IC Engines and the Otto Cycle

Motivation

- The invention of the reciprocating IC-Engine is perhaps the most important technological development in history.
- More than 200 million motor vehicles in U.S. powered by IC-engines
- Transportation sector accounts for ~30% of US energy use. 98% of this energy comes from petroleum; ~50% of US petroleum is imported [Energy Information Administration http://www.eia.doe.gov/emeu/aer/contents.html].

Objectives

- **What are the major components of an IC-Engine?**
- **How does a 4-stroke IC-engine work?**
- **How can we model an IC-engine thermodynamically?**
- **What would be required to refine our model to make it more realistic?**

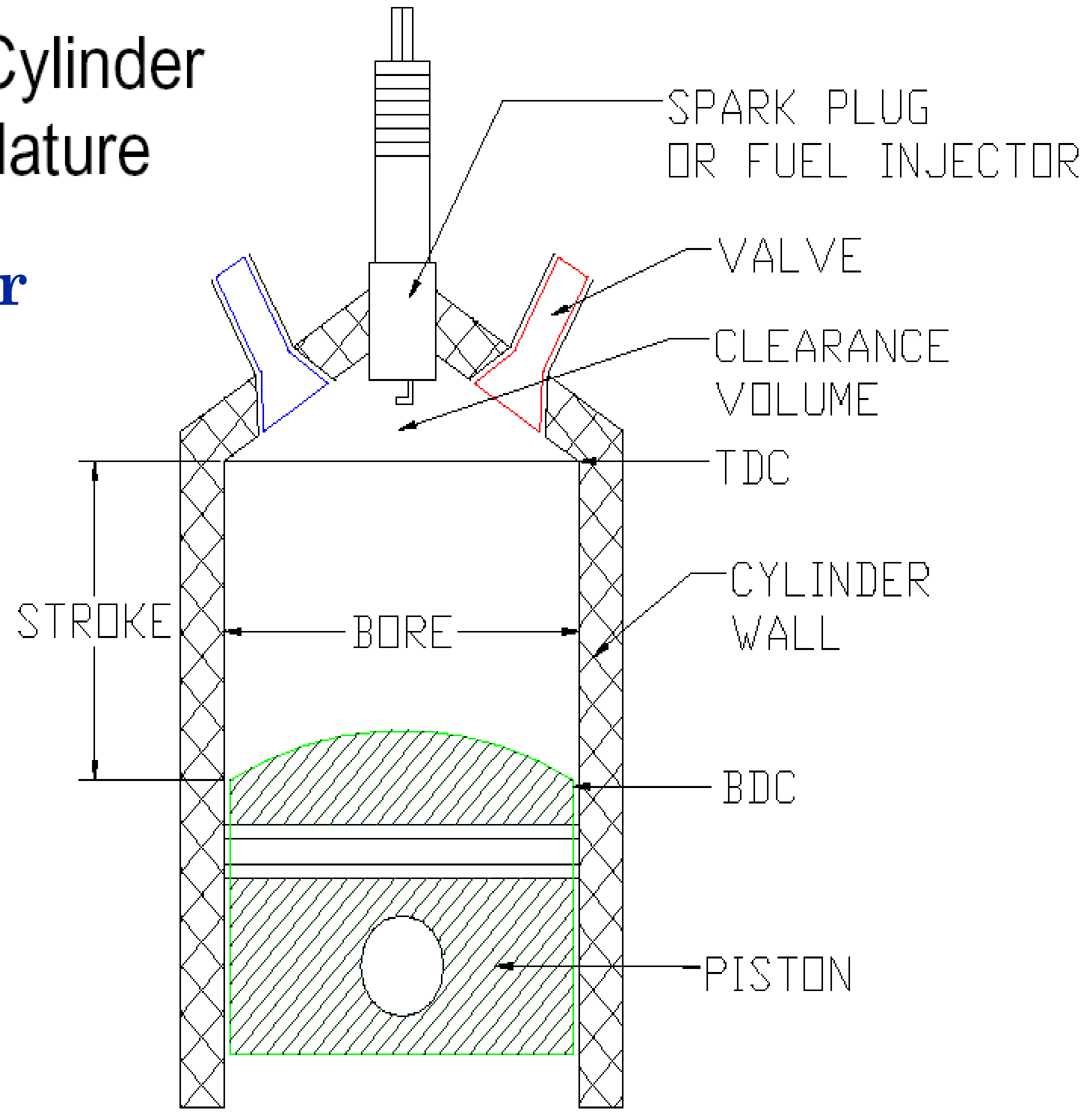
