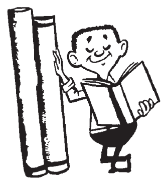
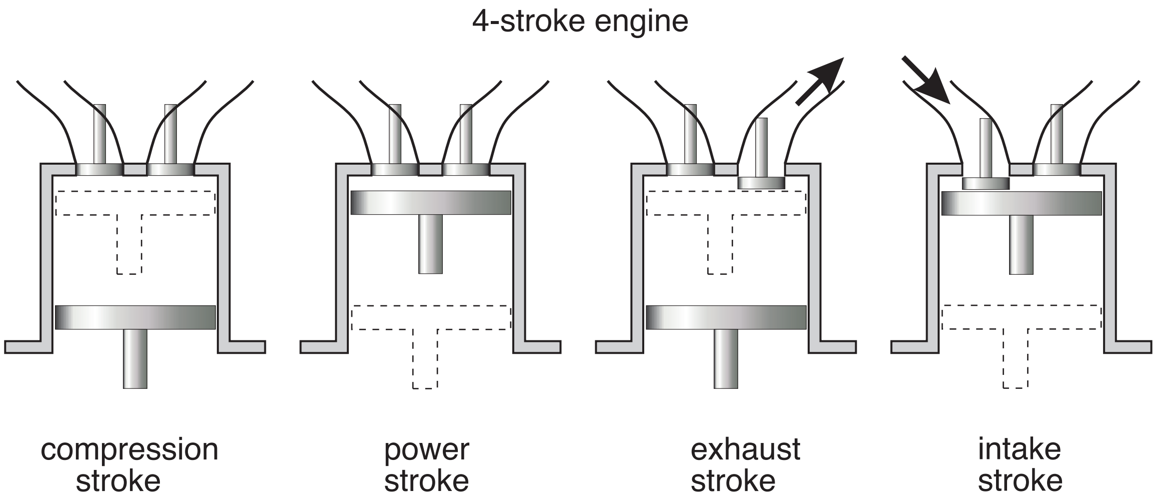
Internal Combustion Engines



Reading	Problems
12.1, 12.7 → 12.12	12.67, 12.74, 12.81, 12.82 12.86, 12.89, 12.94

The Gasoline Engine



- conversion of chemical energy to mechanical energy
- can obtain very high temperatures due to the short duration of the power stroke

Air Standard Cycle

A closed cycle model for the IC engine, such as the gasoline or diesel cycle. Some assumptions must be made in order to model this complex process.

ASSUMPTIONS:

- air is an ideal gas with constant c_p and c_v
- no intake or exhaust processes
- the cycle is completed by heat transfer to the surroundings

- the internal combustion process is replaced by a heat transfer process from a TER
- all internal processes are reversible
- heat addition occurs instantaneously while the piston is at TDC

Definitions

Mean Effective Pressure (MEP): The theoretical constant pressure that, if it acted on the piston during the power stroke would produce the same *net* work as actually developed in one complete cycle.

$$MEP = \frac{\text{net work for one cycle}}{\text{displacement volume}} = \frac{W_{net}}{V_{BDC} - V_{TDC}}$$

The mean effective pressure is an index that relates the work output of the engine to it size (displacement volume).

Otto Cycle

- the theoretical model for the gasoline engine
- consists of four internally reversible processes
- heat is transferred to the working fluid at constant volume

Otto Cycle Efficiency

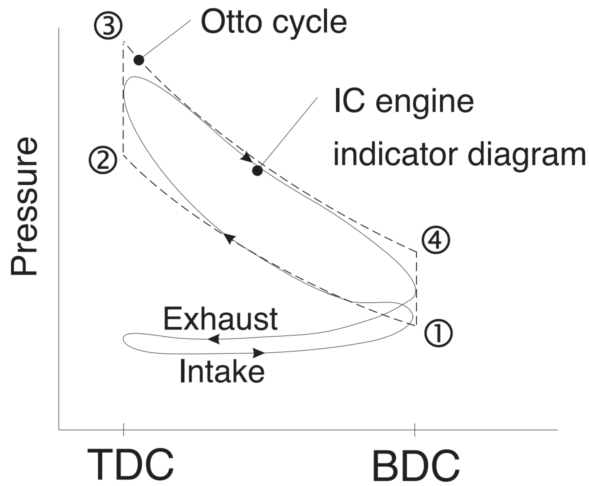
$$\eta = \frac{W_{net}}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{Q_{4-1}}{Q_{2-3}}$$

