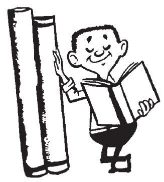
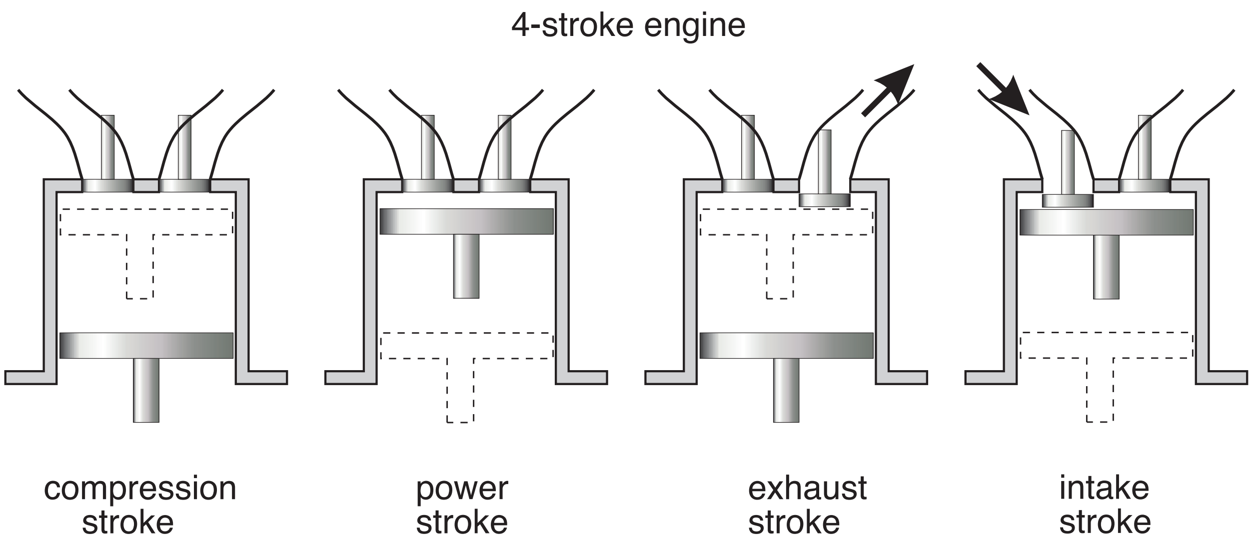
# *Internal Combustion Engines*



| Reading | Problems |
|---|---|
| 9-3 $\longrightarrow$ 9-7 | 9-38, 9-42, 9-55, 9-62, 9-67 |

## IC Engines

- although most gas turbines are also IC engines, the name is usually applied to reciprocating IC engines

