Announcements:
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Office hours for Thermo 01 will be every Sunday and Tuesday from 9:00 – 12:00 am in Dr. Walid’s office (Room 5-213).

Text book:
Thermodynamics An Engineering Approach
Yunus A. Cengel & Michael A. Boles
Chapter 6
THE SECOND LAW OF THERMODYNAMICS
Objectives of CH6: To

• Introduce 2nd law of thermodynamics.
• Identify valid processes that satisfy both 1st and 2nd laws of thermodynamics.
• Discuss thermal energy reservoirs, reversible and irreversible processes, heat engines, refrigerators, and heat pumps.
• Describe the Kelvin–Planck and Clausius statements of 2nd law of thermodynamics.
• Discuss the concepts of perpetual-motion M/Cs.
  * Apply the 2\textsuperscript{nd} law of thermodynamics to cycles and cyclic devices.
  * Apply the 2\textsuperscript{nd} law to develop the absolute thermodynamic temperature scale.
• Describe the Carnot cycle.
• Examine the Carnot principles, idealized Carnot heat engines, refrigerators, and heat pumps.
• Determine the expressions for the thermal efficiencies and coefficients of performance for reversible heat engines, heat pumps, and refrigerators.
Processes occur in a certain direction, and not in the reverse direction.
Bodies with relatively large thermal masses can be modeled as thermal energy reservoirs.
A source supplies energy in the form of heat, and a sink absorbs it.
Heat engines can be characterized by the following:

1. They receive heat from a high-temperature source (solar energy, oil furnace, nuclear reactor, etc.).
2. They convert part of this heat to work (usually in the form of a rotating shaft).
Part of the heat received by a heat engine is converted to work, while the rest is rejected to a sink.
3. They reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.).

4. They operate on a cycle.
The **work-producing device** that **best fits** into the **definition** of a heat engine is the **steam power plant**
\( Q_{in} \) = amount of \textbf{heat supplied} to steam in boiler from a high-temperature source (furnace)

\( Q_{out} \) = amount of \textbf{heat rejected} from steam in condenser to a low temperature sink (the atmosphere, a river, etc.)

\( W_{out} \) = amount of \textbf{work delivered} by steam as it expands in turbine

\( W_{in} \) = amount of \textbf{work required} to compress water to boiler pressure
The net work output of this power plant is simply the difference between the total work output of the plant and the total work input:

\[ W_{\text{net, out}} = W_{\text{out}} - W_{\text{in}} \quad \text{(kJ)} \quad (6-1) \]

The net work output of the system is also equal to the net heat transfer to the system:

\[ W_{\text{net, out}} = Q_{\text{in}} - Q_{\text{out}} \quad \text{(kJ)} \quad (6-2) \]
Thermal Efficiency

Thermal efficiency of a heat engine can be expressed as

\[
\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}}
\]  \hspace{1cm} (6-3)

or

\[
\eta_{th} = \frac{W_{\text{net, out}}}{Q_{\text{in}}}
\]  \hspace{1cm} (6-4)
By substitution by $W_{net, out}$ from Eq. (6-2) in Eq. (6-4) to get

$$W_{net, out} = Q_{in} - Q_{out} \quad (kJ) \quad (6-2)$$

$$\eta_{th} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \quad (6-5)$$
\[ \eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} \]  \hspace{1cm} (6-5)
EXAMPLE 6–1 Net Power Production of a Heat Engine.

Heat is transferred to a heat engine from a furnace at a rate of 80 MW. If the rate of waste heat rejection to a nearby river is 50 MW, determine the net power output and the thermal efficiency for this heat engine.
Solution:

\[ \dot{Q}_H = 80 \text{ MW} \]
\[ \dot{Q}_L = 50 \text{ MW} \]

\[ \dot{W}_{net} = \dot{Q}_H - \dot{Q}_L = 80 \text{ MW} - 50 \text{ MW} = 30 \text{ MW} \]

\[ \eta_{th} = 1 - \frac{\dot{Q}_L}{\dot{Q}_H} \]

Hence, \( \eta_{th} = 1 - \frac{50}{80} \)
i.e., \( \eta_{th} = 0.375 \times 100\% = 37.5\% \)
Basic components of a refrigeration system and typical operating conditions.
The objective of a refrigerator is to remove $Q_L$ from the cooled space.
Coefficient of Performance

The efficiency of a refrigerator is expressed in terms of the coefficient of performance (COP),

\[
\text{COP}_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{\text{net,in}}} \quad (6-7)
\]

\[
W_{\text{net,in}} = Q_H - Q_L \quad (\text{kJ}) \quad (6-8)
\]
Substituting by $W_{net,in}$ from Eq. (6-8) in Eq. (6-7) to get,

$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{(Q_H/Q_L) - 1}$$  
(6-9)

Notice that the value of $COP_R$ can be greater than unity.
Heat Pumps

The objective of a heat pump is to supply $Q_H$ into the warmer space.
\[
COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{\text{net, in}}} \quad (6-10)
\]

which can also be expressed as

\[
COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - (Q_L/Q_H)} \quad (6-11)
\]
EXAMPLE 6–3 Heat Rejection by a Refrigerator.

