Chapter 5 - Second Law of Thermodynamics

Lecture 13

Section 5.1-5.2

MEMS 0051 Introduction to Thermodynamics

Mechanical Engineering and Materials Science Department
University of Pittsburgh

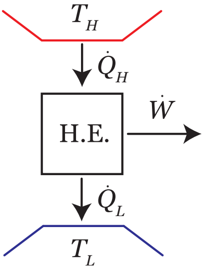
Student Learning Objectives

At the end of the lecture, students should be able to:

- Understand the operation of a heat engine and a refrigerator
- Understand and apply the formulation of thermal conversion efficiency and the coefficient of performance for both refrigerators and heat pumps
- Understand the Kelvin-Planck statement
- Understand the Clausius statement

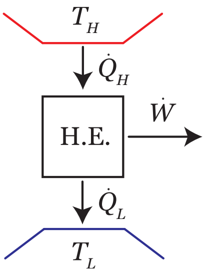
Heat Engines

- We have to introduce the concept of a **thermal reservoir** - a body that is able to maintain a constant temperature regardless of heat input or output
- A heat engine operates between a high-temperature and low-temperature thermal reservoir



Heat Engines

- Think of your car - combustion provides thermal energy, i.e. a high-temperature thermal reservoir
- This thermal energy is converted into mechanical
- The remainder is rejected a low-temperature reservoir



- **Power output** is defined as

$$P_o = Q_H - Q_L$$

- **Thermal efficiency** is defined as

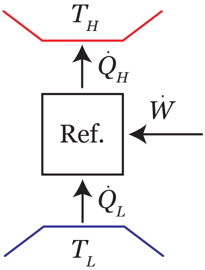
$$\eta_t = \frac{P_o}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

Example #1

- An inventor says he has developed a heat engine that receives 1,000 [kJ] of energy from a high-temperature reservoir, produces 410 [kJ] of power output, and rejects 600 [kJ] of energy to a low-temperature reservoir.
- Evaluate the efficiency of this heat engine. Does it make physical sense?

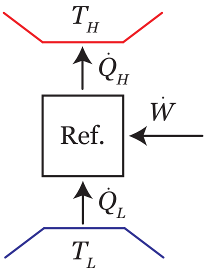
Refrigerators

- Refrigerators require work into the system to move heat from a low-temperature reservoir to a high-temperature reservoir
- Refrigerators do not violate the laws of heat transfer!



Refrigerators

- Phase change processes within the evaporator and condenser of a refrigerator allow for the transference of heat from a low- to high-temperature reservoir
- When analyzing a refrigerator, we are interested in how much heat is rejected from the low-temperature reservoir per unit input work



- The **work in** is defined as

$$W_{in} = Q_H - Q_L$$

- The **Coefficient of Performance** is defined as

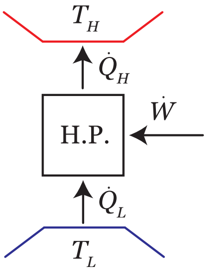
$$\beta = \frac{Q_L}{W_{in}} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

Example #2

- A refrigerator removes 8,000 [kJ/hr] of heat from the interior insulated space while consuming 3,200 [kJ/hr] of power. Determine the coefficient of performance of this particular device.

Heat Pump

- A heat pump is a refrigerator (air conditioner) run in reverse (i.e. Mitsubishi split units)
- When analyzing a heat pump, we are interested in how much heat is delivered to the high-temperature reservoir per unit input work



- The **Coefficient of Performance** is defined as

$$\beta' = \frac{Q_H}{W_{in}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \frac{Q_L}{Q_H}}$$

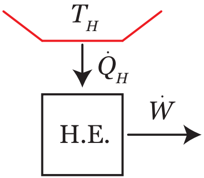
- Notice the prime, which indicates this formulation is for a H.P. only

2^{nd} Law

- The **Second Law of Thermodynamics** places restrictions on heat engines and refrigerators, as well as all process by governing the direction of heat transfer
- The Second Law:
  1. Guides the direction of all processes
  2. Determines the final equilibrium state for spontaneous processes
  3. Establishes the criteria for "ideal" performance
  4. Quantitatively evaluates the factors that preclude the attainment of best theoretical performance

Kelvin-Planck Statement

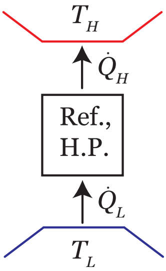
- The **Kelvin-Planck Statement** - it is impossible to construct a device that will operate in a cycle and produce no other effect other than the raising of a weight (i.e. produce work) and the exchange of heat with a single reservoir.



- This implies thermal efficiency cannot equal 100%

Clausius Statement

- The **Clausis Statement** - it is impossible to construct a device that operates in a cycle and produce no effect other than the transfer of heat from a cooler body to a warmer body



- This implies the coefficient of performance $<\infty$

2$^{\text{nd}}$ Law

- Both the K.P. and Clausius Statements are **negative** - they cannot be proven directly, rather only observed
- **Equivalence of Statements** means the truth of one implies the truth of the other, or proving one wrong implies the other is wrong
- These two statements rule out **Perpetual Motion Machines**

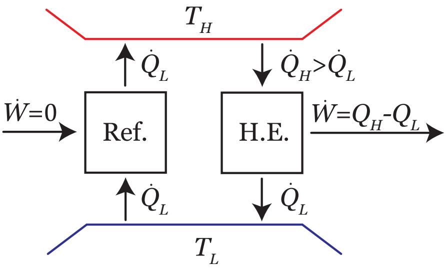
Perpetual Motion Machines

- Perpetual Motion Machines (PMMs) can be broken down into three categories:

1. A PMM of the First Kind would create work from nothing, or mass/energy
2. A PMM of the Second Kind - 100% efficient conversion of heat to work or other forms of energy
3. A PMM of the Third Kind has no friction, running indefinitely yet produces work

Example #3

- Does the following device adhere to the K.P. and Clausius Statements?



Student Learning Objectives

At the end of the lecture, students should be able to:

- Understand the operation of a heat engine and a refrigerator
  - A heat engine accepts heat from a high-temperature reservoir, and rejects heat to a low-temperature reservoir. The difference of these two quantities is the power output.
  - A refrigerator takes heat from a low-temperature reservoir and rejects it to a high-temperature reservoir. The difference of these two quantities is the power input. This device does not violate Fourier's Law of Thermal Conduction, for it is the process of phase change of the refrigerants that allows heat transfer to occur.

Student Learning Objectives

- Understand and apply the formulation of thermal conversion efficiency and the coefficient of performance for both refrigerators and heat pumps
  - The efficiency of a heat pump is the power output per heat input.
  - The coefficient of performance for a refrigerator is the heat removed from the low-temperature reservoir per the power input.
  - The coefficient of performance for a heat pump is the heat supplied to the high-temperature reservoir per power input.

Student Learning Objectives

- Understand the Kelvin-Planck statement
  - The K.P. statement states that a heat engine needs a high- and low-temperature reservoir to operate between, and the temperature of these reservoirs cannot be equal. The K.P. statement limits the efficiency of a heat engine to less than 100%.
- Understand the Clausius statement
  - The Clausius statement states that a refrigerator, and/or heat pump, needs power input to be able to move heat from a low- to high-temperature reservoir. The Clausius statement limits the efficiency of a refrigerator and/or heat pump to less than infinity.

Suggested Problems

- 5.1, 5.2, 5.3, 5.4, 5.7, 5.9, 5.10, 5.13, 5.15, 5.18, 5.19, 5.22, 5.28