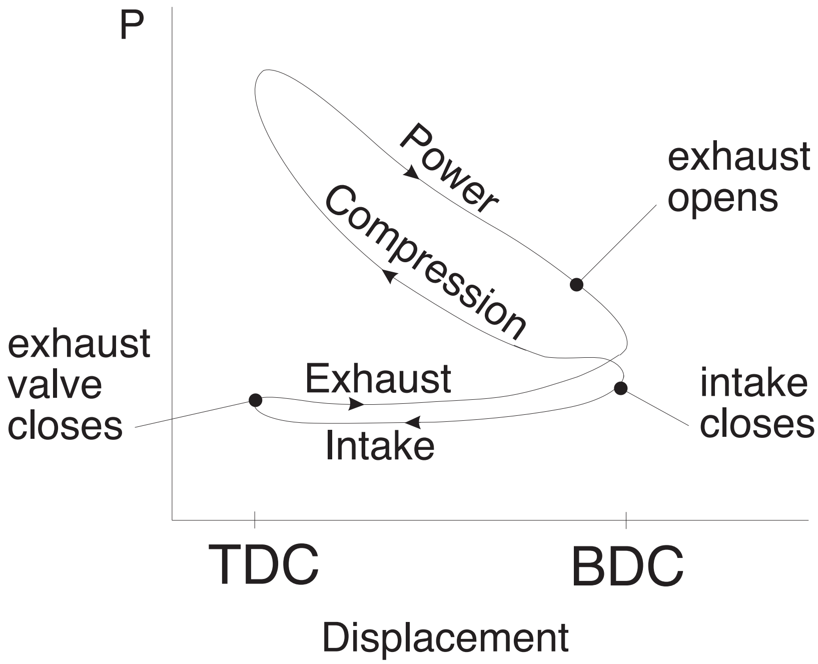



## Air Standard Cycle

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

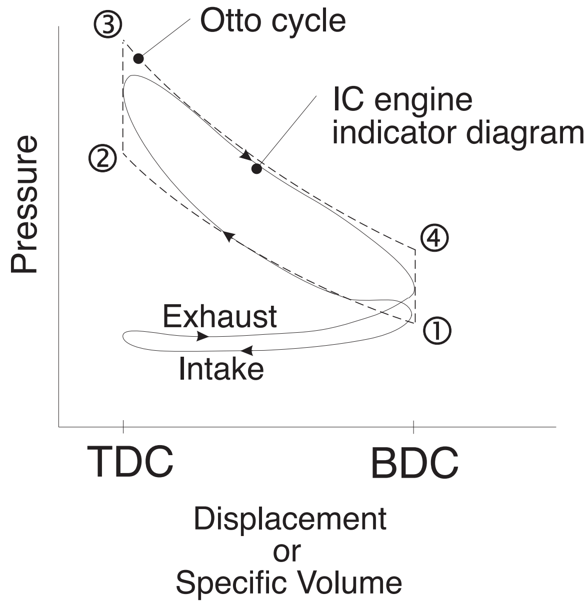
## Definitions

**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.

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

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

## Otto Cycle




The **Otto cycle** consists of four internally reversible processes in series

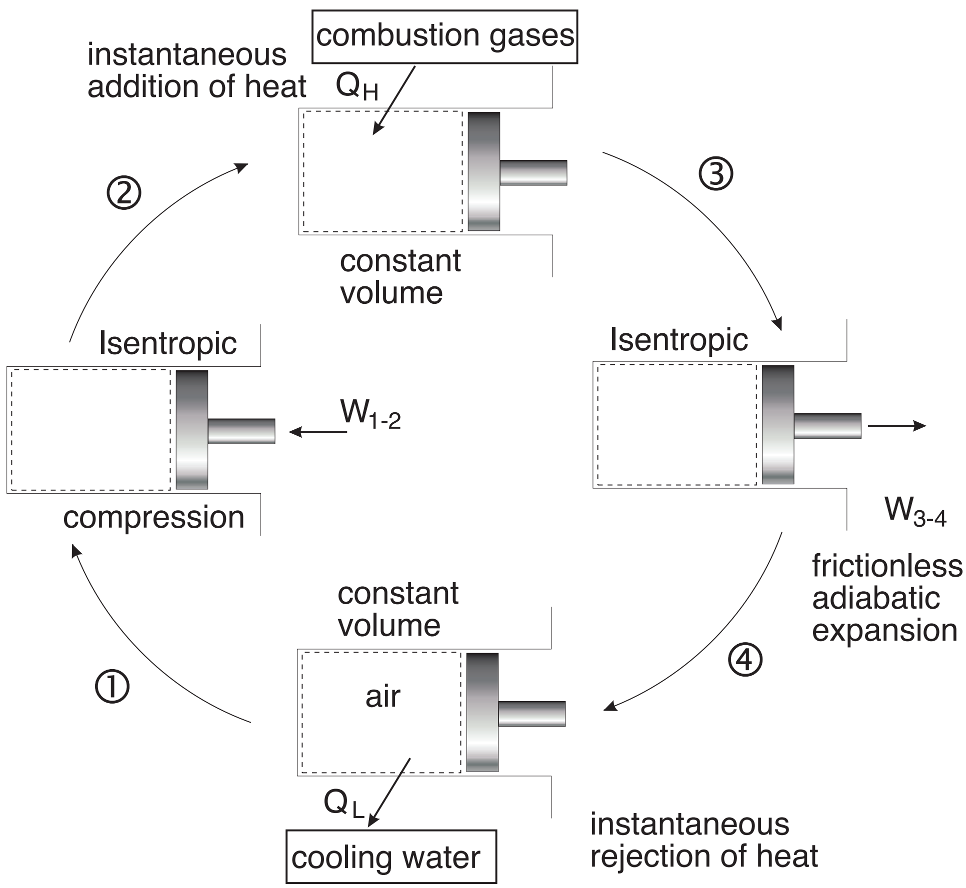
**1 → 2** isentropic compression or air as the piston moves from BDC to TDC