$$Q_H = mc_v(T_3 - T_2) \quad (intake)$$

$$Q_L = mc_v(T_4 - T_1) \quad (exhaust)$$

Therefore

$$\eta = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} = 1 - \left(\frac{T_1}{T_2}\right) \frac{\left(\dfrac{T_4}{T_1} - 1\right)}{\left(\dfrac{T_3}{T_2} - 1\right)}$$



Since processes $\mathbf{1} \rightarrow \mathbf{2}$ and $\mathbf{3} \rightarrow \mathbf{4}$ are isentropic, we know that

$$PV^k = constant$$

$$\frac{mRT_1}{V_1} V_1^k = \frac{mRT_2}{V_2} V_2^k$$

and

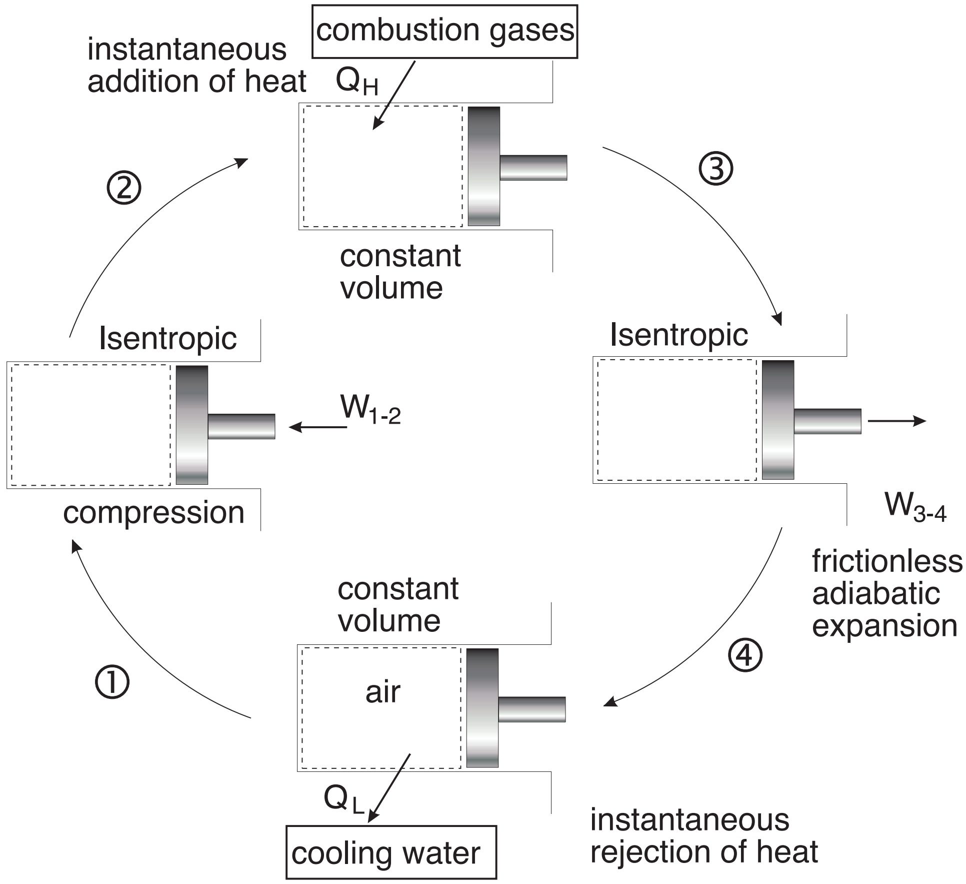
$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} = \left(\frac{V_4}{V_3}\right)^{k-1} = \frac{T_3}{T_4}$$

