LECTURE 10: Heat engines and pumps

Select LEARNING OBJECTIVES:

- Understand that heat can be used to do work (heat engine).
- Understand that you can do work to transfer heat from a cold reservoir to a hot reservoir (heat pump).
- Identify heat engines that are not possible.

TEXTBOOK CHAPTERS:

- Giancoli (Physics Principles with Applications 7th) :: 15-5, 15-6
- Knight (College Physics : A strategic approach 3rd) :: 11.4, 11.5, 11.6
- BoxSand :: [Processes and PV-Diagrams]

WARM UP: Which object would you expect to have a larger emissivity, a white T-shirt or a black T-shirt both made from the same material?

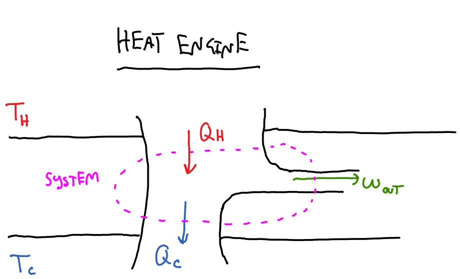
$e_{\text{BLACK T-SHIRT}} > e_{\text{WHITE T-SHIRT}}$

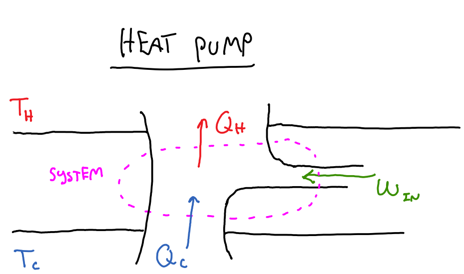
THE DARKER COLORS ABSORB/EMIT MORE ENERGY THAN LIGHTER COLORS... THIS IS WHY YOU FEEL WARMER DURING THE DAY IF WEARING A BLACK T-SHIRT COMPARED TO A WHITE T-SHIRT

Recall that heat is the general term we use for describing the different mechanisms for transferring thermal energy between systems. Perhaps we can tap into some of the energy that is being transferred between systems and use it to do work. As it turns out, this is possible and the devices that accomplish such tasks are referred to as heat engines and heat pumps. This lecture will explore the qualitative nature of heat engines and pumps. We will defer a more quantitative description of heat engines and pumps in a later lecture containing thermodynamic cycles.

We will begin our heat engine/pump (system) discussion by drawing diagrams which help visualize the heat transfers into and out of the system. These will also help indicate the work being done on or by the system. At this moment we do not concern ourselves with the thermodynamic cycle that is occurring within the system, if it helps you can think of these diagrams as an actual car engine (a thermodynamic cycle is occurring within each cylinder producing work). Our diagrams will just be an overview of where energy is being transferred to and from and what work is done.

The diagrams below depict both a heat engine and a heat pump. Both the engine and pump operate between hot and cold reservoirs. Notice the difference between an engine and a pump; an engine allows heat to flow naturally from the hot to cold side and extracts some of that energy to do work on the environment, a heat pump uses work to move energy from the cold side to the hot side.





- 1ST LAW OF THERMODYNAMICS....

$$\Delta E^{TH} = W_{EXT} + Q$$

- OVERALL $\Delta E^{TH}_{SYSTEM} = 0$

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• OVERALL $\Delta E^{th}_{system} = 0$ ← STEADY STATE

• W/ $\Delta E^{th} = 0$

$$\Sigma Q + \Sigma W_{ext} = 0$$

$$Q_H + Q_c + W_{out} = 0$$

$$\underbrace{Q_H}_{IN} = -(\underbrace{Q_c + W_{out}}_{OUT})$$

← USELESS LOST ENERGY

• THERMODYNAMIC EFFICIENCY ≡ e

$$e = \frac{\text{WHAT YOU GET}}{\text{WHAT YOU PAY}} < 1$$

$$e = \frac{|W_{out}|}{Q_{IN}} = \frac{Q_H - |Q_c|}{Q_H}$$

THEORETICAL MAX: $e_{max} = 1 - \frac{T_c}{T_H}$

$$\Delta E^{th} = W_{ext} + Q$$

• OVERALL $\Delta E^{th}_{system} = 0$ ← STEADY STATE

• W/ $\Delta E^{th} = 0$

$$\Sigma Q + \Sigma W_{ext} = 0$$

$$Q_H + Q_c + W_{IN} = 0$$

$$\underbrace{Q_H}_{OUT} = -(\underbrace{Q_c + W_{IN}}_{IN})$$

• COEFFICIENT OF PERFORMANCE (COP)