**2 → 3** constant volume heat addition to the fuel/air mixture from an external source while the piston is at TDC (represents the ignition process and the subsequent burning of fuel)

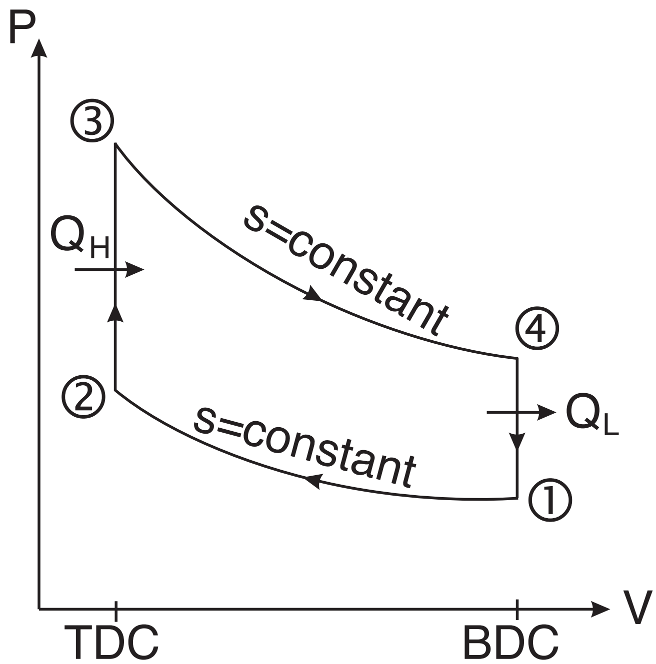
**3 → 4** isentropic expansion (power stroke)

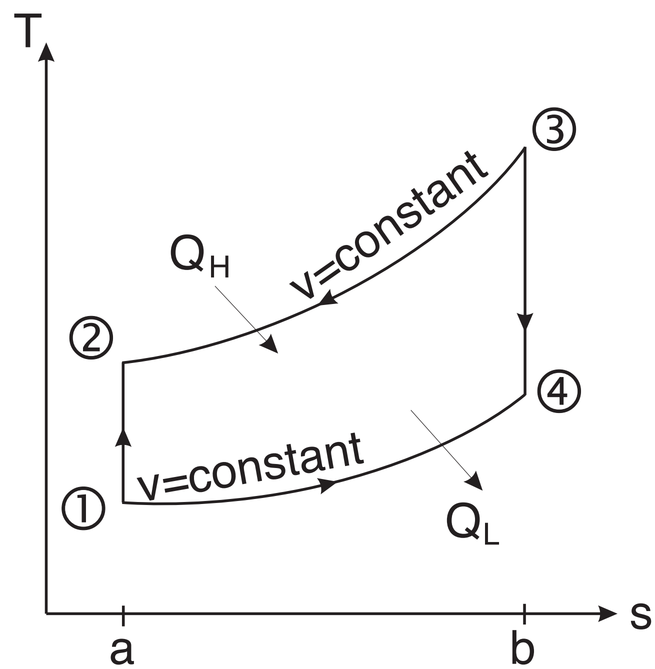
**4 → 1** constant volume heat rejection at BDC