Internal Combustion Engines

- Spark Ignition
  - Nikolaus Otto (1876)
  - Particularly well-suited for use in automobiles
    - » Relatively low cost
    - » Favorable power to weight ratio (petroleum has a high energy density)
    - » High thermal efficiency
- Compression Ignition
  - Rudolf Diesel (1897)
  - Best suited for applications where fuel economy and high power is required
- 4-stroke and 2-stroke

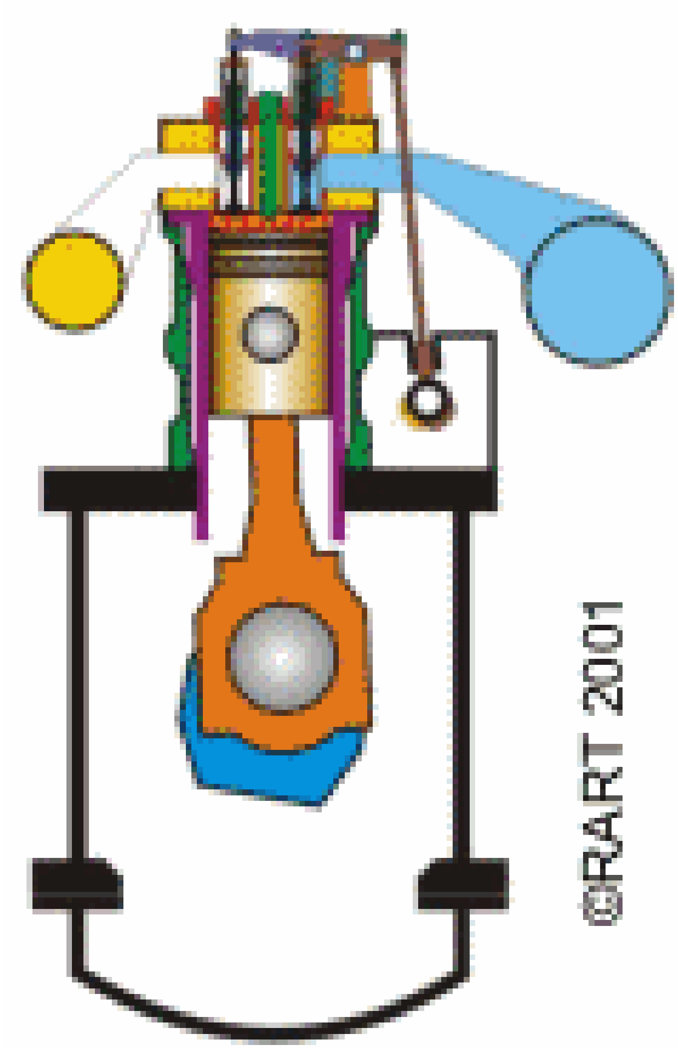
Internal Combustion Engines

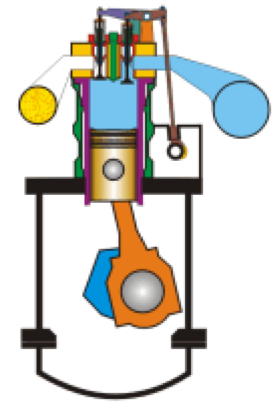
Piston -Cylinder
Nomenclature

- Bottom Dead Center
- Top Dead Center Stroke
- Stroke
- Bore
- Displacement Volume
- Clearance Volume
- Compression Ratio
  $r = V_{bdc}/V_{tdc}$