We can make this equality since

$$\frac{V_1}{V_2} = \frac{V_4}{V_3} = compression\ ratio = r$$

Therefore

$$\frac{T_3}{T_2} = \frac{T_4}{T_1}$$



Substituting into the equation for η gives

$$\eta = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{V_2}{V_1}\right)^{k-1} = 1 - \left(\frac{V_1}{V_2}\right)^{1-k}$$

If we let

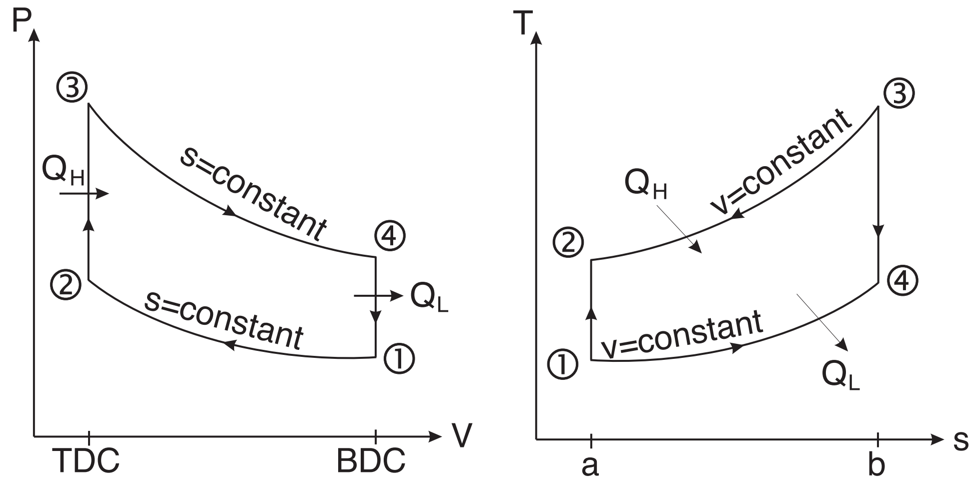
$$r = \frac{V_1}{V_2} = \frac{V_4}{V_3} = compression\, ratio$$

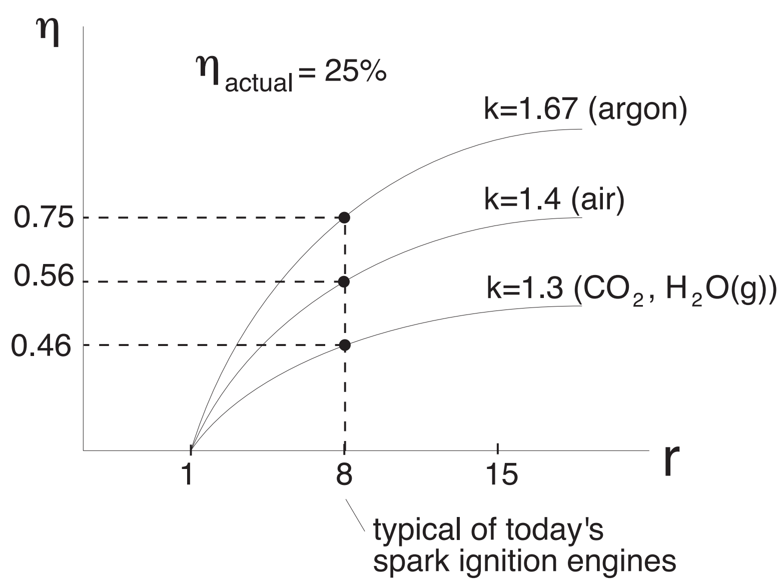
Then

$$\boxed{\eta_{Otto} = 1 - r^{1-k}}$$

Diesel Cycle

- an ideal cycle for the compression ignition engine (diesel engine)