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



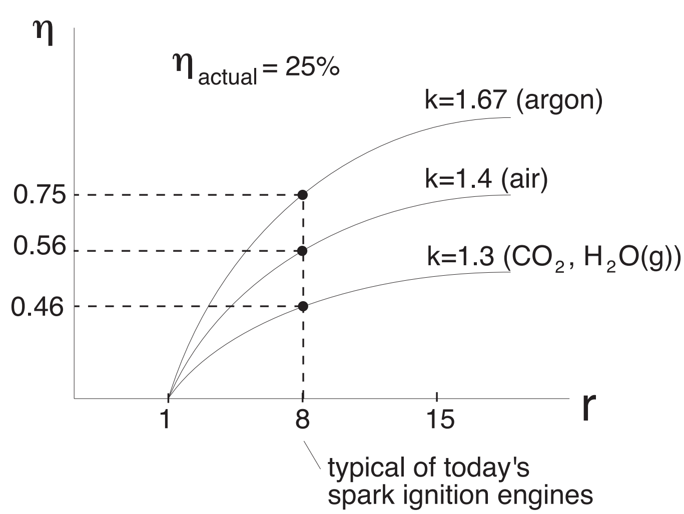
combustion gases
instantaneous
addition of heat
$Q_H$
constant
volume
②
③
Isentropic
compression
$W_{1-2}$
Isentropic
$W_{3-4}$
frictionless
adiabatic
expansion
①
④
constant
volume
air
$Q_L$
cooling water
instantaneous
rejection of heat



