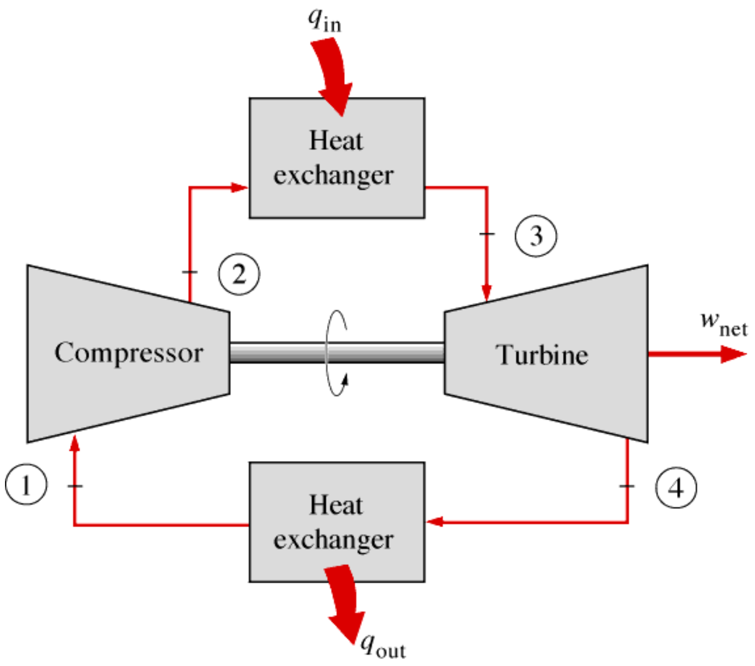
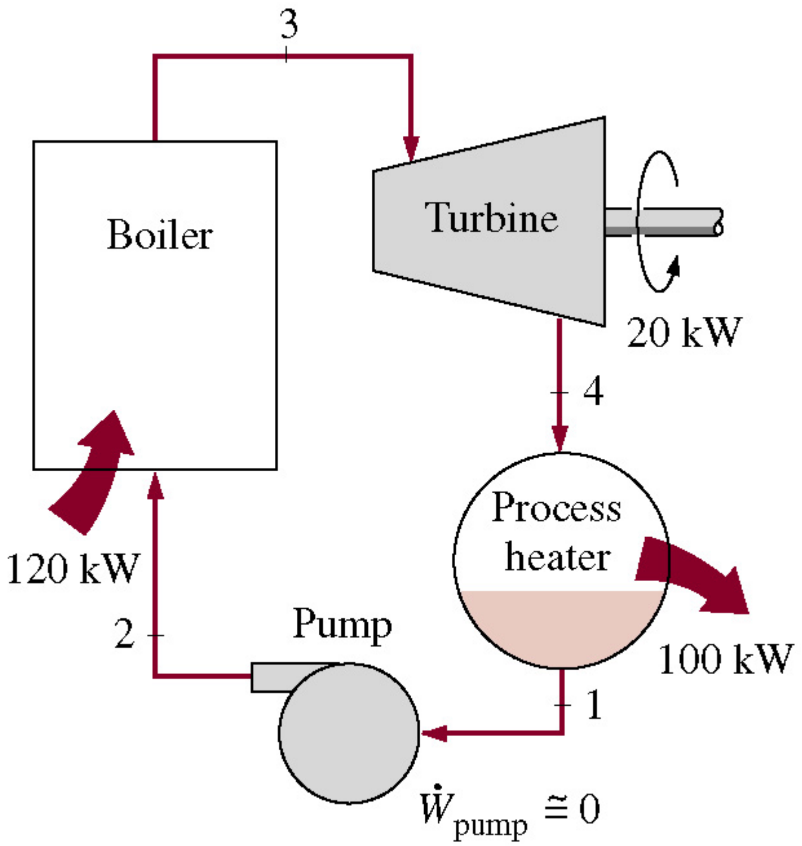
Gas Power Cycles (I)

Categorize Cycles

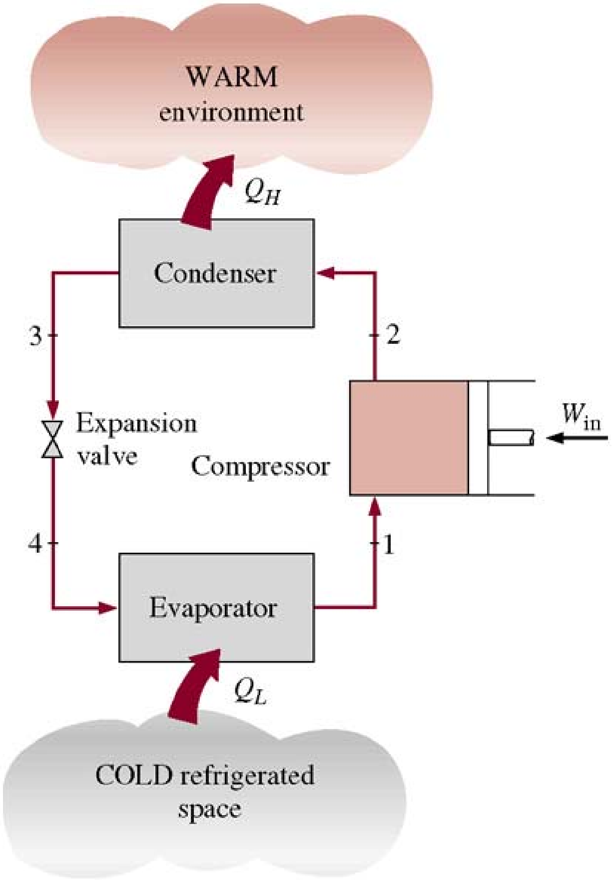
- Thermodynamic cycles can be categorized as *gas* cycles or *vapor* cycles, depending upon the phase of the working fluid.