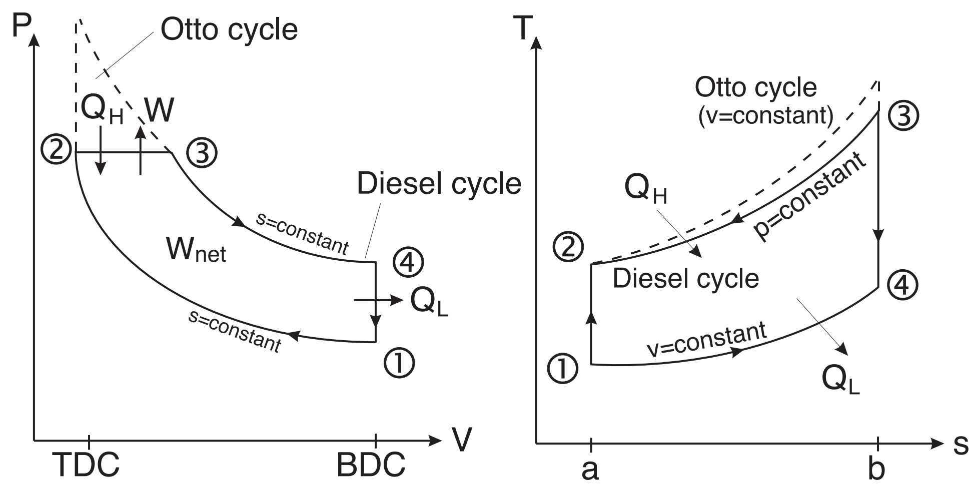




- all steps in the cycle are reversible
- heat is transferred to the working fluid at constant pressure
- heat transfer must be just sufficient to maintain a constant pressure

Diesel Cycle Efficiency

$$\eta = 1 - \frac{c_v(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \left(\frac{1}{k}\right)\left(\frac{T_1}{T_2}\right) \frac{\left(\frac{T_4}{T_1} - 1\right)}{\left(\frac{T_3}{T_2} - 1\right)} \qquad (1)$$



where

$$k = \frac{c_p}{c_v}$$

If we let

$$r = \frac{V_1}{V_2} = compression\, ratio = \frac{V_4}{V_2}$$

$$r_v = \frac{V_3}{V_2} = cutoff\, ratio \rightarrow \; injection\, period$$

From the Otto cycle analysis we know

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} = r^{k-1} \qquad (2)$$

and for an isentropic process

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{k-1} = \left(\frac{V_4}{V_2} \cdot \frac{V_2}{V_3}\right)^{k-1} = \left(\frac{r}{r_v}\right)^{k-1}$$

From this, we can write

$$\frac{T_3}{T_4} = \frac{r^{k-1}}{r_v^{k-1}} = \frac{T_2/T_1}{r_v^{k-1}}$$

and

$$\frac{T_2}{T_1} = \frac{T_3}{T_4}\, r_v^{k-1}$$

or

$$\frac{T_4}{T_1} = \frac{T_3}{T_2}\, r_v^{k-1} \qquad (3)$$

From the ideal gas law

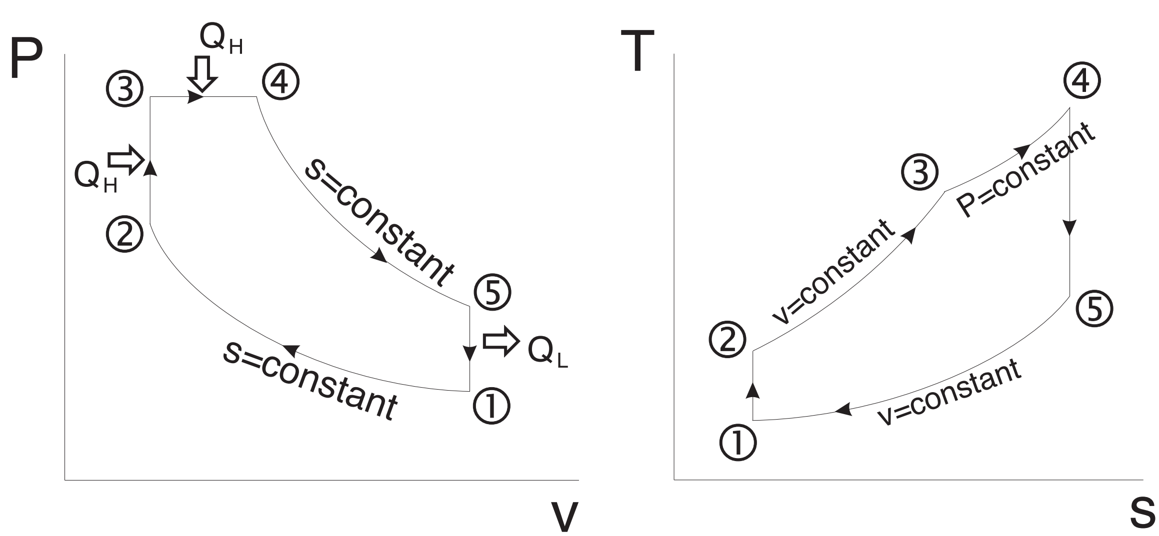
$$P_3 = \frac{RT_3}{V_3} = \frac{RT_2}{V_2} = P_2 \qquad \Rightarrow \qquad \frac{T_3}{T_2} = \frac{V_3}{V_2} = r_v \qquad (4)$$

