CM 3230 Thermodynamics, Fall 2016

Lecture 5

1. Brief historical sketch of heat engine (using heat to produce work)

- **Newcomen Engine**
  - atmospheric engine built by Thomas Newcomen, primarily used to pump water out of coal mines (~1712),
  - check out animation http://www.animatedengines.com/newcomen.html)
  - Remarks:
    a. Work is actually done by the atmosphere, after cylinder approached vacuum.
    b. Valves were "automated" using tappets and weights that depend on the position of the pump.

c. One Newcomen engine known as "Fairbottom Bobs" was purchased, dismantled and then reassembled in H. Ford Museum in Dearborn, MI.

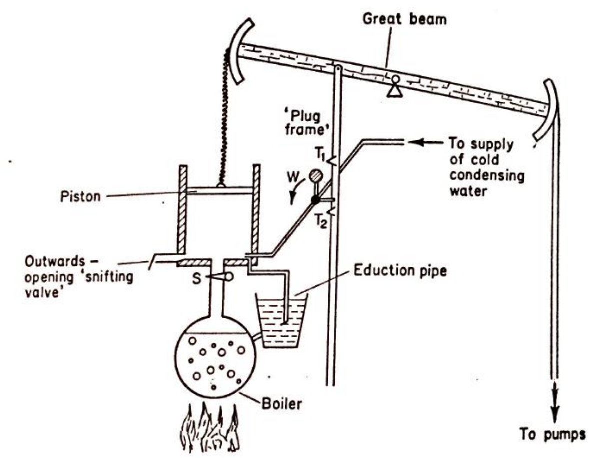

Fig. 1. Newcomen Engine.[1]

[1] Illustration from D.S.L. Cardwell, "From Watt to Clausius", Heinemann Educational Books, Ltd., 1971,p.16

- **James Watt's 2-Cylinder Solution (~1763)**
  - Came across the problem when fixing a model Newcomen engine for a class in Glasgow University: the reduced scale made the engine very inefficient.
  - Had to use latent heat calculation as well as phase-diagram of steam
  - Research results:
    - i) For engine economy, the engine needs to be hot all the time
    - ii) For maximum power, the steam pressure at saturation point needs to be lower (i.e. at lower temperature) so that the atmosphere can push more effectively.

  - **Problem:** *a cylinder can not be simultaneously hot and cold*.

  - **Solution:** <u>use two separate cylinders</u>

  - Also used low-pressure steam to help push piston down. (see Fig. 2)
  - Watt, and business partner Matthew Boulton, dominated the engine industry (with several improved designs) for several years.
  - A Watt-Boulton rotative engine is also housed in Henry Ford Museum.

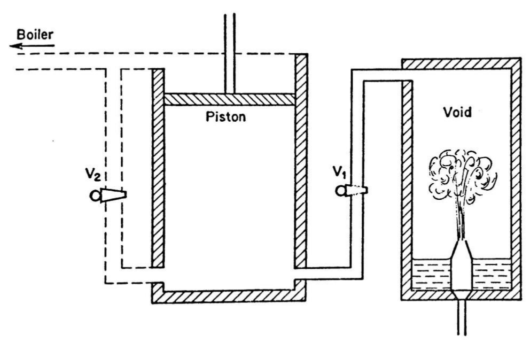

Fig.2. James Watt's two-cylinder engine.[2]

[2] Illustration from D.S.L. Cardwell, "From Watt to Clausius", Heinemann Educational Books, Ltd., 1971,p.49

- **Carnot Cycle**
  - proposed by Sadi Carnot in 1824, inspired by heat engines, specially Watt's steam engine.
  - Inspired by Watt's 2-cylinder engine, concluded that to generate power, one must have a "cold body reservoir" as well as a "hot body reservoir" (isothermal paths). For maximum power, the paths should be reversible, and outside the heating and cooling sub-paths, no heat exchange between gas and surrounding (adiabatic paths).
  - The cycle is idealized but it represents the most efficient heat engine.

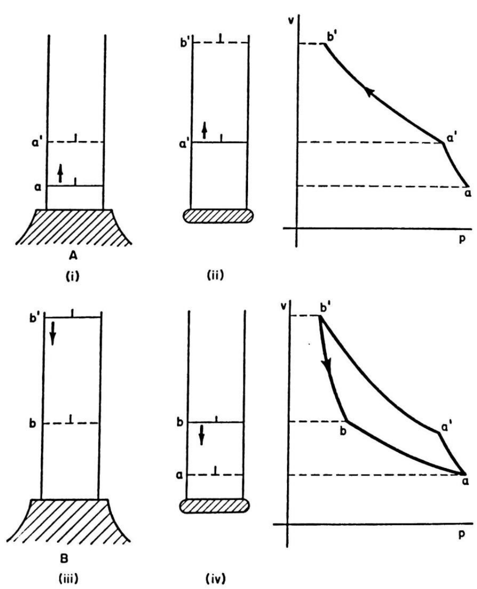

Fig. 3. Carnot's Cycle.[3]

[3] Illustration from D.S.L. Cardwell, "From Watt to Clausius", Heinemann Educational Books, Ltd., 1971,p.194.