The food compartment of a refrigerator, shown in the figure, is maintained at 4 °C by removing heat from it at a rate of 360 kJ/min. If the required power input to the refrigerator is 2 kW, determine (a) the coefficient of performance of the refrigerator and (b) the rate of heat rejection to the room that houses the refrigerator.
Solution:

\[ \dot{Q}_H \]

\[ \dot{W}_{\text{net}, \text{in}} = 2 \text{ kW} \]

\[ \dot{Q}_L = 360 \text{ kJ/min} \]

Food compartment

4°C
\[ \dot{Q}_L = 360 \text{ kJ/min} \]

i.e. \[ \dot{Q}_L = \frac{360}{60} \text{ kW} = 6 \text{ kW} \]

\[ \dot{W}_{\text{net,in}} = 2 \text{ kW} \]

\[ \dot{Q}_H = \dot{Q}_L + \dot{W}_{\text{net,in}} \]

\[ \dot{Q}_H = 6 \text{ kW} + 2 \text{ kW} = 8 \text{ kW} \]

\[ \dot{Q}_H = 8 \times 60 \text{ kJ/min} = 480 \text{ kJ/min} \]
From Eq. (6-7)

\[
COP_R = \frac{\dot{Q}_L}{W_{\text{net},in}} = \frac{6 \text{ kW}}{2 \text{ kW}} = 3
\]
EXAMPLE 6–4 Heating a House by a Heat Pump.

A heat pump is used to meet the heating requirements of a house and maintain it at 20°C. On a day when the outdoor air temperature drops to -2°C, the house is estimated to lose heat at a rate of 80,000 kJ/h. If the heat pump under these conditions has a COP of 2.5, determine (a) the power consumed by the heat pump and
(b) the rate at which heat is absorbed from the cold outdoor air.

Solution:

\[
\dot{Q}_H = 80000 \text{ kJ/h} = \frac{80000}{3600} \text{ kW}
\]

\[
\dot{Q}_H = 22.22 \text{ kW}
\]

But, from Eq. (6-10)

\[
COP_{HP} = \frac{\dot{Q}_H}{W_{\text{net,in}}}
\]
Hence,
\[ W_{\text{net,in}} = \frac{\dot{Q}_H}{\text{COP}_{HP}} = \frac{22.22 \text{ kW}}{2.5} \]

i.e., \[ W_{\text{net,in}} = 8.88 \text{ kW} \]

But, from Eq. (6-8)
\[ \dot{Q}_L + W_{\text{net,in}} = \dot{Q}_H \]
Hence,
\[ \dot{Q}_L = \dot{Q}_H - \dot{W}_{\text{net, in}} = 22.22 \text{ kW} - 8.88 \text{ kW} \]
i.e.,
\[ \dot{Q}_L = 13.34 \text{ kW} \]
\[ \dot{Q}_L = 13.34 \text{ kW} = 13.34 \times 3600 \text{ kj/h} \]
\[ \dot{Q}_L = 48024 \text{ kj/h} \]
Thermal efficiency of any heat engine is given by Eq. 6–6 as

$$\eta_{th} = 1 - \frac{Q_L}{Q_H} \quad (6-6)$$

But by definition, for Carnot engine, or any reversible heat engine

$$\left(\frac{Q_H}{Q_L}\right)_{rev} = \frac{T_H}{T_L} \quad (6-16)$$
Then the efficiency of a Carnot engine, or any reversible heat engine, becomes

$$\eta_{\text{th, rev}} = 1 - \frac{T_L}{T_H}$$  \hspace{1cm} (6-18)

Carnot efficiency represents the limit of efficiency of any thermal heat engine, i.e.

$$\eta_{\text{th}} \leq \eta_{\text{th, rev}}$$
EXAMPLE 6–5 Analysis of a Carnot Heat Engine.