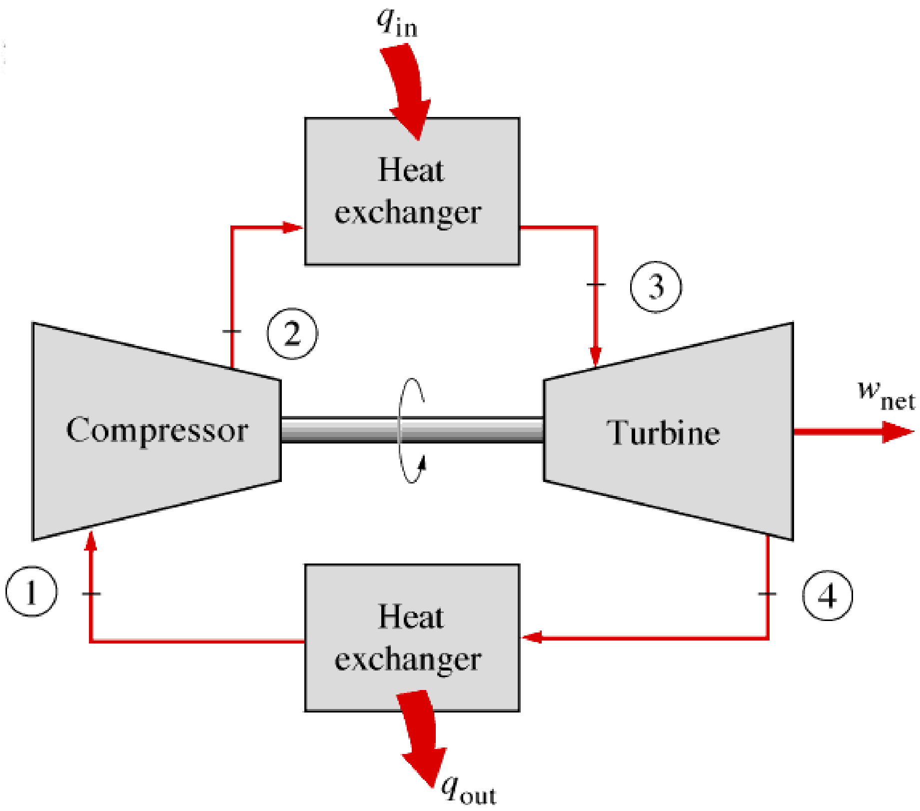




Classification of Cycles

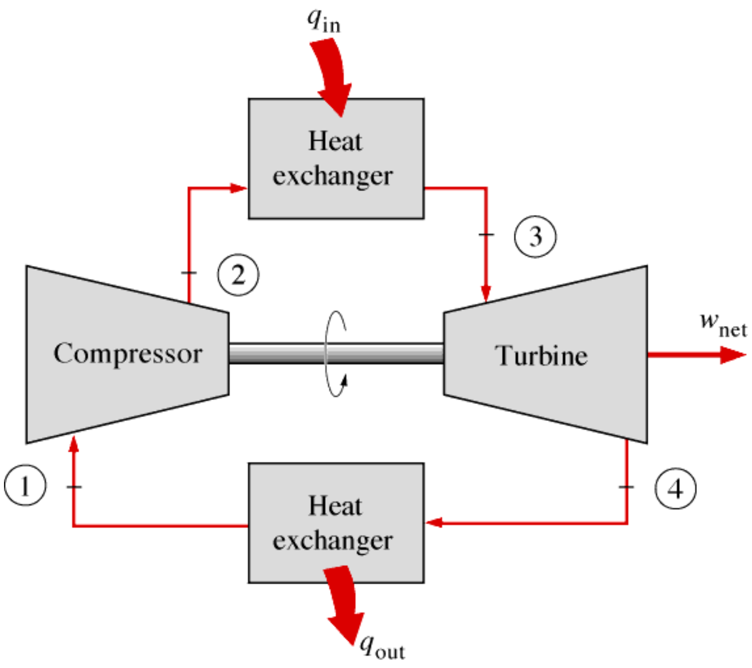
- ***Thermodynamic cycles*** **can be divided into two general categories:** ***refrigeration*** **cycles and** ***Power*** **cycles.**

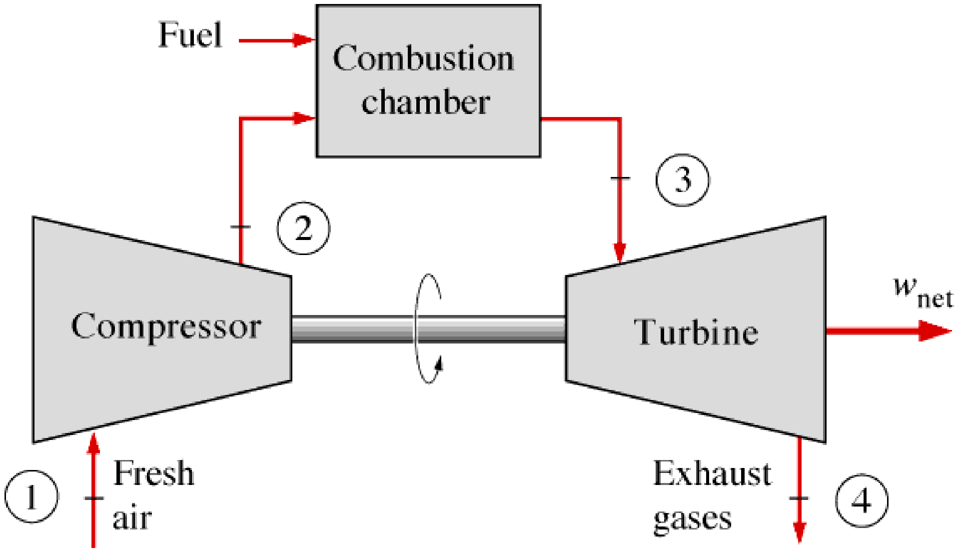




Categorize Cycles

- **Thermodynamic cycles can be categorized yet another way: *closed* and *open* cycles.**

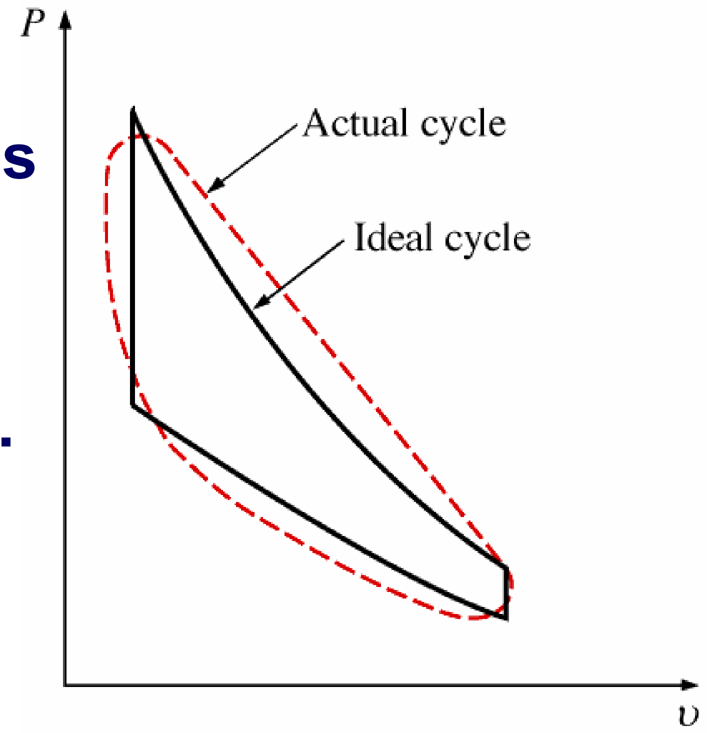




8–1 Basic Considerations in the Analysis of Power Cycles

The idealizations in the analysis of power cycles can be summarized as follows:

- **The cycle does not involve any friction (no pressure drop in pipes).**
- **All processes take place in a quasi-equilibrium manner.**
- **Heat transfer through the components is negligible.**
- **Neglect KE and PE except for nozzles and diffusers.**

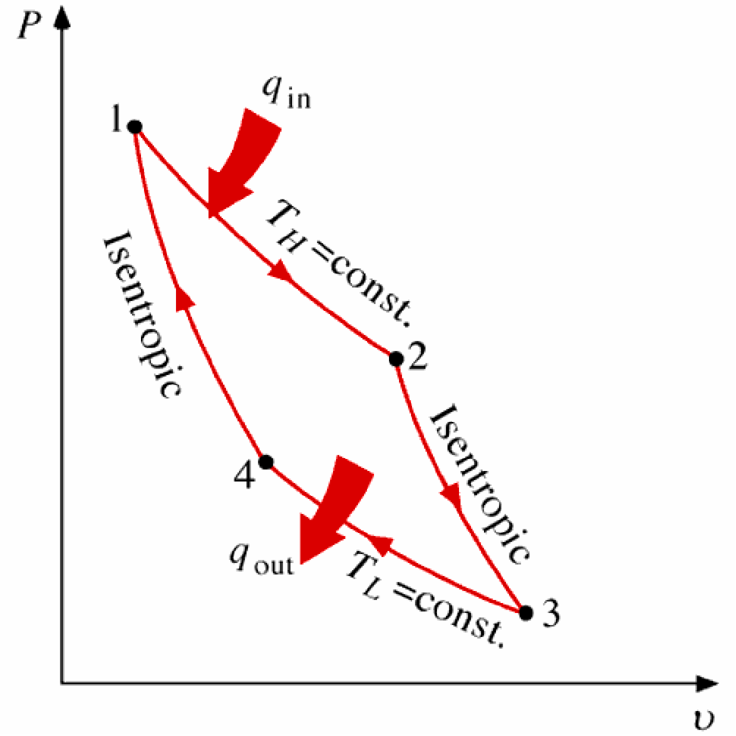


The analysis of many complex processes can be reduced to a manageable level by utilizing some idealizations.