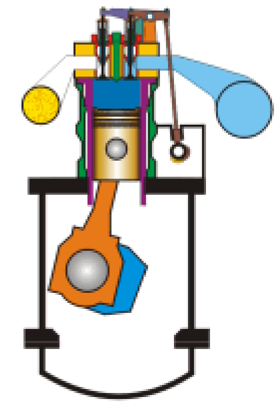


4-stroke Spark Ignition (SI) engine

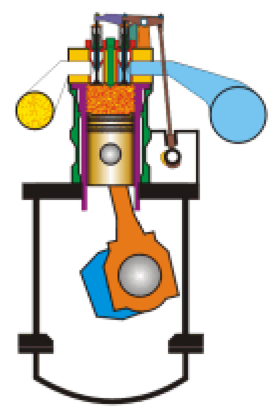




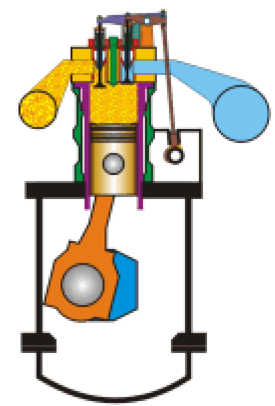
1. Induction



2. Compression

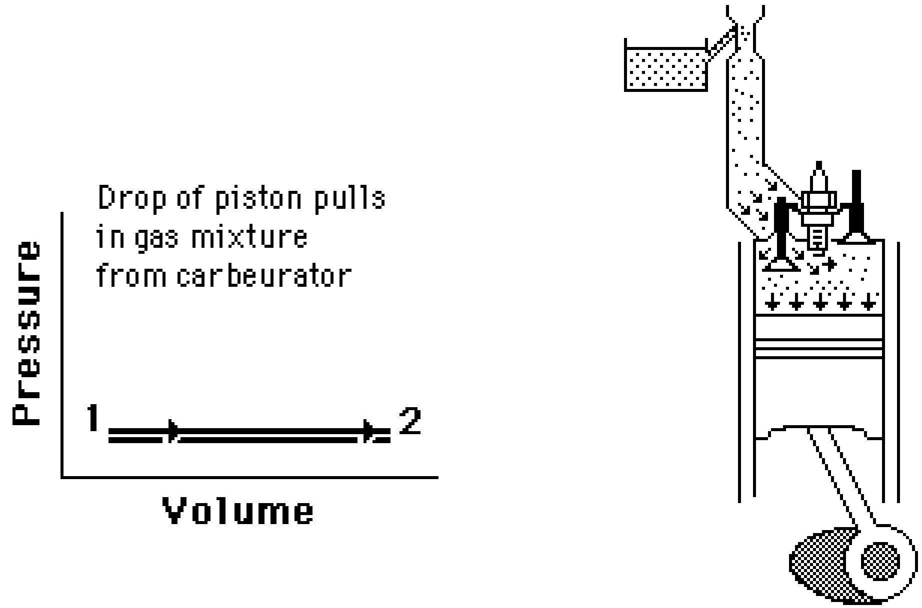


3. Expansion (Power)



4. Exhaust

P-V diagram of Modeled 4-stroke SI engine cycle



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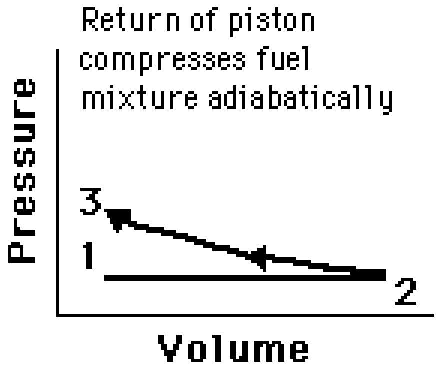

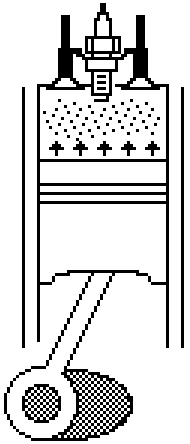

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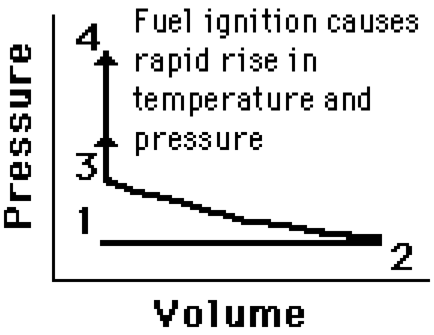