$$COP_{HEATING} = \frac{|Q_H|}{W_{IN}} = \frac{|Q_H|}{|Q_H| - Q_c}$$

$$COP_{COOLING} = \frac{|Q_c|}{W_{IN}} = \frac{Q_c}{|Q_H| - Q_c}$$

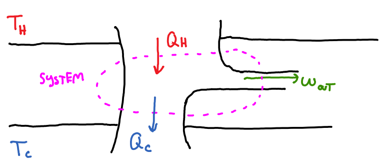
THEORETICAL MAX

$$COP_{HEATING\,MAX} = \frac{T_H}{T_H - T_c}$$

$$COP_{COOLING\,MAX} = \frac{T_c}{T_H - T_c}$$

Note that the efficiency is always less than 1, indicating that you can never get more energy out than what you put in. This would be a violation of the 1st law of thermodynamics if the efficiency as greater than 1.

PRACTICE: A heat engine does 10 J of work and exhausts 15 J of waste heat during each cycle. What is the engine's thermal efficiency?



$$e = \frac{GET}{PAY} = \frac{|W_{OUT}|}{Q_{IN}} = \frac{Q_H - |Q_c|}{Q_H} = \frac{25 - 15}{25} = \frac{10}{25} = 0.4$$

$W_{OUT} = -10\ J$

$Q_c = -15\ J$

W/ $\Delta E^{th} = 0$ $\quad Q_H + Q_c + W_{OUT} = 0$

$Q_H = -(W_{OUT} + Q_c)$

$Q_H = -(-25\ J)$

PRACTICE: You wish to produce a heat engine that has a 50% efficiency. You can access runoff water at 350 K from the local factory. What is the maximum temperature your cold reservoir could be and possibly achieve this kind of efficiency?

$$e_{max} = 1 - \frac{T_c}{T_H}$$

$$T_H e_{max} = T_H - T_c$$

$$T_c = T_H(1 - e_{max})$$

W/ $e_{max} = 0.5$ & $T_H = 350\ K$

$$T_c = 175\ K$$

$T_H e_{max} = T_H - T_c$

$T_c = T_H(1 - e_{max})$

+ $T_H = 350\ K$

$T_c = 175\ K$

PRACTICE: A 60% efficient device uses chemical energy to generate 600 J of electric energy. A second device uses twice as much chemical energy to generate half as much electric energy. What is the second devices efficiency?

1ST) $e = \frac{GET}{PAY} = \frac{ELECTRIC}{CHEM}$

$0.6 = \frac{600\ J}{U^{CHEM}} \rightarrow U^{CHEM} = 1000\ J$ (PAY)

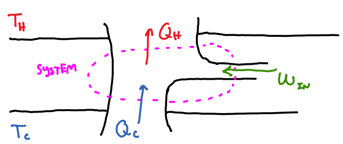
2ND) If $U^{CHEM} = 2(1000)\ J = 2000\ J$

AND $U^E = \frac{1}{2}(600)\ J = 300\ J$

$e = \frac{GET}{PAY} = \frac{U^E}{U^{CHEM}} = \frac{300}{2000}$

$e = 0.15$ or 15%

PRACTICE: A heat pump has a COP of 3 and is rated to do work at 1500 W. How much heat can this heat pump add to a room per minute?



$COP_{HEATING} = \frac{GET}{PAY}$

$COP_{HEATING} = \frac{Q_H}{W_{IN}}$

$1500\ W = 1500\ \frac{J}{s}$

$1500\ \frac{J}{s} \times \frac{60\ SEC}{1\ MIN} = 90000\ J$ (W_{IN})

$Q_H = COP_{HEATING}\, W_{IN}$

$Q_H = 3(90000\ J)$

$Q_H = 270000\ J$

If the heat pump were turned around to act as an air conditioner in the summer, what would you expect its COP to be, assuming all else stays the same?

$COP = \frac{Q_c}{W_{IN}}$

$W_{IN} + Q_c + Q_H = 0$

$Q_c = -(Q_H + W_{IN})$

$Q_c = -(-270000 + 90000)$

$Q_c = 180000\ J$

$COP = \frac{180000}{90000}$

$COP = 2$

Questions for discussion:

(1) A refrigerator operates for a certain amount of time, during which the amount of work done by the electrical energy supplied to the refrigerator is 800 J. How much heat is delivered to the room containing the refrigerator?

a. More than 800 J
b. Less than 800 J
c. 800 J