8−2 Carnot Cycle and Its Value in Engineering

The Carnot cycle is composed of four totally reversible processes:

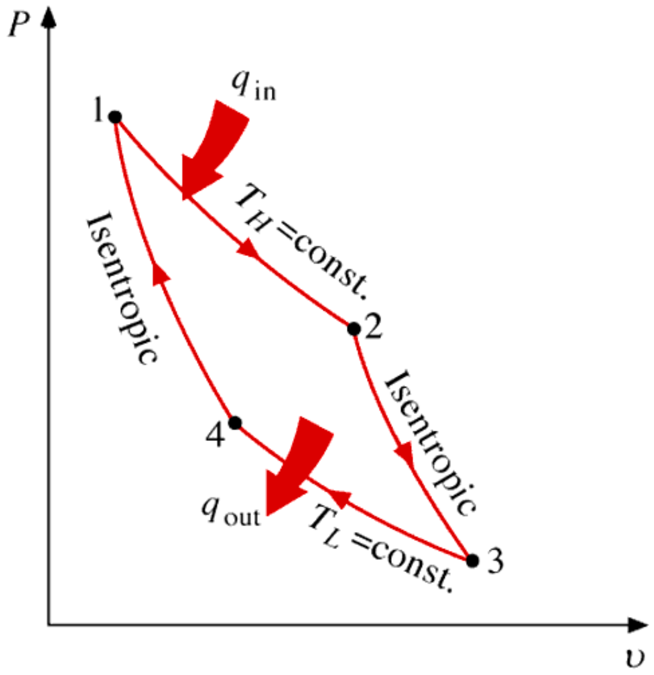
1. **isothermal heat addition,**
2. **isentropic expansion,**
3. **isothermal heat rejection,**
4. **isentropic compression**



$$\boxed{\eta_{th,Carnot} = 1 - \frac{T_L}{T_H}}$$

Why Carnot Cycle?

Reversible isothermal heat transfer is very difficult to achieve since this requires a very large surface and very long time. The real processes takes place in a fraction of a second.!!



The real value of Carnot Cycle is that it gives us an upper limit to which real cycles can be compared to. Moreover,

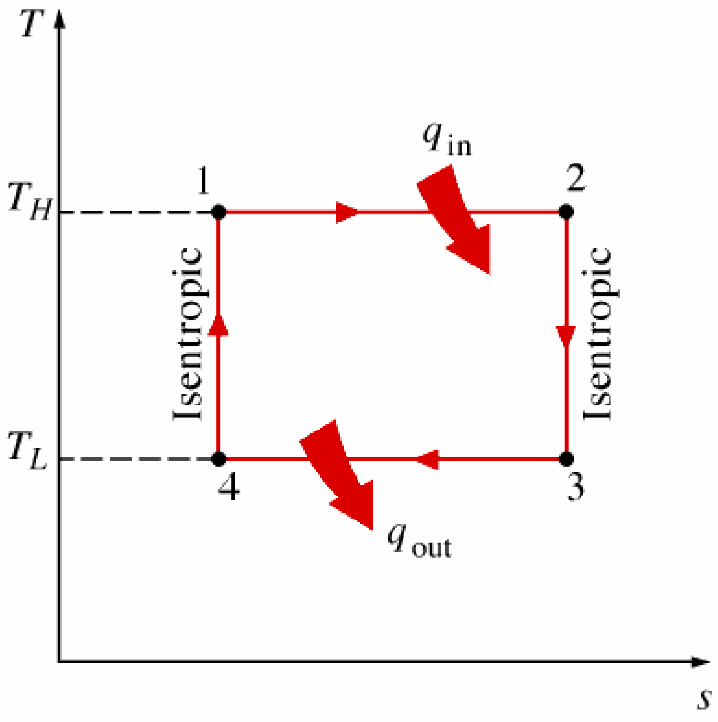
$$\eta_{th,Carnot} = 1 - \frac{T_L}{T_H}$$

Thermal efficiency increases with an increase in the average temperature at which heat is supplied to the system or with a decrease in the average temperature at which heat is rejected from the system.

Limit of T_H and T_L in a Carnot Cycle

The *highest* temperature in the cycle is limited by the maximum temperature that the components of the heat engine, such as the piston or turbine blades, can withstand.

The *lowest* temperature is limited by the temperature of the cooling medium utilized in the cycle such as a lake, a river, or atmospheric air.



8−3 Air-Standard Assumptions

To reduce the analysis of an actual gas power cycle to a manageable level, we utilize the following approximations, commonly know as the air-standard assumptions:

1. The working fluid is air, which continuously circulates in a closed loop and always behaves as **an ideal gas**.
2. Al the processes that make up the cycle are **internally reversible.**
3. The **combustion process** is replaced by a heat-addition process from an external source.
4. The **exhaust process** is replaced by a **heat rejection process** that restores the working fluid to its initial state.

Fifth assumption: constant specific heats

Another assumption that is often utilized to simplify the analysis even more is that the air has ***constant specific heats whose values are determined at room temperature.***

When this assumption is utilized, the air-standard assumptions are called the ***cold-air-standard assumptions*.**

A cycle for which the air-standard assumptions are applicable is frequently referred to as an *air-standard cycle*.

The air-standard assumptions stated above provide considerable simplification in the analysis without significantly deviating from the actual cycles.

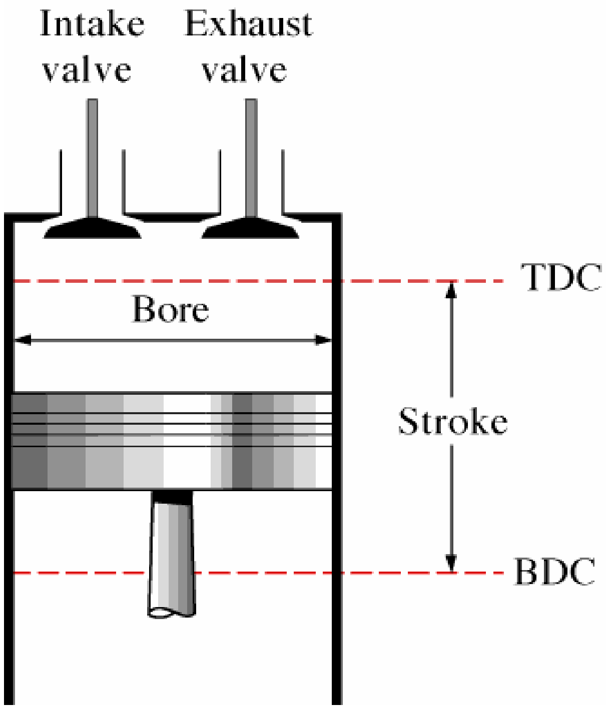
8−4 An Overview of Reciprocating Engines

Before discussing the Otto cycle, The basic components of a reciprocating engine are shown in the figure at right.

The piston reciprocating in the cylinder between two fixed positions namely

the *top dead center* (*TDC*, the smallest volume of the cylinder), and

the *bottom dead center* (*BDC*, the largest volume in the cylinder).