Substituting (2), (3), and (4) into (1)

$$\boxed{\eta_{Diesel} = 1 - \frac{1}{r^{k-1}}\left(\frac{1}{k}\right)\left(\frac{r_v^k - 1}{r_v - 1}\right)}$$

Dual Cycle (Limited Pressure Cycle)

- better representation of the combustion process in both the gasoline and the diesel engines



Dual Cycle Efficiency

Given

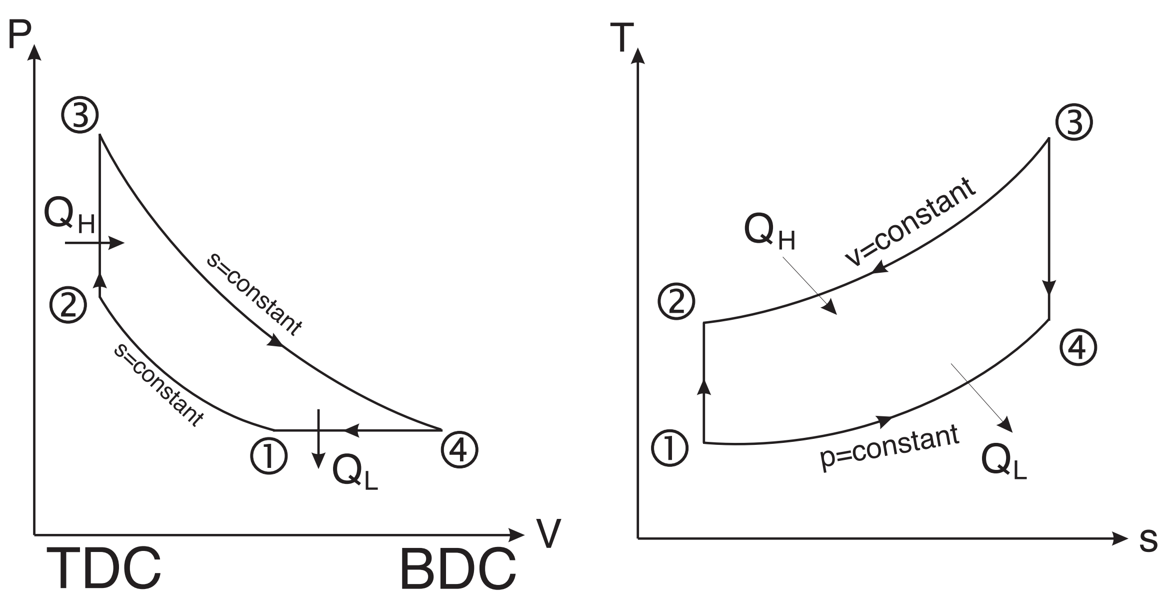
$$
\begin{aligned}
r &= \frac{V_1}{V_2} = compression\,ratio \\
r_v &= \frac{V_4}{V_3} = cutoff\,ratio \\
r_p &= \frac{P_3}{P_2} = pressure\,ratio
\end{aligned}
$$

$$\boxed{\eta_{Dual} = 1 - \frac{r_p r_v^k - 1}{\left[(r_p - 1) + k r_p (r_v - 1)\right] r^{k-1}}}$$