A Carnot heat engine, shown in the figure receives 500 kJ of heat per cycle from a high-temperature source at 652°C and rejects heat to a low-temperature sink at 30°C. Determine (a) the thermal efficiency of this Carnot engine and (b) the amount of heat rejected to the sink per cycle.
Solution:
\[ Q_H = 500 \text{ kJ} \]

\[ T_H = 652 \, ^\circ C \quad T_L = 30 \, ^\circ C \]

\[ \eta_{\text{th,C}} = \eta_{\text{th,rev}} = 1 - \frac{T_L}{T_H} \]

Hence,

\[ \eta_{\text{th,C}} = 1 - \frac{(30 + 273)K}{(652 + 273)K} = 0.672 \]
Hence, for this reversible heat engine

\[ \eta_{th,C} = \eta_{th,rev} = 1 - \frac{Q_{L,rev}}{Q_{H,rev}} \]

Hence,

\[ 0.672 = \eta_{th,rev} = 1 - \frac{Q_{L,rev}}{500 \text{ kJ}} \]

\[ Q_{L,rev} = (1 - 0.672) \times 500 \text{ kJ} = 164 \text{ kJ} \]
A refrigerator or a heat pump that operates on the reversed Carnot cycle is called a **Carnot refrigerator**, or a **Carnot heat pump**. The coefficient of performance of any refrigerator or heat pump, reversible or irreversible, is.
\[ \text{COP}_R = \frac{1}{Q_H/Q_L - 1} \quad \text{and} \quad \text{COP}_{HP} = \frac{1}{1 - Q_L/Q_H} \]

But by definition, for Carnot engine, or any reversible heat engine

\[ \left( \frac{Q_H}{Q_L} \right)_{rev} = \frac{T_H}{T_L} \quad \text{(6-16)} \]
Hence,

\[
\text{COP}_{R,\text{rev}} = \frac{1}{T_H/T_L - 1}
\]  
(6-20)

and

\[
\text{COP}_{\text{HP,rev}} = \frac{1}{1 - T_L/T_H}
\]  
(6-21)

Carnot coefficient of performance represents the limit of coefficient of performance of any refrigerator or heat pump, i.e.
$COP_R < COP_{R,rev}$

and

$COP_{HP} < COP_{HP,rev}$
EXAMPLE 6–7 Heating a House by a Carnot Heat Pump

A heat pump is to be used to heat a house during the winter, as shown in the figure. The house is to be maintained at 21°C at all times. The house is estimated to be losing heat at a rate of 135,000 kJ/h when the outside temperature drops to 5°C. Determine the minimum power required to drive this heat pump.
\( \dot{Q}_H = 135,000 \text{ kJ/h} \)

\( T_H = 21 \, ^\circ \text{C} \)

\( T_L = -5 \, ^\circ \text{C} \)

From Eq. (6-21)

\[
\text{COP}_{\text{HP,rev}} = \frac{1}{1 - \frac{T_L}{T_H}}
\]
\[ T_H = 21 \, ^\circ C = 21 + 273 = 284 \, K \]
\[ T_L = -5 \, ^\circ C + 273 = 268 \, K \]

\[ \text{COP}_{HP, \text{rev}} = \frac{1}{1 - \frac{T_L}{T_H}} = \frac{1}{1 - \frac{268}{284}} \]

\[ \text{COP}_{HP, \text{rev}} = 17.75 \]
\[ \text{COP}_{\text{HP,rev}} = \frac{1}{1 - \frac{\dot{Q}_L}{\dot{Q}_H}} \]

\[ 17.75 = \frac{1}{1 - \frac{\dot{Q}_L}{135,000 \text{ kJ/h}}} \]

\[ 1 - \frac{1}{17.75} = \frac{\dot{Q}_L}{135,000 \text{ kJ/h}} \]
\[ \dot{Q}_L = 127,394 \text{ kJ/h} \]

\[ \dot{W}_{net,in} = \dot{Q}_H - \dot{Q}_L = 135,000 \frac{\text{kJ}}{\text{h}} - 127,394 \frac{\text{kJ}}{\text{h}} \]

Hence,

\[ \dot{W}_{net,in} = 7605.6 \frac{\text{kJ}}{\text{h}} = \frac{7605.6}{3600} \text{ kW} = 2.11 \text{ kW} \]
Homework

6–17, 6–18, 6–20, 6–21, 6–29C, 6–39, 6–40, 6–46, 6–47, 6–50, 6–51, 6–71, 6–72, 6–77, 6–78, 6–86, 6–87, 6–88, 6–90, 6–91, 6–94, 6–95, 6–96.