Some Terminologies

Stroke **— The distance between the TDC and the BDC is the largest distance that the piston can travel.**

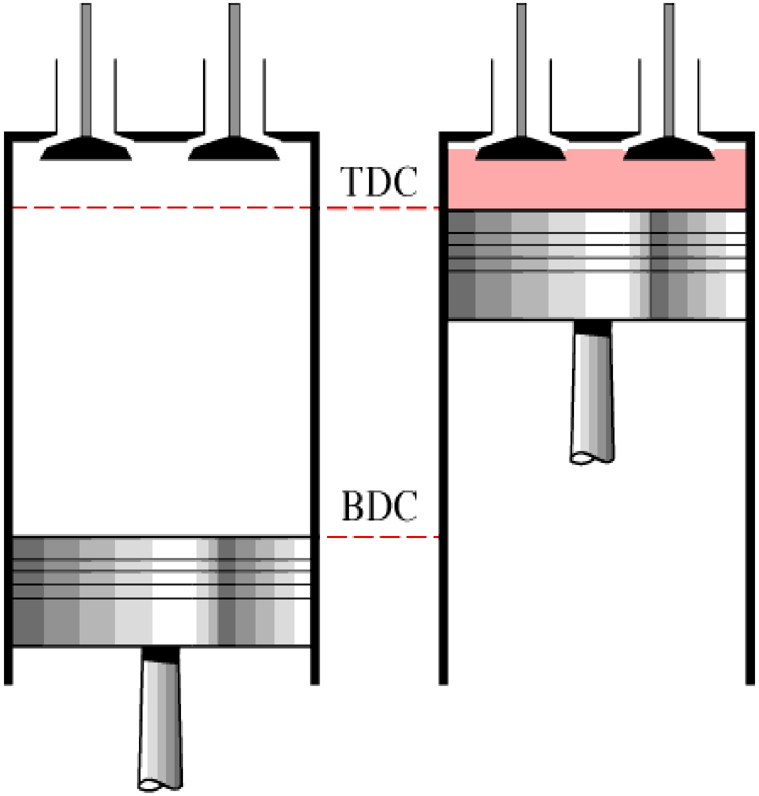
Bore **— The diameter of the piston.**

Intake valve **— The port that the air or air-fuel mixture is drawn into the cylinder.**

Exhaust valve **— The port that the combustion products are expelled from the cylinder.**

Clearance volume **— The minimum volume formed in the cylinder when the piston is at TDC.**

Displacement volume **— The volume displaced by the piston as it moves between TDC and BDC.**



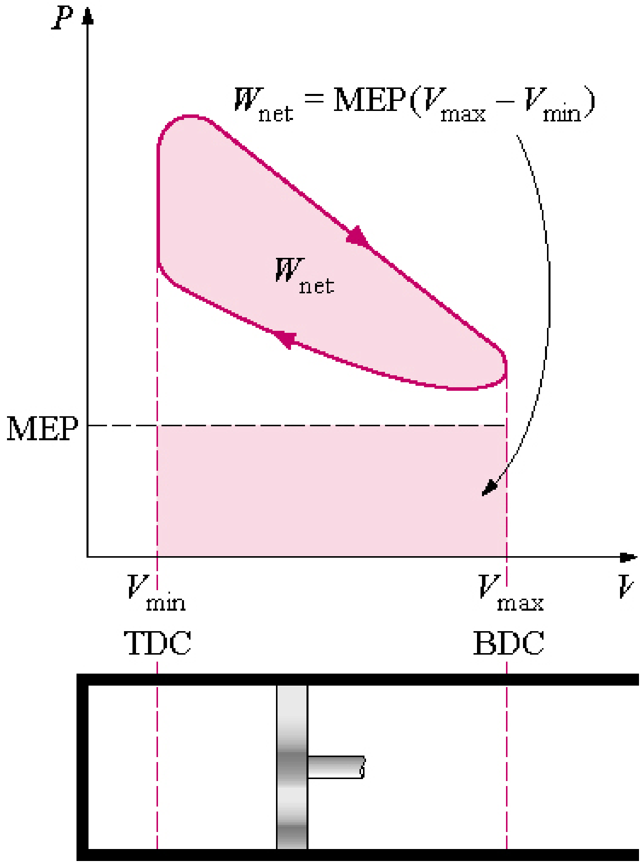
(*a*) Displacement volume

(*b*) Clearance volume

Compression ratio of the engine.

The ratio of the maximum volume formed in the cylinder to the minimum (clearance) volume is called the *compression ratio* of the engine.

$$r = \frac{V_{\max}}{V_{\min}} = \frac{V_{BDC}}{V_{TDC}}$$



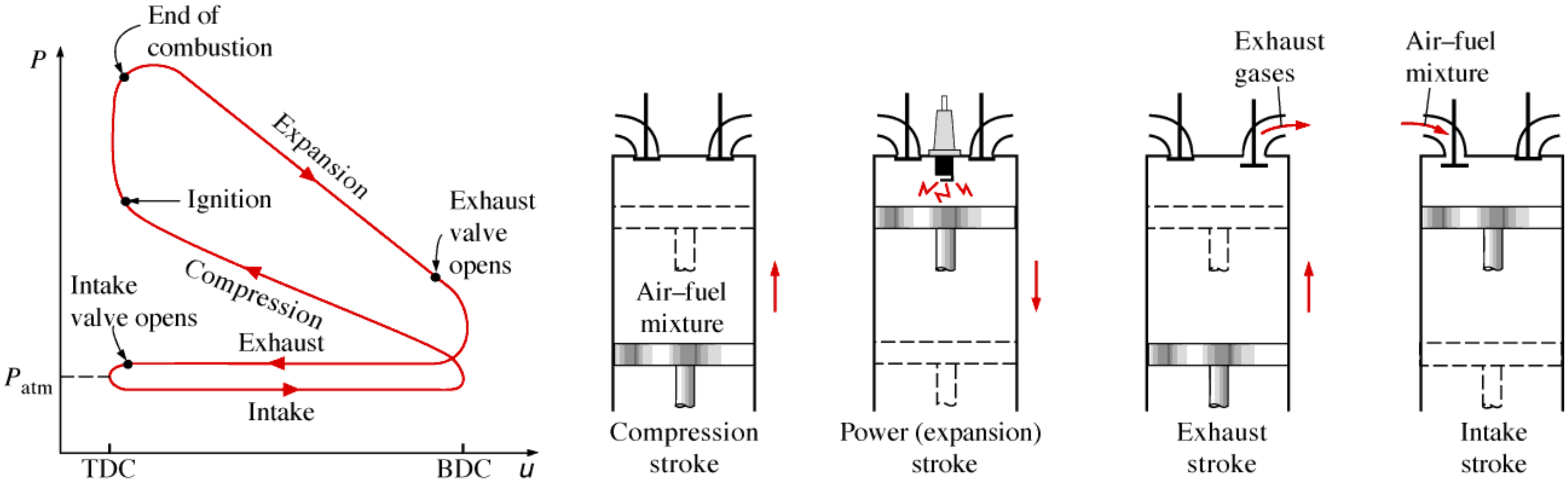
Notice that the compression ratio is a volume ratio and should not be confused with the pressure ratio.