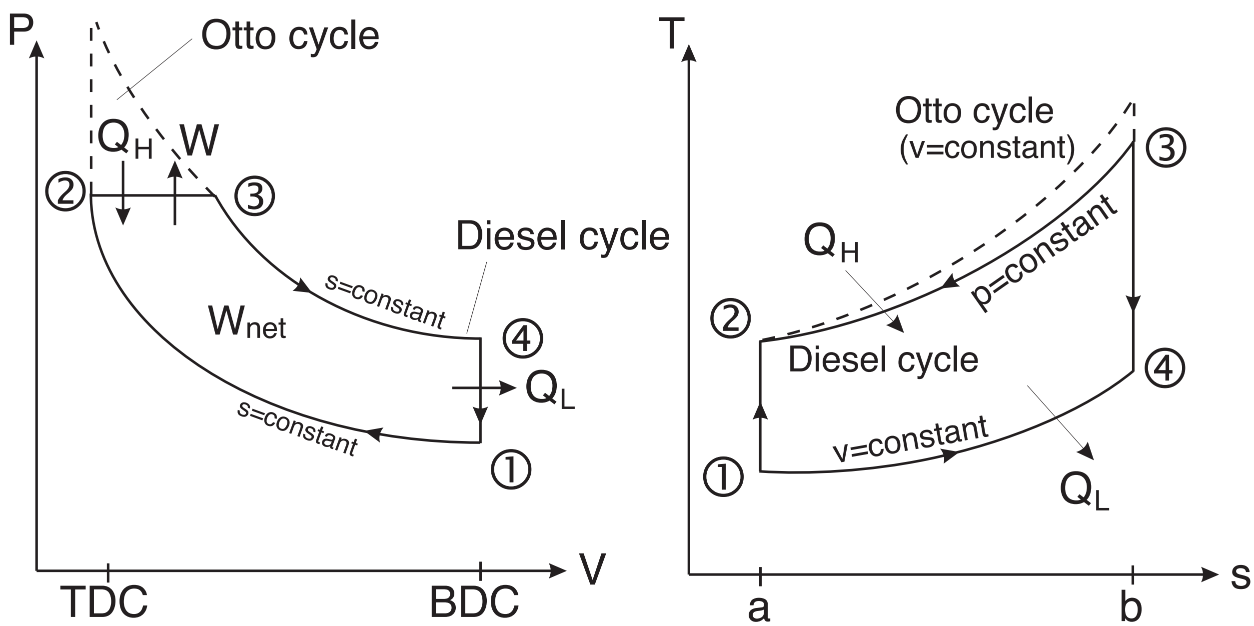

**Why not go to higher compression ratios?**

- there is an increased tendency for the fuel to detonate as the compression ratio increases
- the pressure wave gives rise to engine knock
- can be reduced by adding tetraethyl lead to the fuel
- not good for the environment

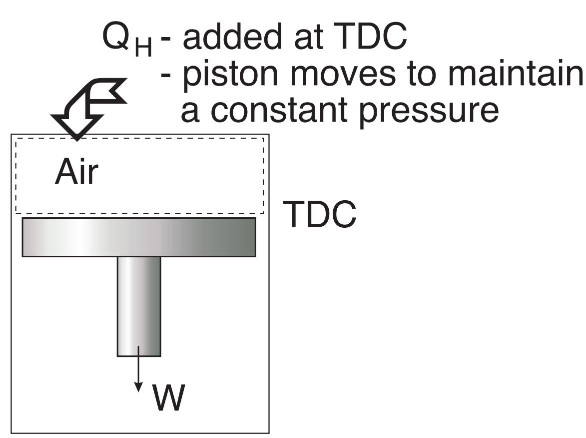


## Diesel Cycle

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




**Aside: The Air Standard Diesel Cycle**




- assumes heat addition occurs during a constant pressure process that starts with the piston at TDC

First, look at $Q_L$. From the 1st law

$$\frac{U_4}{m} - \frac{U_1}{m} = \frac{Q_L}{m} = c_v(T_4 - T_1)$$

Next look at $Q_H$

$$\begin{aligned}
Q_H &= W_{2-3} + (U_3 - U_2) \\
\frac{Q_H}{m} &= \frac{W_{2-3}}{m} + \left(\frac{U_3}{m} - \frac{U_2}{m}\right) \\
&= \int_2^3 P dv + (u_3 - u_2) \\
&= (Pv_3 - Pv_2) + (u_3 - u_2) \\
&= (u_3 + Pv_3) - (u_2 + Pv_2) \\
&= h_3 - h_2 \\
&= c_p(T_3 - T_2)
\end{aligned}$$

## Diesel Cycle Efficiency

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

Where we note

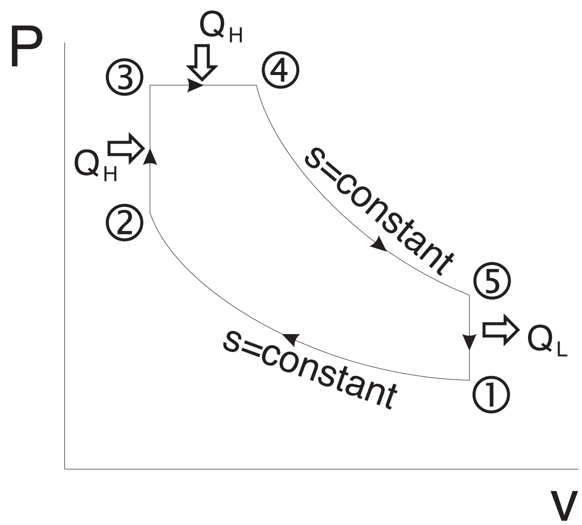
$$\eta_{Diesel} = 1 - \frac{1}{r^{k-1}} \underbrace{\left(\frac{1}{k}\right) \left(\frac{r_v^k - 1}{r_v - 1}\right)}_{=1 \textit{ in the Otto Cycle}}$$