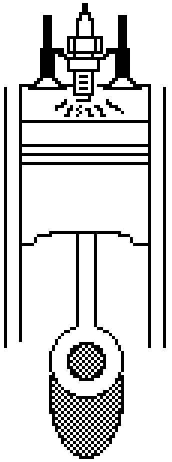

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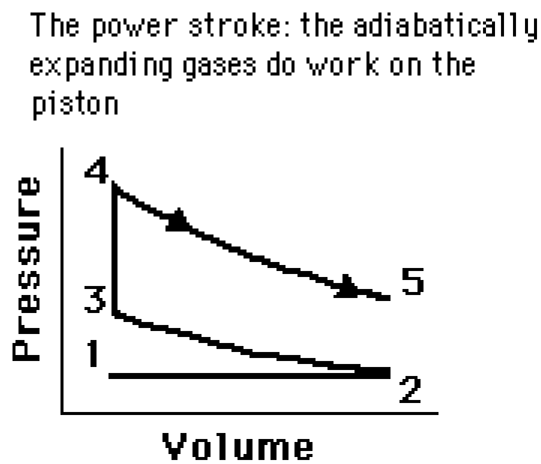

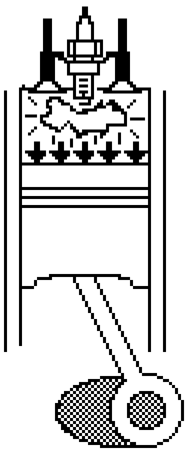

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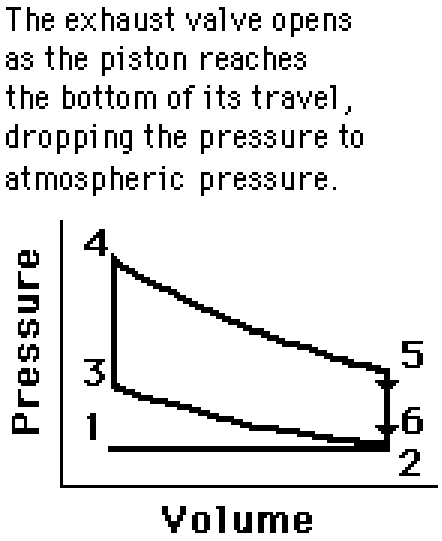

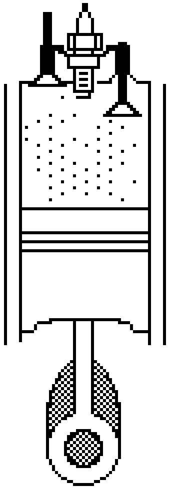

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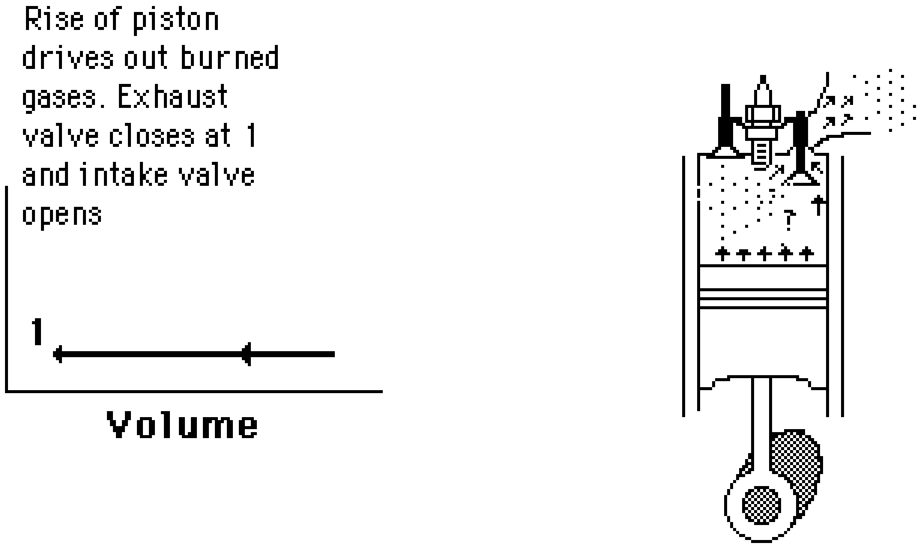