Mean Effective Pressure

It is a fictitious pressure that, if it acted on the piston during the entire power stroke, would produce the same amount of net work as that produced during the actual cycle.

$$MEP = \frac{W_{net}}{V_{\max} - V_{\min}}$$

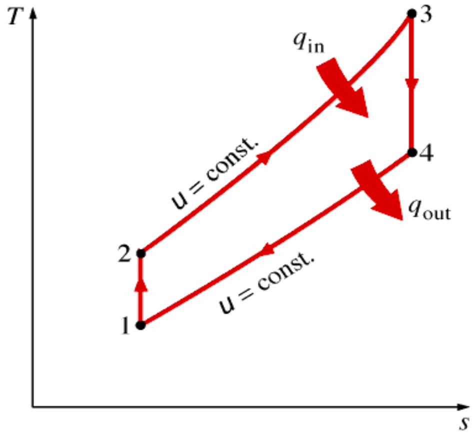
8–5 Spark-Ignition Engines



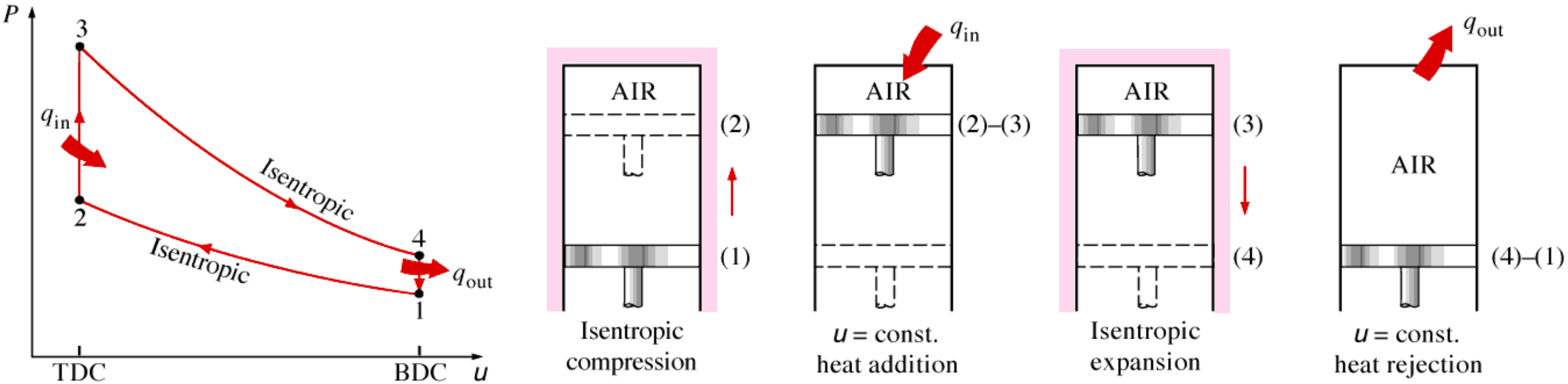
(*a*) Actual four-stroke spark-ignition engine

Figures above show the actual cycle in spark-ignition (SI) engine and their *P*-υ diagrams.

8−5 Otto Cycle: The ideal Cycle for Spark-Ignition Engines

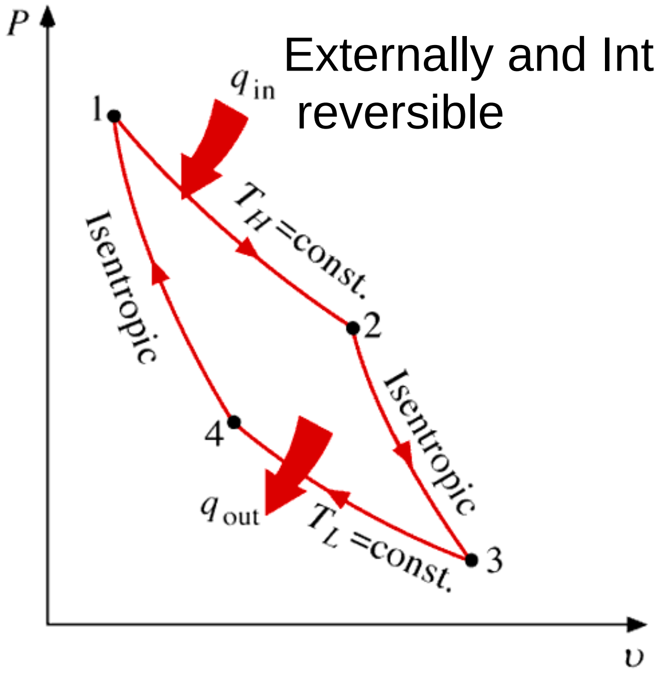


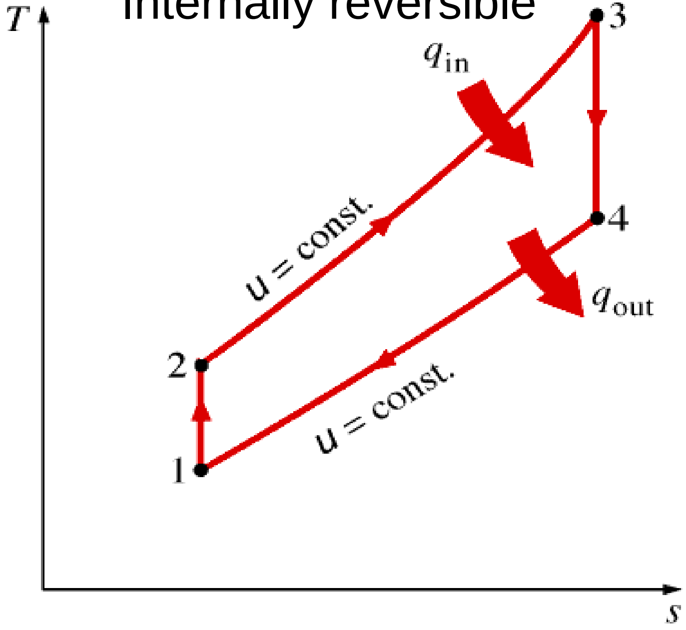
1→2	**Isentropic compression**
2→3	**Constant volume heat addition**
3→4	**Isentropic expansion**
4→1	**Constant volume heat rejection**



(*b*) Ideal Otto cycle

Why do not we use the Carnot cycle to represent the actual spark-Ignition engine instead of the Otto Cycle


Externally and Internally reversible

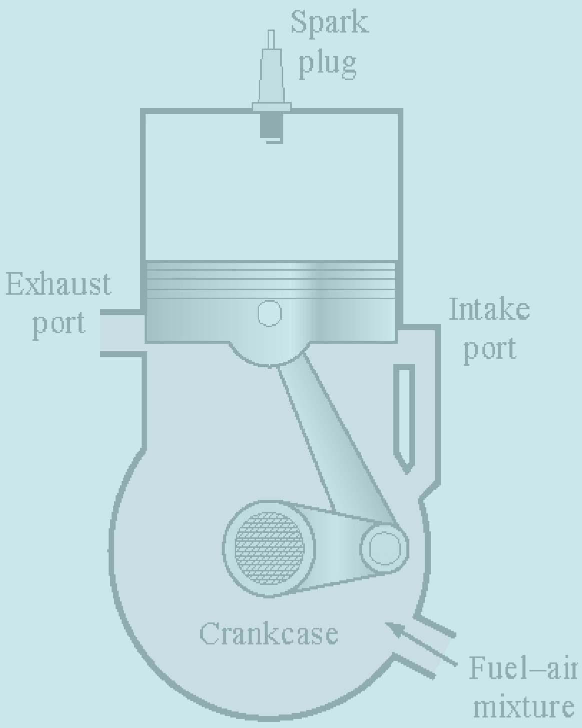

Internally reversible

This is due to hardware problem. We can not manufacture a SI engine in which head addition/rejection take place at a constant temperature.