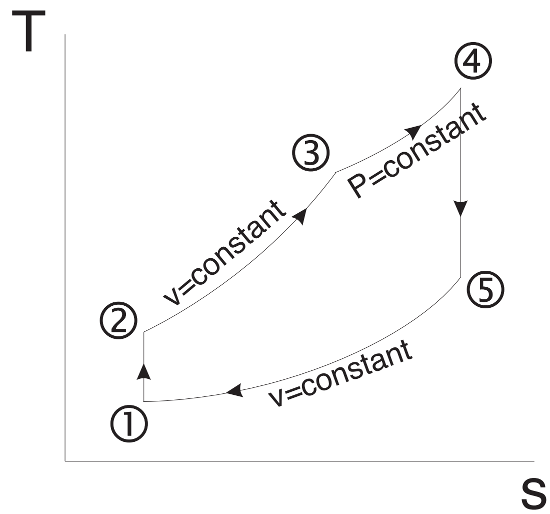
## Comparison of the Otto and the Diesel Cycle

- $\eta_{Otto} > \eta_{Diesel}$ for the same compression ratio
- but a diesel engine can tolerate a higher ratio since only air is compressed in a diesel cycle and spark knock is not an issue
- direct comparisons are difficult

## Dual Cycle (Limited Pressure Cycle)

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




| | |
|---|---|
| 1 - 2 | isentropic compression |
| 2 - 3 | constant volume fuel injection and initial combustion |
| | $\longrightarrow$ modelled as a reversible, constant volume heat addition |
| 3 - 4 | isobaric expansion as the fuel burns |
| | $\longrightarrow$ modelled as a reversible, isobaric heat addition |
| 4 - 5 | isentropic expansion |
| 5 - 1 | exhausting of spent gases |
| | $\longrightarrow$ modelled as a constant volume heat rejection process |

## Dual Cycle Efficiency

Given

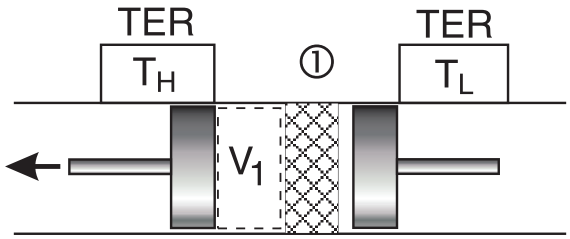
$$
\begin{aligned}
r &= \frac{V_1}{V_2} = compression\, ratio \\
r_v &= \frac{V_4}{V_3} = cutoff\; ratio \\
r_p &= \frac{P_3}{P_2} = pressure\, ratio
\end{aligned}
$$

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

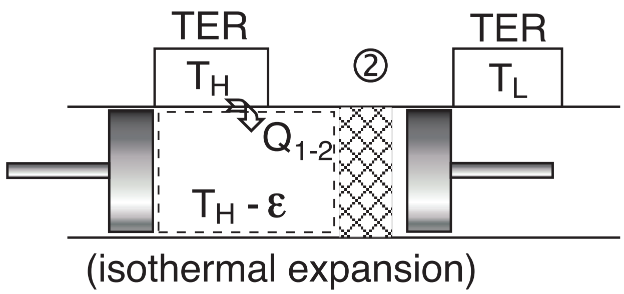
Note: if $r_p = 1$ we get the diesel efficiency.

