4.5: The Second Law of Thermodynamics (Summary)

Key Terms

**Carnot cycle**
cycle that consists of two isotherms at the temperatures of two reservoirs and two adiabatic processes connecting the isotherms

**Carnot engine**
Carnot heat engine, refrigerator, or heat pump that operates on a Carnot cycle

**Carnot principle**
principle governing the efficiency or performance of a heat device operating on a Carnot cycle: any reversible heat device working between two reservoirs must have the same efficiency or performance coefficient, greater than that of an irreversible heat device operating between the same two reservoirs

**Clausius statement of the second law of thermodynamics**
heat never flows spontaneously from a colder object to a hotter object

**Coefficient of performance**
measure of effectiveness of a refrigerator or heat pump

**Cold reservoir**
sink of heat used by a heat engine

**Disorder**
measure of order in a system; the greater the disorder is, the higher the entropy

**Efficiency (e)**
output work from the engine over the input heat to the engine from the hot reservoir

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<table>
<thead>
<tr>
<th>term</th>
<th>definition</th>
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<tr>
<td>entropy</td>
<td>state function of the system that changes when heat is transferred between the system and the environment</td>
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<tr>
<td>entropy statement of the second law of thermodynamics</td>
<td>entropy of a closed system or the entire universe never decreases</td>
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<tr>
<td>heat engine</td>
<td>device that converts heat into work</td>
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<tr>
<td>heat pump</td>
<td>device that delivers heat to a hot reservoir</td>
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<td>hot reservoir</td>
<td>source of heat used by a heat engine</td>
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<tr>
<td>irreversibility</td>
<td>phenomenon associated with a natural process</td>
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<td>irreversible process</td>
<td>process in which neither the system nor its environment can be restored to their original states at the same time</td>
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<tr>
<td>isentropic</td>
<td>reversible adiabatic process where the process is frictionless and no heat is transferred</td>
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<tr>
<td>Kelvin statement of the second law of thermodynamics</td>
<td>it is impossible to convert the heat from a single source into work without any other effect</td>
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<tr>
<td>perfect engine</td>
<td>engine that can convert heat into work with 100% efficiency</td>
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<tr>
<td>perfect refrigerator (heat pump)</td>
<td>refrigerator (heat pump) that can remove (dump) heat without any input of work</td>
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<tr>
<td>refrigerator</td>
<td>device that removes heat from a cold reservoir</td>
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<tr>
<td>reversible process</td>
<td>process in which both the system and the external environment theoretically can be returned to their original states</td>
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<tr>
<td>third law of thermodynamics</td>
<td>absolute zero temperature cannot be reached through any finite number of cooling steps</td>
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**Key Equations**

- Result of energy conservation: $W = Q_h - Q_c$
- Efficiency of a heat engine: $e = \frac{W}{Q_h} = 1 - \frac{Q_c}{Q_h}$
- Coefficient of performance of a refrigerator: $K_R = \frac{Q_c}{W} = \frac{Q_c}{Q_h - Q}$
Coefficient of performance of a heat pump
\( K_P = \frac{Q_h}{W} = \frac{Q_h}{Q_h - Q_c} \)

Resulting efficiency of a Carnot cycle
\( e = 1 - \frac{T_c}{T_h} \)

Performance coefficient of a reversible refrigerator
\( K_R = \frac{T_c}{T_h - T_c} \)

Performance coefficient of a reversible heat pump
\( K_P = \frac{T_h}{T_h - T_c} \)

Entropy of a system undergoing a reversible process at a constant temperature
\( \Delta S = \frac{Q}{T} \)

Change of entropy of a system under a reversible process
\( \Delta S = S_B - S_A = \int_{A}^{B} \frac{dQ}{T} \)

Entropy of a system undergoing any complete reversible cyclic process
\( \oint dS = \oint \frac{dQ}{T} = 0 \)

Change of entropy of a closed system under an irreversible process
\( \Delta S \geq 0 \)

Change in entropy of the system along an isotherm
\( \lim_{T \to 0} (\Delta S)_T = 0 \)

Summary

4.2 Reversible and Irreversible Processes

- A reversible process is one in which both the system and its environment can return to exactly the states they were in by following the reverse path.
- An irreversible process is one in which the system and its environment cannot return together to exactly the states that they were in.
- The irreversibility of any natural process results from the second law of thermodynamics.

4.3 Heat Engines

- The work done by a heat engine is the difference between the heat absorbed from the hot reservoir and the heat discharged to the cold reservoir, that is, \( W = Q_h - Q_c \).
- The ratio of the work done by the engine and the heat absorbed from the hot reservoir provides the efficiency of the engine, that is, \( e = \frac{W}{Q_h} = 1 - \frac{Q_c}{Q_h} \).

4.4 Refrigerators and Heat Pumps

- A refrigerator or a heat pump is a heat engine run in reverse.
- The focus of a refrigerator is on removing heat from the cold reservoir with a coefficient of performance \( K_R \).
- The focus of a heat pump is on dumping heat to the hot reservoir with a coefficient of performance \( K_P \).
4.5 Statements of the Second Law of Thermodynamics

- The Kelvin statement of the second law of thermodynamics: It is impossible to convert the heat from a single source into work without any other effect.
- The Kelvin statement and Clausius statement of the second law of thermodynamics are equivalent.

4.6 The Carnot Cycle

- The Carnot cycle is the most efficient engine for a reversible cycle designed between two reservoirs.
- The Carnot principle is another way of stating the second law of thermodynamics.

4.7 Entropy

- The change in entropy for a reversible process at constant temperature is equal to the heat divided by the temperature. The entropy change of a system under a reversible process is given by \( \Delta S = \int_{A}^{B} \frac{dQ}{T} \).
- A system’s change in entropy between two states is independent of the reversible thermodynamic path taken by the system when it makes a transition between the states.

4.8 Entropy on a Microscopic Scale

- Entropy can be related to how disordered a system is—the more it is disordered, the higher is its entropy. In any irreversible process, the universe becomes more disordered.
- According to the third law of thermodynamics, absolute zero temperature is unreachable.

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