Two-Stroke Engines

In two-stroke engines, the crankcase is sealed, and the outward motion of the piston is used to slightly pressurize the air-fuel mixture in the crankcase, as shown in the figure at right. The intake and exhaust valves are replaced by openings in the lower portion of the cylinder wall.

During the latter part of the power stroke, the piston uncovers first the exhaust port, allowing the exhaust gases to be partially expelled, and then the intake port, allowing the fresh air-fuel mixture to rush in and drive most of the remaining exhaust gases out of the cylinder. This mixture then is compressed and ignited.



Advanced Technologies in Two-Stroke Engines

The two-stroke engines are generally less efficient than their four-stroke counterparts because of the incomplete expulsion of the exhaust of the fresh air-fuel mixture with the exhaust gases. However, they are relatively simple and inexpensive.

Advances in several technologies ─ such as *direct fuel injection*, *stratified charge combustion*, and *electronic controls* ─ brought about a renewed interest in two-stroke engines that can offer high performance and fuel economy while satisfying the future stringent emission requirements. (*Please refer to page 343 of C & T text*)

Major car companies have research programs under way on two-stroke engines which are expected to make a comeback in the future.

Thermal Efficiency of an Otto Cycle

Apply the 1st law of thermodynamics to process 23, we get

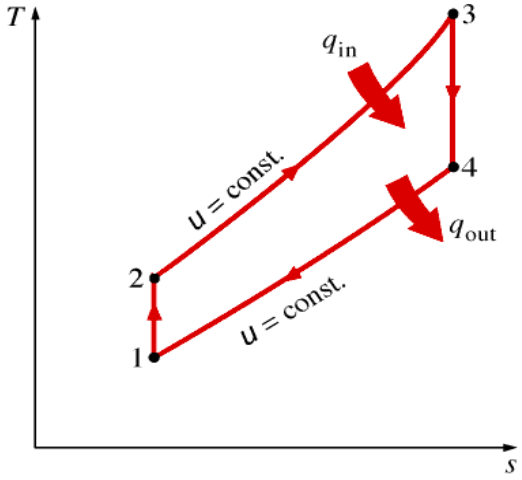
$$\eta_{th,Otto} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

$$q_{23} - \cancel{w_{23}} = u_3 - u_2$$

$$\Rightarrow q_{in} = u_3 - u_2 = C_v\left(T_3 - T_2\right)$$

$$q_{41} - \cancel{w_{41}} = u_4 - u_1$$

$$\Rightarrow q_{out} = u_4 - u_1 = C_v\left(T_4 - T_1\right)$$



$$\eta_{th,Otto} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

$$\eta_{th,Otto} = 1 - \frac{T_1\left(T_4 / T_1 - 1\right)}{T_2\left(T_3 / T_2 - 1\right)}$$

Thermal Efficiency of an Otto Cycle

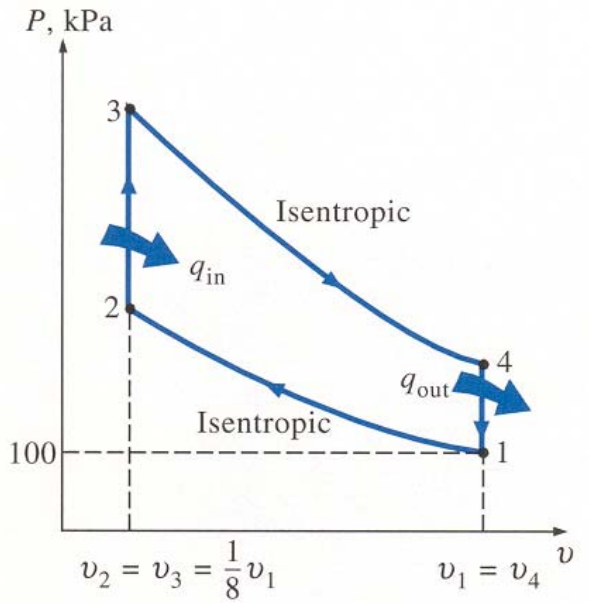
But $$\frac{T_1}{T_2} = \left(\frac{\upsilon_2}{\upsilon_1}\right)^{k-1} = \left(\frac{\upsilon_3}{\upsilon_4}\right)^{k-1} = \frac{T_4}{T_3}; \Rightarrow \frac{T_3}{T_2} = \frac{T_4}{T_1}$$

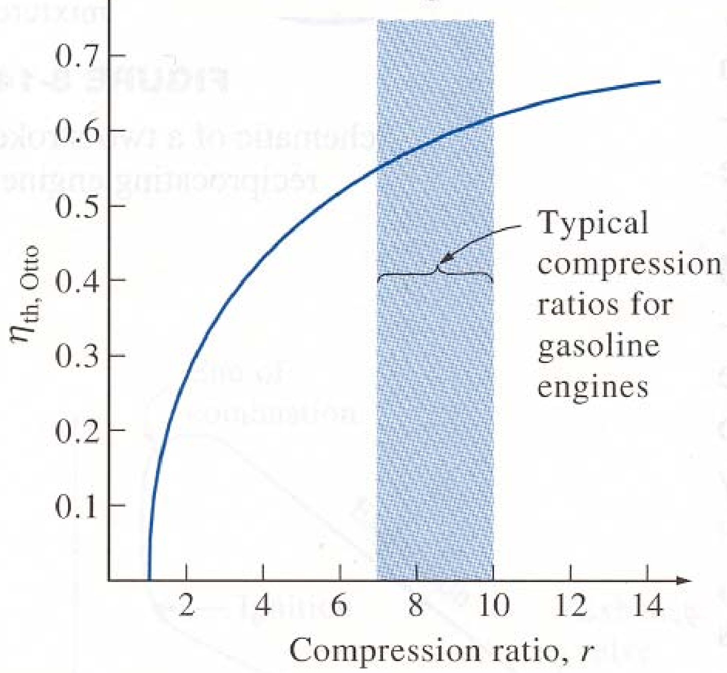
$$\eta_{th,Otto} = 1 - \frac{T_1\left(T_4/T_1 - 1\right)}{T_2\left(T_3/T_2 - 1\right)}$$

$$= 1 - \frac{T_1}{T_2} = 1 - \frac{1}{r^{k-1}}$$

where $r = \dfrac{V_{\max}}{V_{\min}} = \dfrac{V_1}{V_2} = \dfrac{\upsilon_1}{\upsilon_2}$

$$\boxed{\eta_{th,otto} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{r^{k-1}}}$$

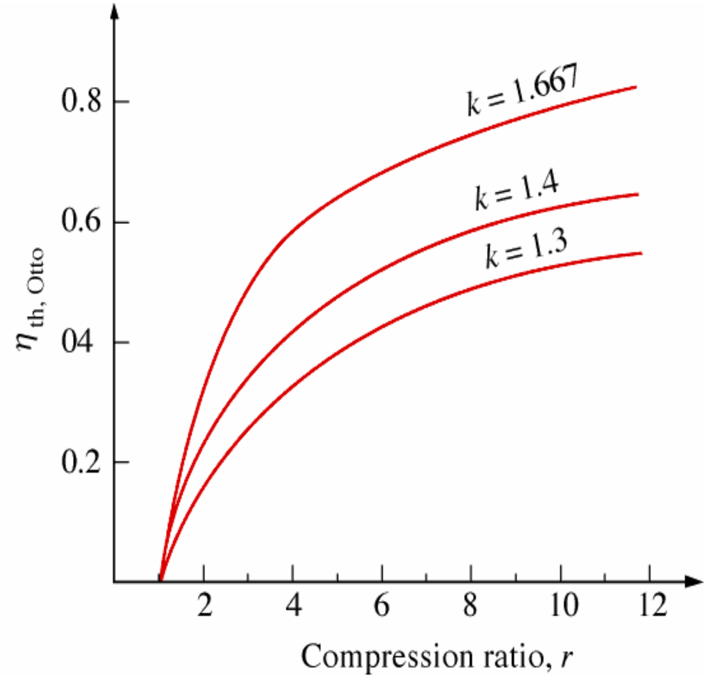




Engine Knock and thermal Efficiency of an Engine

The thermal efficiency of the ideal Otto cycle increases with both the compression ratio and the specific heat ratio.