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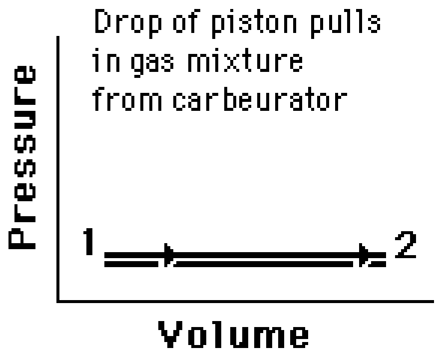

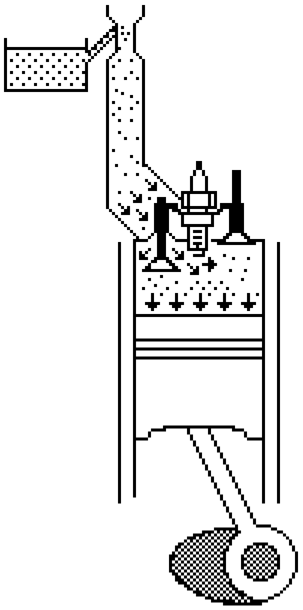

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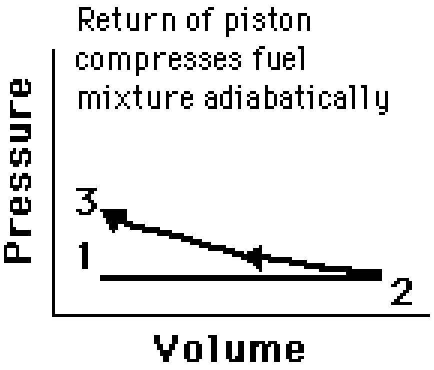

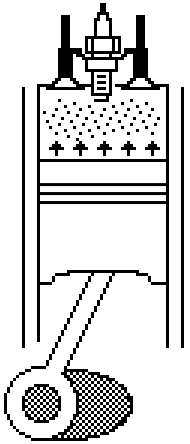

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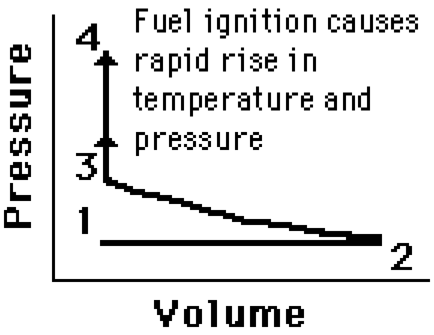
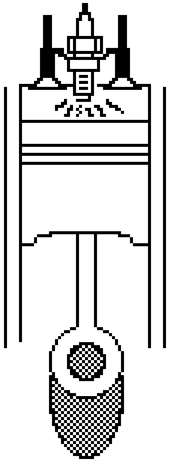
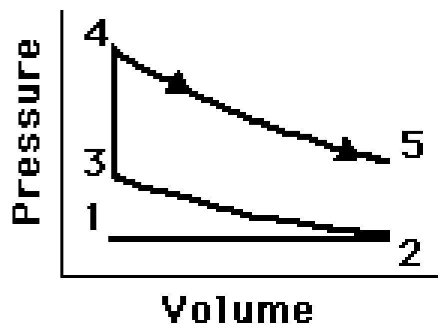
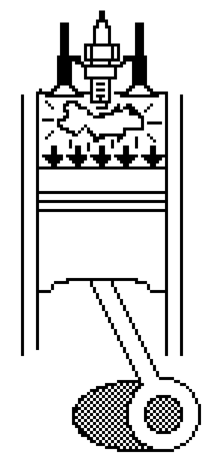