## Stirling Cycle

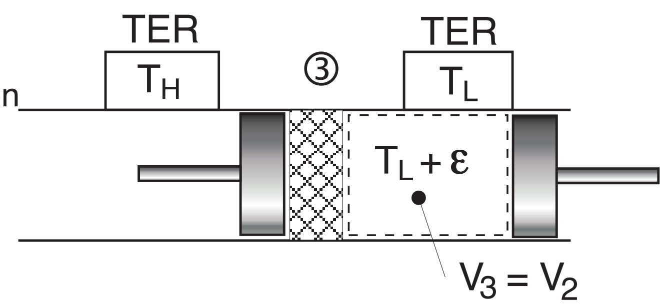
① → ②
isothermal expansion
at high temperature
- heat is added,
volume expands




② → ③
constant volume
process

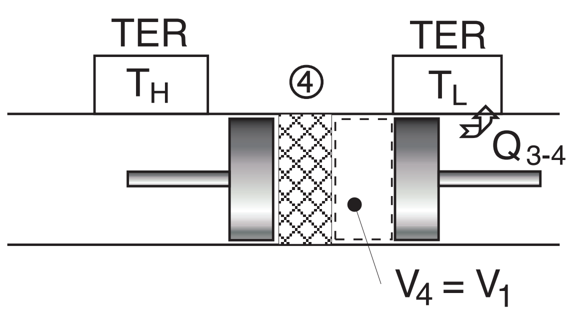



③ → ④
isothermal compression
at low temperature

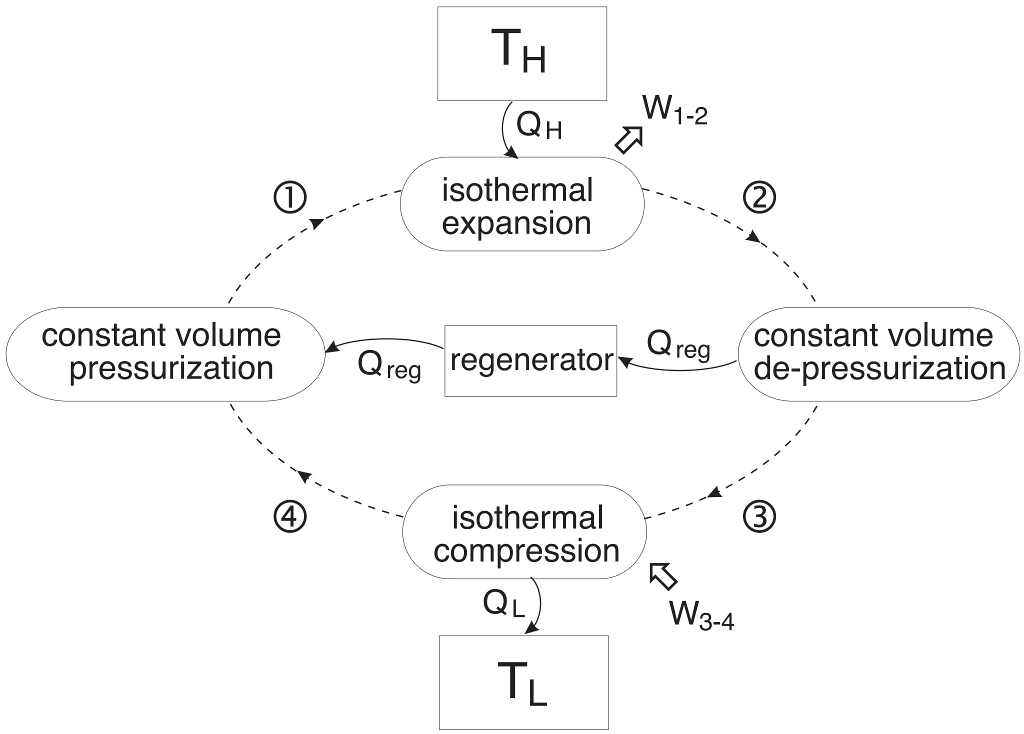


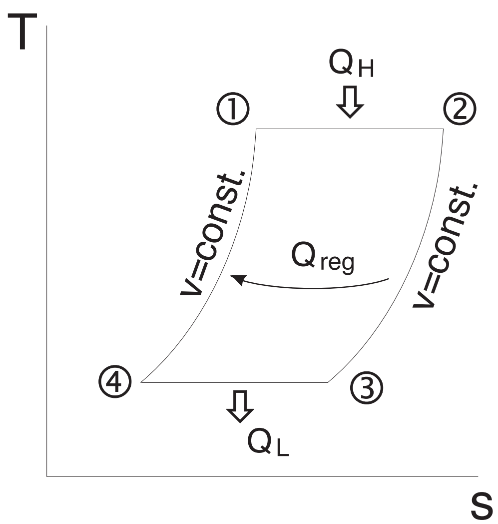

heat the regenerator
by pushing the hot
gas through it

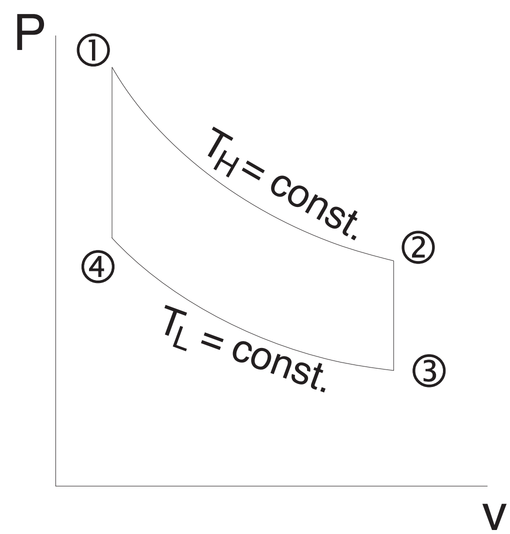
