

Lecture 11 Carnot Cycle

(Sec.3.6 of Hess – 2nd Law of Thermodynamics)

- Thermodynamic processes can be divided into three different categories:
 - (1) reversible processes
 - (2) non-existing (impossible) processes
 - (3) real (natural) processes

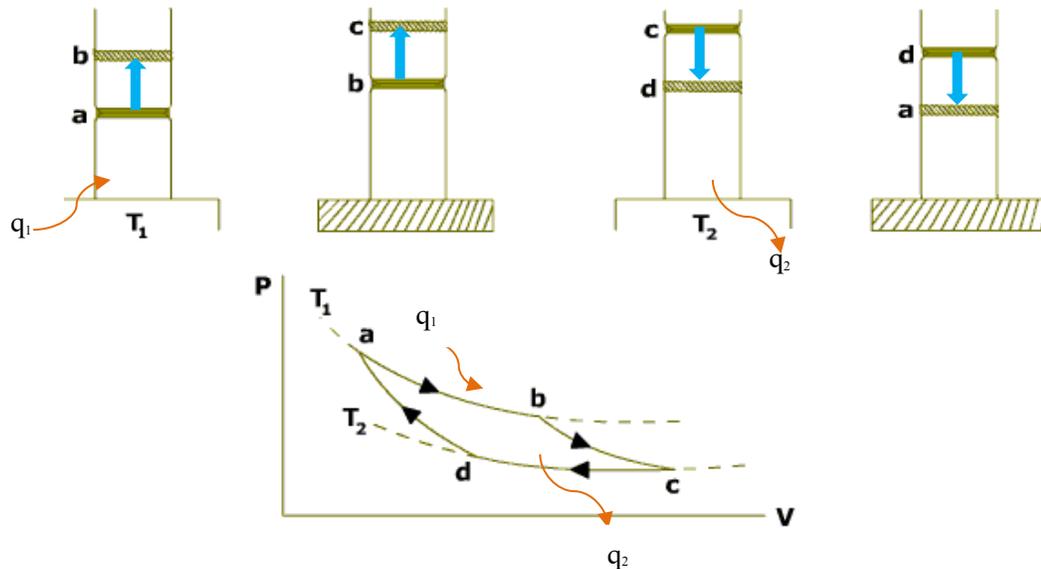
- (1) Reversible processes: If each state of the system is in equilibrium so that a reversal in the direction of an infinitesimal change returns the system and environment to their original states (determined by p, α, T). For example:
Carnot cycle, which will be discussed later in this lecture, is an example of reversible processes.

- (2) Non-existing or impossible processes
For example:
 - (a) Compression of a gas with no external pressure
 - (b) Let the heat flow from a cold body to a warm body without doing work.

- (3) Natural processes are always more or less irreversible
For example:
 - (a) Heat conduction through a finite temperature gradient
 - (b) Combination of oxygen and hydrogen at room temperature in water
 - (c) Diffusion of one gas into another
 - (d) Cloud formation

12.1 The Carnot Cycle

- Carnot cycle: Carnot cycle refers to thermodynamic processes occurring in Carnot's ideal heat engine.
- Carnot's engine and cycle: it consists of the following cyclic processes in a P-V (or α - p) diagram.



(1) **$a \Rightarrow b$: isothermal expansion**

The cylinder is placed on a hot reservoir, which **adds an amount of heat q_1** into the cylinder with the temperature kept constant (T_1).

Equation of state: $dq = pd\alpha$, $dq = q_1$.

(2) **$b \Rightarrow c$: adiabatic expansion**

The cylinder is placed on an insulated stand, which keeps expanding, but the temperature falls from T_1 to T_2 ($T_2 < T_1$) since there is no heat added (adiabatic). Equation of state: $0 = c_v dT + pd\alpha$, $dT = T_2 - T_1 < 0$.

(3) **$c \Rightarrow d$: isothermal compression**

The cylinder is placed on stand a cold reservoir, which **extracts an amount of heat q_2** from the cylinder with the temperature kept constant at T_2 .

Equation of state: $dq = pd\alpha$, $dq = -q_2$.

(4) **$d \Rightarrow a$: adiabatic compression**

The cylinder is placed on stand an insulated stand, which keeps compressing, but the temperature rises from T_2 to T_1 ($T_1 > T_2$) due to compression and adiabatic process. Equation of state: $0 = c_v dT + pd\alpha$, $dT = T_1 - T_2 > 0$.

This video may help you to understand the [Carnot cycle](#).

All the above processes are reversible and in equilibrium, which can be illustrated in a P-V (or α - p) diagram as shown above.

The net work done during the Carnot cycle is the area enclosed by ABCD, i.e.,

$$w = \oint p d\alpha = \oint dq - \oint c_v dT = q_1 - q_2$$

i.e., in this cyclic operation the engine has done work by transferring a certain amount of heat from a warmer body (H) to a cooler body (S).

- [Efficiency of a heat engine](#): If during one cyclic process of an engine, a quantity of heat Q_1 is absorbed and heat Q_2 is rejected, the amount of mechanical work done by the engine is $Q_1 - Q_2$, then the [efficiency of the engine \(\$\eta\$ \)](#) (only true for a cyclic process) is defined as

$$\eta = \frac{\text{Mechanical work done by the engine}}{\text{Heat absorbed by the engine}} = \frac{Q_1 - Q_2}{Q_1} \quad (4.1.1)$$

or, for a unit mass,

$$\eta = \frac{q_1 - q_2}{q_1} = 1 - \frac{q_2}{q_1}. \quad (4.1.2)$$

The efficiency of the Carnot heat engine is

$$\eta = \frac{q_1 - q_2}{q_1} = 1 - \frac{q_2}{q_1} = 1 - \frac{T_2}{T_1} \quad (4.1.3)$$

Q: Does $q_2/q_1 = T_2/T_1$? [Will be proved in the next lecture.]

- A steady-state, mature tropical cyclones behave like a Carnot cycle
 - Leg 1 is regarded as an isothermal expansion process
 - Leg 2 can be approximately regarded as an adiabatic expansion process
 - Leg 3 is isothermal compression process
 - Leg 4 can approximately be viewed as an adiabatic compression process

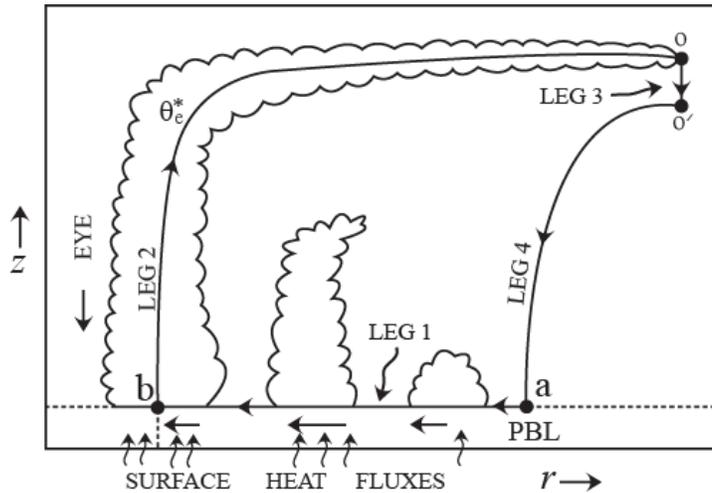


Fig. 9.19: Idealized Carnot cycle for a steady-state, mature tropical cyclone, based on the WISHE mechanism (Emanuel 1986, 1989). Solid curves represent hypothetical air trajectory in a Carnot cycle. (Lin 2007; Adapted after Emanuel 1997)