- ➢ **When high *compression ratios* are used, the temperature of the air-fuel mixture rises above the auto-ignition temperature produces an audible noise, which is called *engine knock*. (*antiknock, tetraethyl lead*? → unleaded gas)**

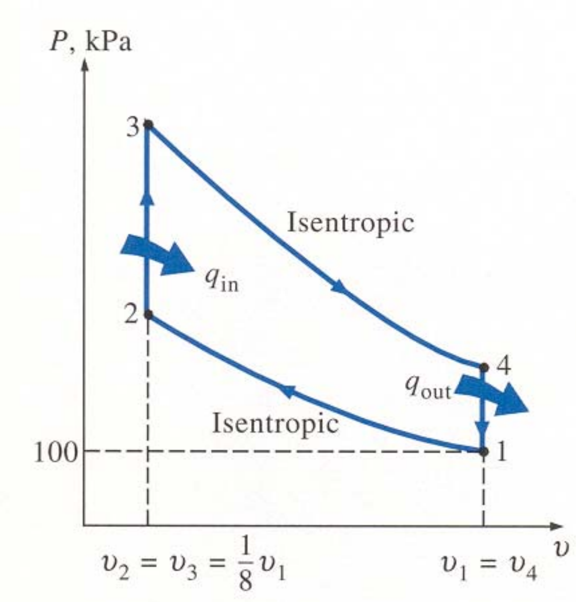


- ➢ **For a given compression ratio, an ideal Otto cycle using a monatomic gas (such as argon or helium, *k* = 1.667) as the working fluid will have the highest thermal efficiency.**

Example

The Ideal Otto Cycle

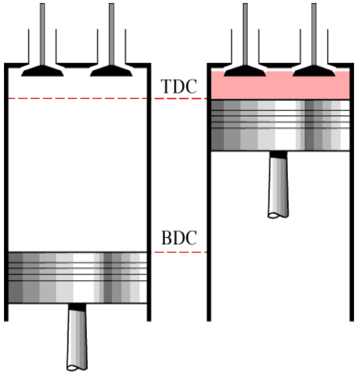
An ideal Otto cycle has a compression ratio of 8. At the beginning of the compression process, the air is at 100 kPa and 17^{o}C, and 800 kJ/kg of heat is transferred to air during the constant-volume heat-addition process. Accounting for the variation of specific heats of air with temperature,



determine *a*) the maximum temperature and pressure that occur during the cycle, *b*) the net work output, *c*) the thermal efficiency, and *d*) the mean effective pressure for the cycle. <*Answers: a) 1575.1 K, 4.345 MPa, b) 418.17 kJ/kg, c) 52.3%, d) 574.4 kPa*>

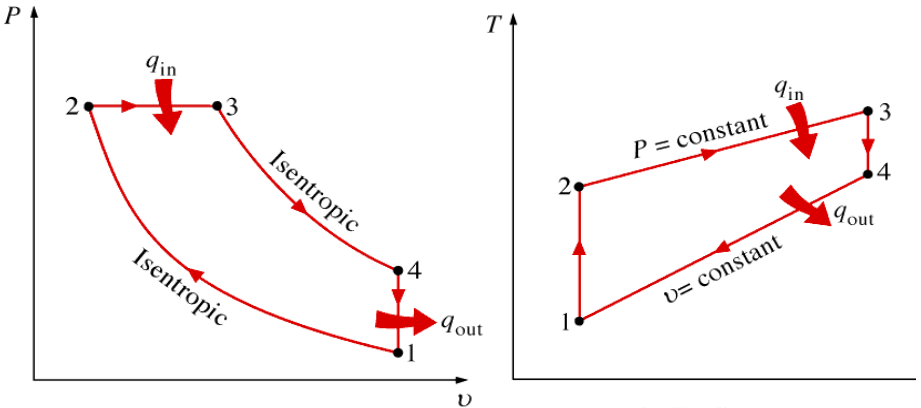
Sol:

Diesel Engine: Ideal Cycle for CI Engines



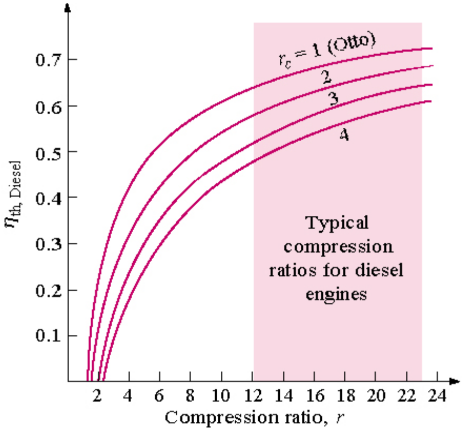
(*a*) Displacement volume

(*b*) Clearance volume



(a) *P*-υdiagram

(b) *T*-*s* diagram



In CI engines (also known as diesel engines), AIR not (fuel Mixture) is compressed to a temperature that is above the auto-ignition temperature of the fuel, and combustion starts on contact as the fuel is injected into this hot air. Therefore, diesel engines can be designed to operate at much higher compression ratios, typically between 12 and 24.

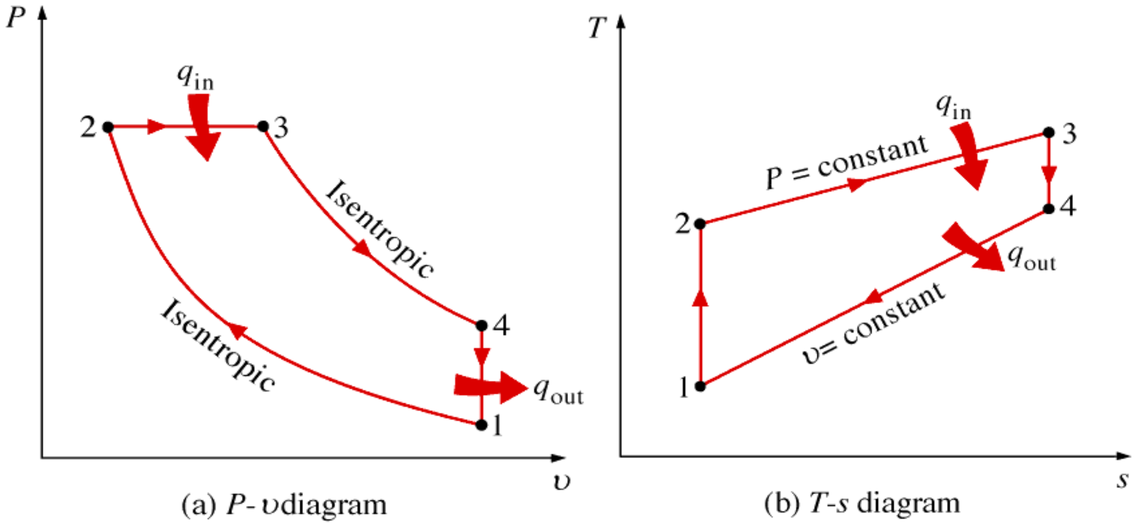
The fuel injection process in diesel engines starts when the piston approaches TDC and continues during the first part of the power stroke. Therefore, the combustion process in these engines takes place over a longer interval. <u>Because of this longer duration, the combustion process in the ideal Diesel cycle is approximated as a constant-pressure heat-addition process</u>. In fact, this is the *ONLY* process where the Otto and the Diesel cycles differ.