2. The Carnot Cycles (assume an ideal gas with constant c_p)

a) To produce work using hot and cold reservoir (Carnot engine)

- Isothermal expansion ($1 \to 2$), adiabatic expansion ($2 \to 3$), isothermal compression ($3 \to 4$), adiabatic compression ($4 \to 1$)

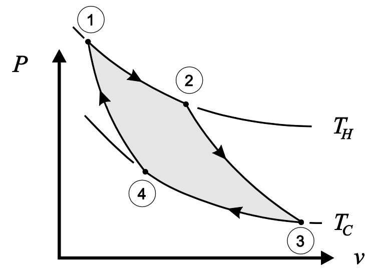

Fig. 4. Carnot engine cycle.

- Sample given conditions/data: $T_H(=T_1)$, $T_C(=T_4)$, v_1, v_3 and c_p.
- Can compute for pressure and molar volume at all points.
  - i) $P_1 = RT_H/v_1$, $P_3 = RT_C/v_3$
  - ii) $P_2 = P_3(T_H/T_C)^{k/(k-1)}$, $P_4 = P_1(T_C/T_H)^{k/(k-1)}$
    Note: $P_1/P_2 = P_4/P_3$ for the cycle

  - iii) $v_2 = RT_H/P_2$, $v_4 = RT_C/P_4$
    (or $v_2 = v_1(P_1/P_2)$, $v_4 = v_3(P_3/P_4)$)
    Note: $v_2/v_1 = v_3/v_4$
- Can also find Δu, q_{in} and w_{by} of each sub-path.
  - i) $\Delta u_{1\to 2} = 0$, $q_{in,1\to 2} = RT_H \ln(v_2/v_1) = w_{by,1\to 2}$
    $\Delta u_{3\to 4} = 0$, $q_{in,3\to 4} = RT_C \ln(v_4/v_3) = w_{by,3\to 4}$
  - ii) $q_{in,2\to 3} = 0$, $w_{by,2\to 3} = -\Delta u_{2\to 3} = c_v(T_H - T_C)$
    $q_{in,4\to 1} = 0$, $w_{by,4\to 1} = -\Delta u_{4\to 1} = c_v(T_C - T_H)$

- Net work done by gas:

$$\begin{aligned} w_{by,net} &= RT_H \ln(v_2/v_1) + RT_C \ln(v_3/v_4) \\ &\qquad + c_v(T_H - T_C) + c_v(T_C - T_H) \\ &= R(T_H - T_C)\ln(v_2/v_1) \quad [\text{ because } v_2/v_1 = v_3/v_4\ ] \end{aligned}$$

- Efficiency : $\eta = w_{by,net}/q_{in,1\to 2}$

$$\eta = \frac{R(T_H - T_C)\ln(v_2/v_1)}{RT_H \ln(v_2/v_1)} = \frac{T_H - T_C}{T_H}$$

→ also known as "<u>Carnot efficiency</u>" : the ideal maximum work that can be obtained from an engine

Note: it only depends on the temperatures of the hot and cold reservoirs
→ does not depend on the working fluid (i.e. not dependent on any particular constant value of c_p ; as long as the ideal gas behavior is a good approximation)

b) To extract (pump) heat from a cold reservoir to a hot reservoir (Carnot refrigerator)

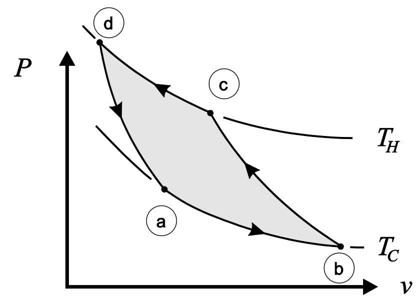

Fig. 5. Carnot refrigeration cycle.

- Similar calculations, except (1,2,3,4) is replaced by (d,c,b,a), and paths are in reversed directions. Thus,
    i) $\Delta u_{a\to b} = 0,\ q_{in,a\to b} = RT_C \ln(v_b/v_a) = w_{by,b\to a}$
    $\Delta u_{c\to d} = 0,\ q_{in,c\to d} = RT_H \ln(v_d/v_c) = w_{by,c\to d}$
    ii) $q_{in,b\to c} = 0,\ w_{by,b\to c} = -\Delta u_{b\to c} = c_v(T_C - T_H)$
    $q_{in,d\to a} = 0,\ w_{by,d\to a} = -\Delta u_{d\to a} = c_v(T_H - T_C)$
- Net work done on gas:

$$\begin{aligned} w_{on,net} &= RT_C \ln(v_a/v_b) + RT_H \ln(v_c/v_d) \\ &\qquad + c_v(T_H - T_C) + c_v(T_C - T_H) \\ &= R(T_H - T_C)\ln(v_a/v_b) \quad [\text{ because } v_d/v_c = v_b/v_a\ ] \end{aligned}$$

- Coefficient of performance (COP)

$$\mathrm{COP} = \frac{q_{in,a\to b}}{w_{on,net}} = \frac{T_C}{T_H - T_C}$$

Q: Can we have $\eta > 1$? Can we have $COP > 1$?