

Lecture 10 Thermodynamics of refrigeration machines and heat pumps

Goal of the lecture: to study the thermodynamic principles governing refrigeration machines and heat pumps, including their performance parameters, operating cycles, and efficiency indicators.

Brief lecture notes: This lecture focuses on the thermodynamic basis of refrigeration and heat pump systems. It examines the fundamental refrigeration cycles, such as the reversed Carnot and vapor-compression cycles, and explains the mechanisms of heat transfer from low- to high-temperature regions. Emphasis is placed on the Coefficient of Performance (COP), energy efficiency, and comparison between refrigerators and heat pumps. The lecture also covers working fluids (refrigerants), system components, and the influence of real-world losses on performance. Modern applications in air conditioning, food preservation, and renewable energy integration are also discussed.

Main part

Refrigeration and heat pump systems operate on the reverse thermodynamic cycles that transfer heat from a lower-temperature region to a higher-temperature region, requiring external work input. According to the Second Law of Thermodynamics, this process cannot occur spontaneously; thus, mechanical work must be supplied to achieve the desired heat transfer.

A refrigeration machine removes heat Q_L from a cold space and rejects it as Q_H to a warmer environment, while a heat pump does the opposite — it supplies useful heat Q_H to a heated space by extracting energy from a low-temperature source. Both are based on the reversed Carnot cycle, which represents the ideal model for such systems.

Stage	Process Name	Description	Diagram Comment
1	Isentropic compression	Refrigerant vapor is adiabatically compressed, increasing its pressure and temperature.	Work input to compressor.
2	Isothermal heat rejection	Heat is rejected at constant temperature in the condenser.	Refrigerant condenses to liquid.
3	Isentropic expansion	Expansion (or throttling) reduces temperature and pressure.	Produces cooling effect.
4	Isothermal heat absorption	Heat is absorbed at constant temperature in the evaporator.	Provides cooling from low-temperature reservoir.

The Vapor-Compression Cycle

In real systems, the vapor-compression refrigeration cycle replaces the ideal Carnot cycle due to practical limitations. It includes four components:

1. Compressor – compresses the refrigerant vapor to a high pressure and temperature.
2. Condenser – releases heat to the surroundings as the vapor condenses into liquid.

3. Expansion valve (throttle) – reduces pressure, causing partial vaporization.
4. Evaporator – absorbs heat from the cooled space as the refrigerant evaporates.

The vapor-compression cycle is represented on P–h (pressure–enthalpy) or T–s (temperature–entropy) diagrams, showing the cyclic behavior of the refrigerant as it undergoes phase changes.

Performance and Efficiency

The performance of refrigeration machines and heat pumps depends on:

- Temperature difference between source and sink (smaller difference → higher COP).
- Type of refrigerant used.
- Compressor and expansion device efficiency.
- Heat exchanger design (condensers and evaporators).

The ideal COP from the Carnot model serves as a benchmark, but real systems operate at 40–60% of the theoretical value due to mechanical and thermal losses.

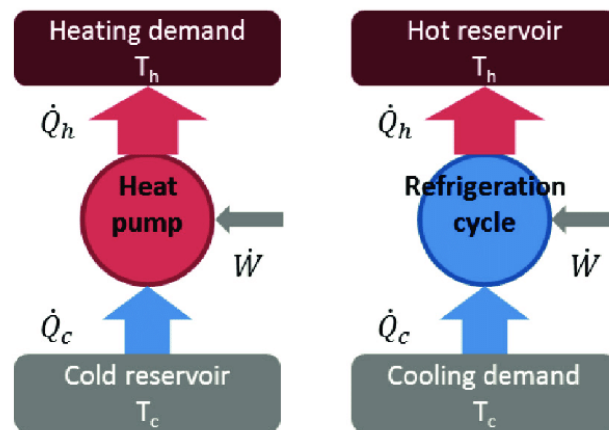
Different systems can be compared by their working principle and performance:

- The vapor-compression system is the most common and efficient, using mechanical compression and phase change of refrigerants ($\text{COP} \approx 2\text{--}6$).
- The absorption refrigeration system uses thermal energy (often waste heat or solar) instead of mechanical work, typically achieving lower COP ($\approx 0.5\text{--}1.5$).
- The gas cycle refrigeration system (based on reversed Brayton cycle) is used in aircraft cooling systems where weight is critical but efficiency is moderate ($\text{COP} \approx 0.3\text{--}0.8$).
- The heat pump is thermodynamically identical to a refrigerator but used for space heating, achieving COP values of 3–5 in moderate climates.

This comparison highlights how system design and application purpose affect efficiency and energy use.

Applications and Modern Developments

Refrigeration and heat pumps are crucial in air conditioning, industrial process cooling, cryogenic systems, food storage, and climate control. Modern advancements include the use of eco-friendly refrigerants (R-134a, CO₂, NH₃, hydrocarbons) and the integration of heat pumps with renewable energy systems, significantly improving overall energy sustainability. Heat pumps are increasingly applied in district heating and waste heat recovery, making them vital for energy transition and carbon reduction strategies.



$$COP_{heat\ pump} = \frac{\dot{Q}_h}{\dot{W}} = \frac{T_h}{T_h - T_c}$$

$$COP_{refrigeration\ cycle} = \frac{\dot{Q}_c}{\dot{W}} = \frac{T_c}{T_h - T_c}$$

Questions for Self-Control

1. What is the main difference between a refrigerator and a heat pump in terms of purpose and operation?
2. How is the coefficient of performance (COP) defined for refrigeration systems?
3. Why does the reversed Carnot cycle represent the ideal model for refrigeration?
4. What are the main components of a vapor-compression cycle?
5. How do real systems differ from the ideal Carnot refrigerator in terms of efficiency?

Literature

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