Thermal efficiency of Ideal Diesel Cycle

$$q_{in} - w_{b,out} = u_3 - u_2 \Rightarrow q_{in} = h_3 - h_2 = C_p\left(T_3 - T_2\right)$$

$$q_{out} = u_4 - u_1 = C_v\left(T_4 - T_1\right)$$

$$\eta_{th,Diesel} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{k\left(T_3 - T_2\right)} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k\left(r_c - 1\right)}\right]$$



(a) P-υdiagram (b) T-s diagram

Where,

$$r = \frac{\upsilon_1}{\upsilon_2}$$

and

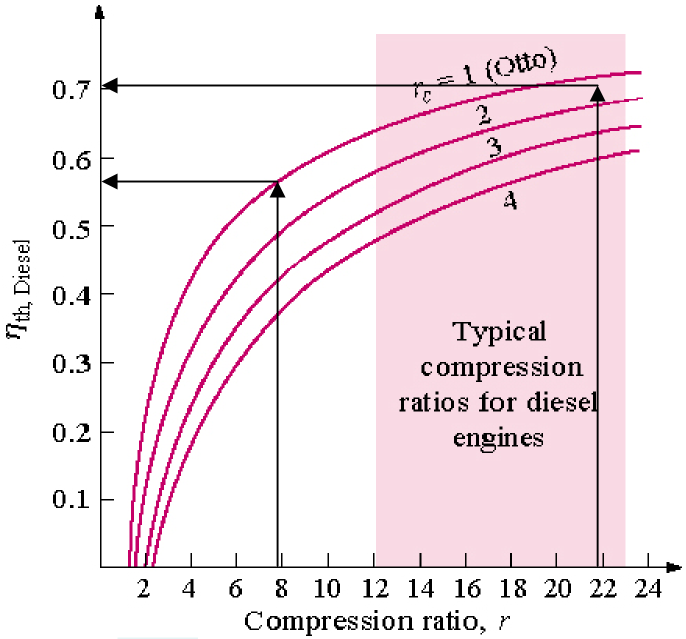
$$r_c = \frac{\upsilon_3}{\upsilon_2}$$

Thermal efficiency of Ideal Diesel Cycle

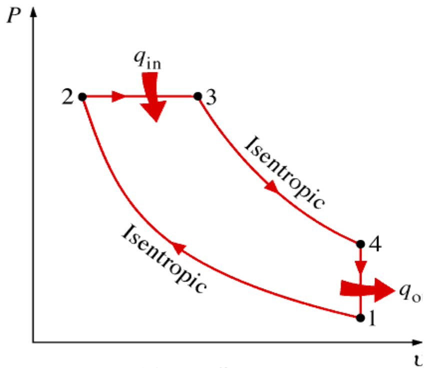
The efficiency of a Diesel cycle differs from the efficiency of Otto cycle by the quantity in the brackets. (See Slide #22)

$$\eta_{th,Diesel} = 1 - \frac{1}{r^{k-1}} \boxed{\left[\frac{r_c^{k} - 1}{k\left(r_c - 1\right)}\right]}$$

The quantity in the brackets is always greater than 1. Therefore, $\eta_{th,Otto} > \eta_{th,Diesel}$ when both cycles operate on the same compression ratio. Also as the *cuttoff ratio, r_c* decreases, the efficiency of the Diesel cycle increases. (See figure at right)



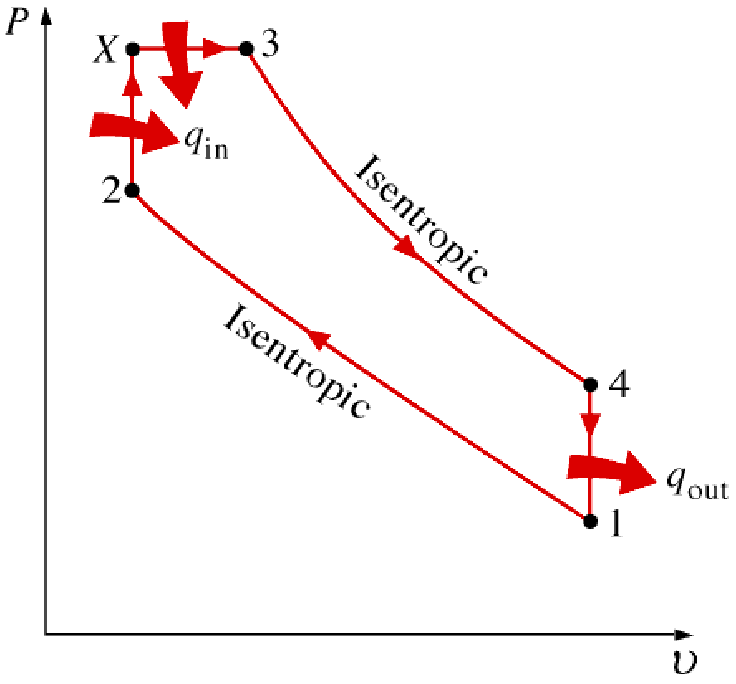
The higher efficiency and lower fuel costs (?) of diesel engines make them the clear choice in applications requiring relatively large amounts of power, such as in locomotive engines, large ships, and heavy trucks.



(a) P- υdiagram

P-υ Diagram of an Ideal Dual Cycle

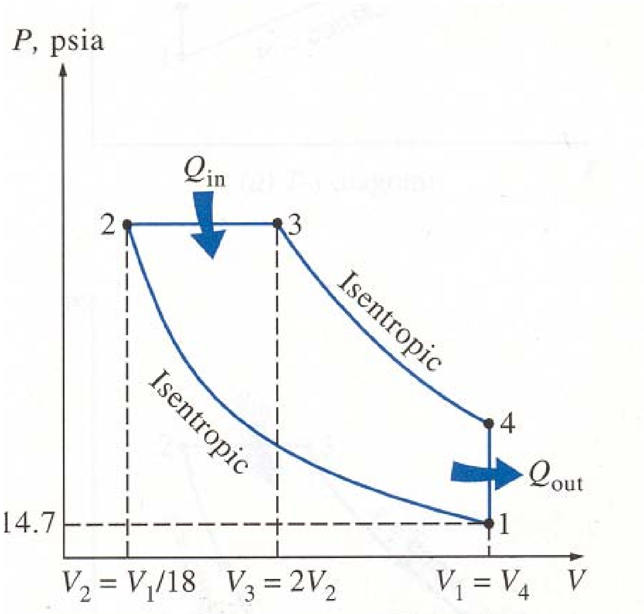
Approximating the combustion process in internal combustion engines as a constant-volume or constant-pressure heat-addition process is overly simplistic and not quite realistic. Dual cycle model with the combination of these two heat transfer processes would be better approach.



Example

The Ideal Diesel Cycle

An ideal diesel cycle with air as the working fluid has a compression ratio of 18 and a cut off ratio of 2. At the beginning of the compression process, the working fluid is at 14.7 psia, 80^{o}F, and 117 in^3. Utilizing the cold-air-standard assumptions,



Determine

***a*) the temperature and pressure of the air at the end of each process,**

***b*) the net work output and the thermal efficiency, and**

***c*) the mean effective pressure.**