P-V diagram of Modeled 4-stroke SI engine cycle

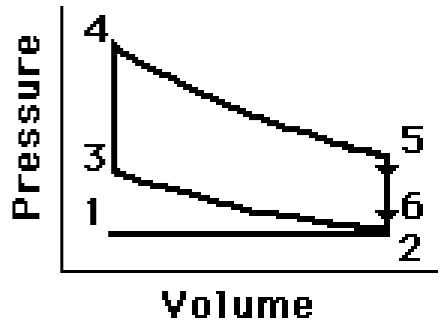
The power stroke: the adiabatically expanding gases do work on the piston

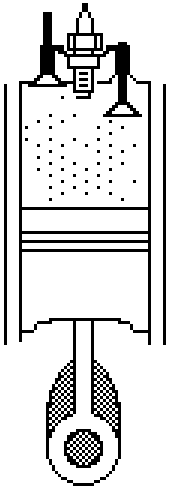




P-V diagram of Modeled 4-stroke SI engine cycle

The exhaust valve opens
as the piston reaches
the bottom of its travel,
dropping the pressure to
atmospheric pressure.





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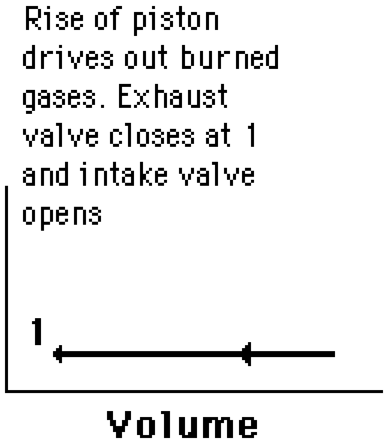
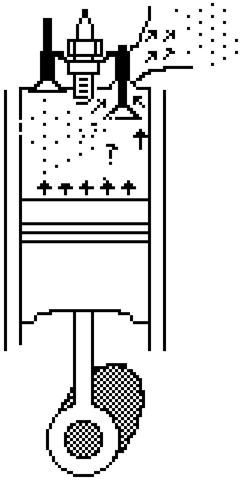
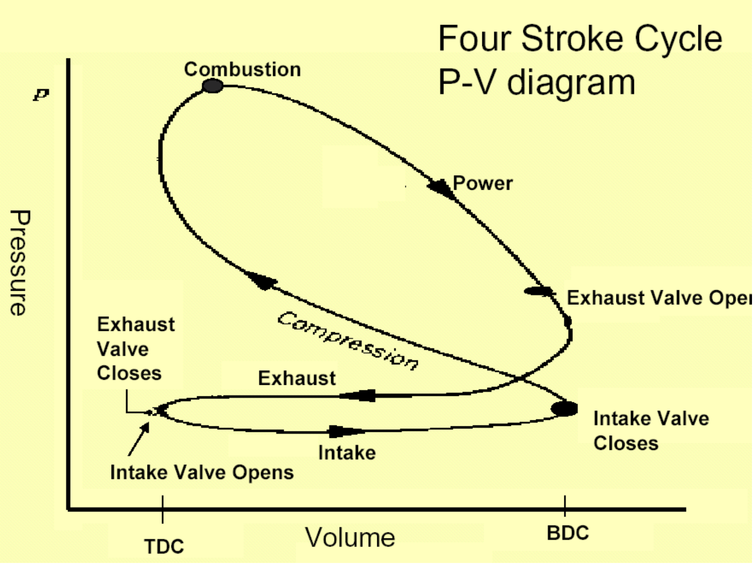




Detailed Analysis of Engine Cycle

- Combustion process
- Irreversibilities (friction and gradients)
- Heat transfer
- Work to charge cylinder and exhaust products

