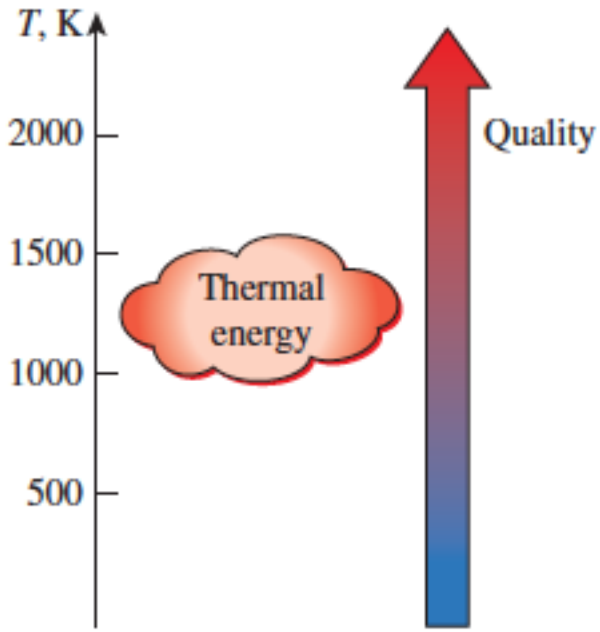
Quality



T_H, K	η_{th}, %
925	67.2
800	62.1
700	56.7
500	39.4
350	13.4

Energy has *quality* as well as *quantity*

Higher the T_H higher the conversion of heat to work



Quality

Work is more valuable form of energy
- Work con be converted 100 % to heat but not reverse!

- Quantity is conserved, not quality

- One unit of high-quality energy is more useful then 3 unit of low-quality energy

- Wasting energy equivalent to converting it to less useful form (low-quality) of energy

- Thus assessment of process should not be done on the basis of quantity (first law) only

The Carnot refrigerator and heat pump

A refrigerator or heat pump based on reversed Carnot cycle is called Carnot refrigerator or Carnot HP

$$\mathrm{COP_R} = \frac{1}{Q_H/Q_L - 1} \quad \text{and} \quad \mathrm{COP_{HP}} = \frac{1}{1 - Q_L/Q_H}$$

Q_L: amount of heat absorbed from the low T medium

Q_H: amount of the heat rejected to the high T medium

COP for reversible R, and HP

$$\mathrm{COP_{R,rev}} = \frac{1}{T_H/T_L - 1}$$

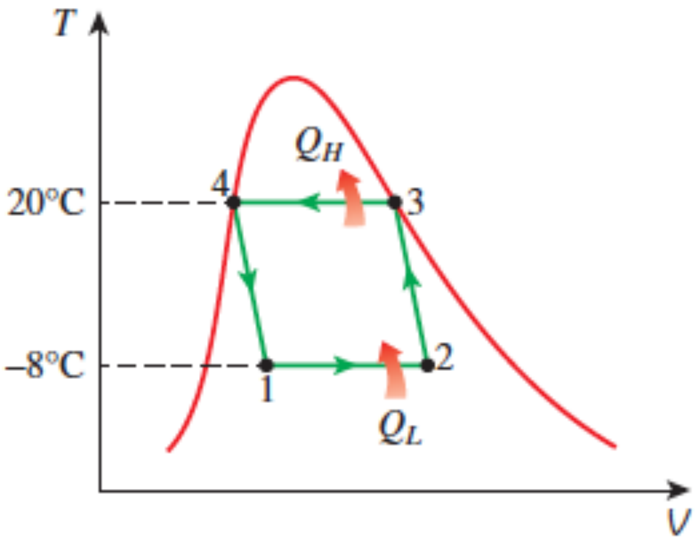
$$\mathrm{COP_R} \begin{cases} < \mathrm{COP_{R,rev}} & \text{irreversible refrigerator} \\ = \mathrm{COP_{R,rev}} & \text{reversible refrigerator} \\ > \mathrm{COP_{R,rev}} & \text{impossible refrigerator} \end{cases}$$

$$\mathrm{COP_{HP,rev}} = \frac{1}{1 - T_L/T_H}$$

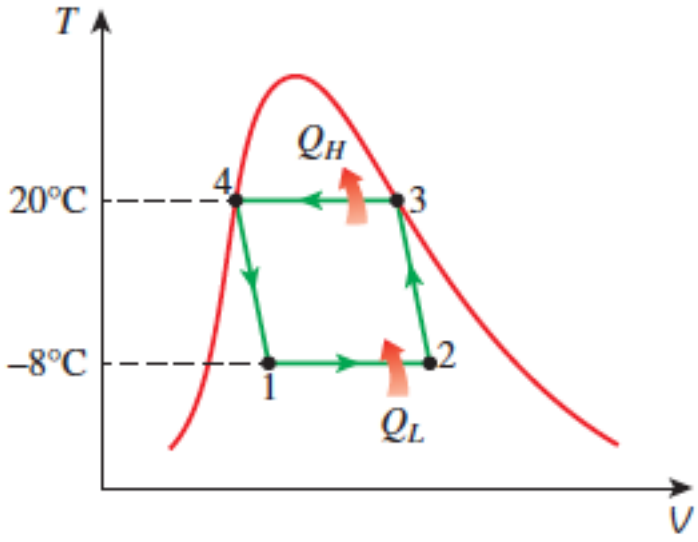
Highest coefficient of performance

Example

A Carnot refrigeration cycle is executed in a closed system in the saturated liquid–vapor mixture region using 0.8 kg of refrigerant-134a as the working fluid. The maximum and the minimum temperatures in the cycle are 20 and -8°C, respectively. It is known that the refrigerant is saturated liquid at the end of the heat rejection process, and the net work input to the cycle is 15 kJ. Determine the fraction of the mass of the refrigerant that vaporizes during the heat addition process, and the pressure at the end of the heat rejection process.



Example



Summary

- Introduction to the second law
- Thermal energy reservoirs
- Heat engines
  - Thermal efficiency
  - The 2nd law: Kelvin-Planck statement
- Refrigerators and heat pumps
  - Coefficient of performance (COP)
  - The 2nd law: Clasius statement
- Perpetual motion machines
- Reversible and irreversible processes
  - Irreversibilities, Internally and externally reversible processes
- The Carnot cycle
  - The reversed Carnot cycle
- The Carnot principles
- The thermodynamic temperature scale
- The Carnot heat engine
  - The quality of energy
- The Carnot refrigerator and heat pump