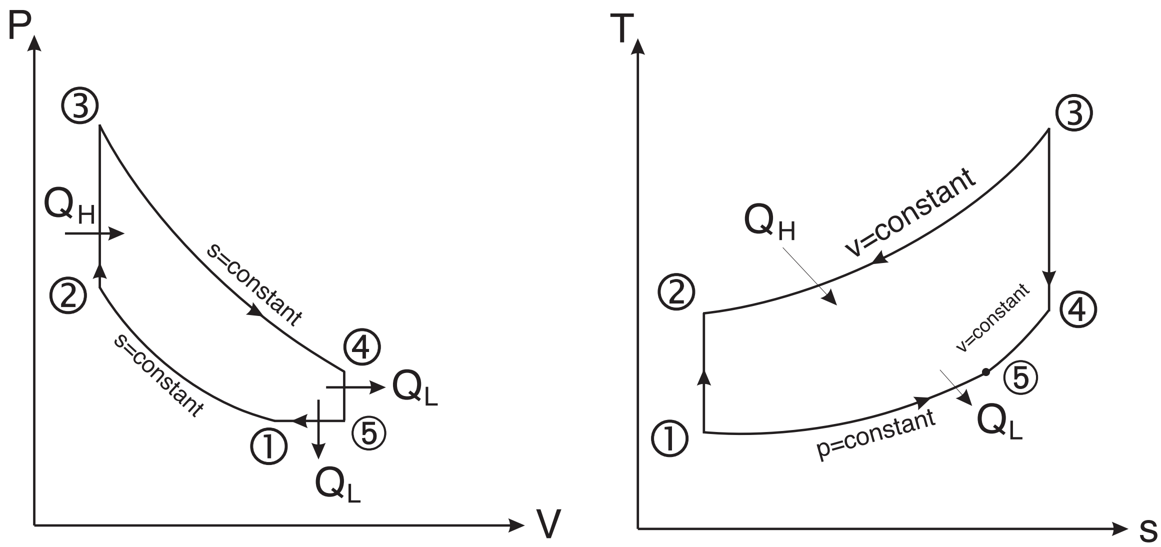
Note: if $r_p = 1$ we get the diesel efficiency.

Atkinson and Miller Cycles

Similar to the Otto cycle but with constant pressure heat rejection that allows for a higher expansion ratio (more work extraction) compared to the compression ratio and in turn a higher cycle efficiency.