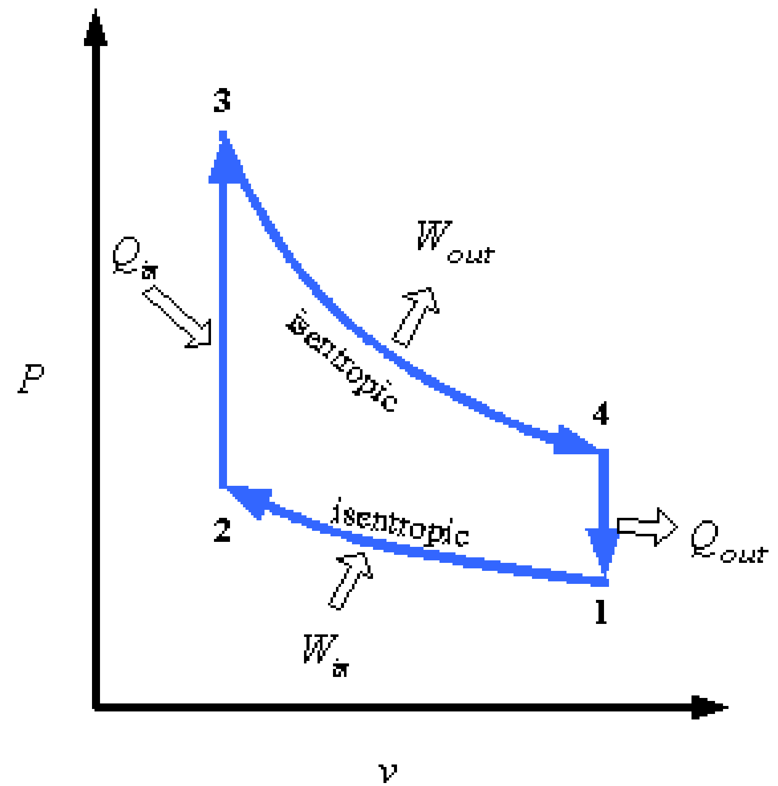


We will simplify this considerably and do some meaningful analysis.

We still gain insight into the thermodynamics.

Model: Air Standard Otto Cycle

- Working fluid is a fixed amount of air, modeled as an ideal gas
- Compression and expansion are isentropic
- Combustion is replaced by a heat addition from an external source (at constant volume)
- At BDC, there is a constant volume heat rejection
- No exhaust or intake processes
- Specific heats may or may not be assumed constant (ex. 1 explores this)



Air Standard Otto Cycle Analysis

- **Task--Given:**
  (1) the initial conditions at state 1
  (P_1, T_1, V_1)
  (2) the compression ratio (r)
  (3) the heat added (Q_{in} from combustion):
- **Find:**
  - **properties at states 2, 3 and 4**
  - **performance parameters**
    - » **Net work done per cycle**
    - » **Thermal efficiency**
- **Tools that we'll use:**
  - **Ideal gas relations**
  - **Isentropic relations**
  - **First Law of Thermodynamics**

Air Standard Otto Cycle Analysis

- **Given:**
  (1) the initial conditions at state 1
  (P_1, T_1, V_1)
  (2) the compression ratio (r)
  (3) the heat added (Q_{in} from combustion):
- **State 1→2 Isentropic Compression**

Get T_2 from $$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1}$$ **(assume k is constant)**

Get P_2 from $$P_2 = P_1\left(\frac{V_1}{V_2}\right)\left(\frac{T_2}{T_1}\right)$$

Air Standard Otto Cycle Analysis

- **State 2→3 Constant Volume Heat Addition**

From 1st law: Get T3 from

$C_v(T_3 - T_2) = q_{in}$ (get mass in system from ideal gas law)

Get P_3 from

$$P_3 = P_2\left(\frac{T_3}{T_2}\right)$$

Air Standard Otto Cycle Analysis

- **State 3→4 Isentropic expansion**

Get T_4 from

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{k-1}$$

(assume k is constant)

Get P_4 from

$$P_4 = P_3\left(\frac{V_3}{V_4}\right)\left(\frac{T_4}{T_3}\right)$$

Air Standard Otto Cycle Analysis

- **Performance Parameters**

From 1st Law:

$$w_{cycle} = q_{in} - q_{out}$$

$$= c_v(T_3 - T_2) - c_v(T_4 - T_1)$$

Thermal Efficiency

$$\eta = w_{cycle}/q_{in} = 1 - q_{out}/q_{in}$$

Let's refine our analysis

- What would you change about the analysis to make it more realistic?

Looking Ahead: How does thermal efficiency depend on compression ratio?

- Derivation
- Discussion of Diesel engines and the Diesel cycle (higher compression ratio)
  - How does it differ?
  - What are its advantages, disadvantages?
- Refinements→fuel-air Otto cycle