

Lecture 5 The Second Law of Thermodynamics: Postulates, Consequences, and Heat Engines

Goal of the lecture: To study the fundamental postulates of the second law of thermodynamics, understand its physical implications, and analyze its application to the operation and efficiency of heat engines.

Brief lecture notes: This lecture introduces the second law of thermodynamics — one of the most fundamental principles governing all natural and engineering processes. Unlike the first law, which deals only with the conservation of energy, the second law establishes the direction of energy transformations and defines the concept of irreversibility. It explains why certain processes occur spontaneously while others do not and sets the theoretical limits for the efficiency of energy conversion systems, such as heat engines, refrigerators, and heat pumps. We will discuss the Clausius and Kelvin–Planck postulates, the concept of entropy, reversibility and irreversibility, and the Carnot cycle as an ideal model of heat engine operation.

Main part

While the first law of thermodynamics ensures energy conservation, it says nothing about the direction of processes. For example, the first law cannot explain why heat spontaneously flows from a hot object to a cold one but never the reverse. The second law introduces the concept of irreversibility and provides the criterion that determines the direction of spontaneous processes. It tells us that all natural processes tend to move toward a state of greater entropy or disorder.

Postulates of the Second Law

Two equivalent statements express the essence of the second law:

1. Kelvin–Planck Statement:

It is impossible to build a cyclic device that converts all absorbed heat from a single reservoir entirely into work.

2. Clausius Statement:

It is impossible to construct a device operating in a cycle that transfers heat from a colder body to a hotter body without external work input.

These statements establish that some portion of heat must always be rejected, and no process can be 100% efficient.

Entropy and the Clausius Inequality

The second law introduces **entropy (S)**, a property that quantifies the dispersal of energy in a system. For a reversible process, the change in entropy is defined as:

$$dS = \frac{\delta Q_{rev}}{T}$$

where δQ_{rev} is the heat transfer in a reversible process, and T is the absolute temperature.

For any cyclic process, the Clausius inequality holds:

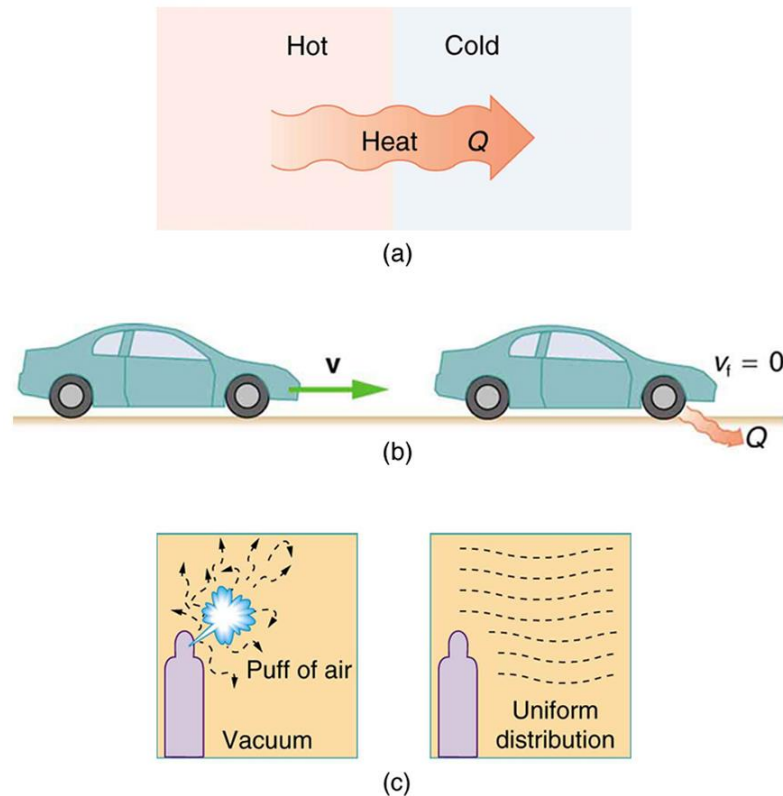
$$\oint \frac{\delta Q}{T} \leq 0$$

The equality applies for reversible cycles, and the inequality for irreversible ones. This relation sets a clear boundary between ideal and real processes.

Heat Engines

A heat engine is a device that converts heat energy into work by operating between two temperature reservoirs. The working fluid in the engine absorbs heat from a high-temperature source, performs work, and rejects some heat to a low-temperature sink.

Figure 1. Schematic representation of a simple heat engine.



The Carnot Cycle

The Carnot cycle represents an ideal reversible engine that provides the *maximum possible efficiency* between two temperatures T_H and T_C . It consists of four stages:

1. Isothermal expansion at T_H — absorption of heat Q_H ;
2. Adiabatic expansion — temperature drops to T_C ;
3. Isothermal compression at T_C — rejection of heat Q_C ;
4. Adiabatic compression — return to the initial state.

The efficiency of a Carnot engine depends only on the reservoir temperatures:

$$\eta_{\text{Carnot}} = 1 - \frac{T_C}{T_H}$$

Although real engines are less efficient due to irreversibilities, the Carnot efficiency sets the upper limit for all.

Comparative Characteristics

Aspect	Reversible Process	Irreversible Process
Heat transfer	Infinitesimally slow	Finite temperature difference

Aspect	Reversible Process	Irreversible Process
Entropy change	$\Delta S = 0(\text{system} + \text{surroundings})$	$\Delta S > 0$
Efficiency	Maximum possible	Less than Carnot
Example	Carnot cycle	Real engines, turbines
Energy losses	None	Due to friction, heat loss, mixing

Practical Implications

The second law governs the quality of energy. Although total energy remains constant, its *usefulness* decreases during every real process. This law guides engineers in designing efficient systems such as power plants, refrigeration cycles, and chemical processes. Understanding entropy generation helps in minimizing energy losses and improving overall system performance. In broader terms, the second law connects thermodynamics to sustainability by explaining why complete recycling of energy is impossible and why waste heat must always exist.

Questions for Self-Control

1. What are the main postulates of the second law of thermodynamics?
2. How does the second law define the direction of natural processes?
3. What is entropy and how is it related to reversible heat transfer?
4. Why is the efficiency of real heat engines always less than that of the Carnot cycle?
5. What practical limitations does the second law impose on energy conversion systems?

Literature

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