The Atkinson Cycle



The Miller Cycle

Atkinson Cycle Efficiency

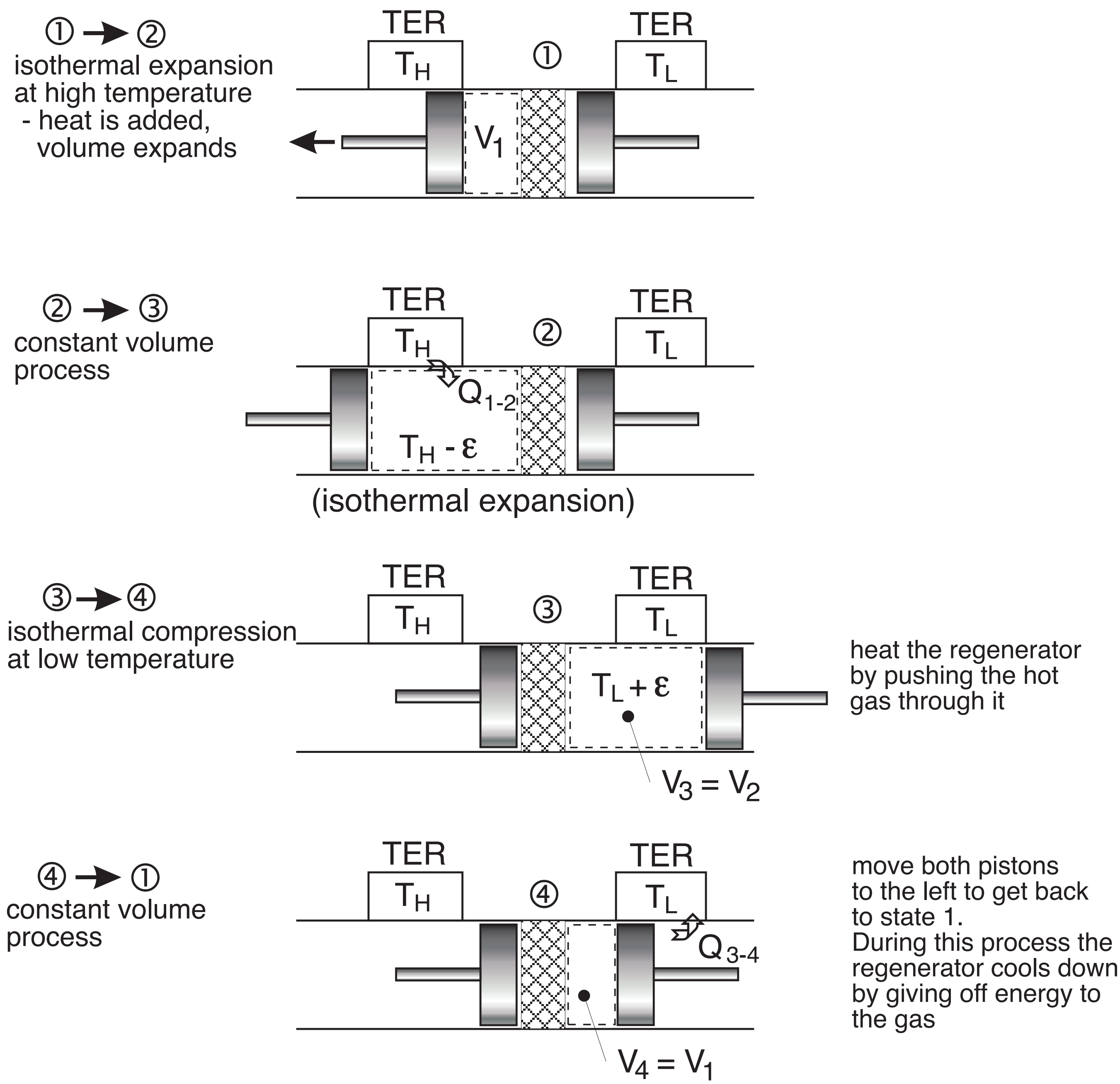
If we let

$$r = \frac{V_1}{V_2} = compression\ ratio$$

$$r_\alpha = \frac{V_4}{V_3} = expansion\ ratio \text{ (larger than the compression ratio)}$$

$$\begin{aligned}\eta &= 1 - k \cdot r^{1-k} \cdot \frac{\left[\frac{r_\alpha}{r} - 1\right]}{\left[\frac{r_\alpha^k}{r^k} - 1\right]} \\ &= 1 - k\left[\frac{r_\alpha - r}{r_\alpha^k - r^k}\right]\end{aligned}$$

Stirling Cycle



- reversible regenerator used as an energy storage device
- possible to recover all heat given up by the working fluid in the constant volume cooling process
- all the heat received by the cycle is at T_H and all heat rejected at T_L
- $\eta_{Stirling} = 1 - T_L/T_H$ (Carnot efficiency)

PROBLEM STATEMENT:

An air-standard Diesel cycle has a compression ratio of $\mathbf{15}$ and the heat transferred to the working fluid per cycle is $\mathbf{1600}\ \boldsymbol{kJ/kg}$. At the beginning of the compression process, the pressure is $\mathbf{0.1}\ \boldsymbol{MPa}$ and the temperature is $\mathbf{17}\ \boldsymbol{°C}$. Assuming variable specific heats for air, determine:

a) the pressure and temperature at each point in the cycle
b) the thermal efficiency