④ → ①
constant volume
process



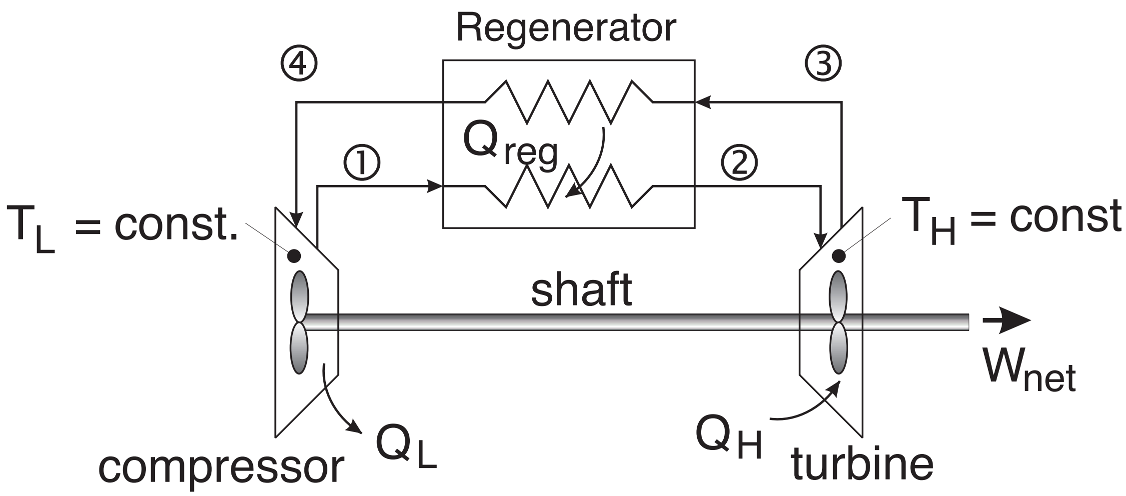

move both pistons
to the left to get back
to state 1.
During this process the
regenerator cools down
by giving off energy to
the gas


$T_H$
$Q_H$
$W_{1\text{-}2}$
①
isothermal expansion
②
constant volume pressurization
$Q_{reg}$
regenerator
$Q_{reg}$
constant volume de-pressurization
④
isothermal compression
③
$Q_L$
$W_{3\text{-}4}$
$T_L$

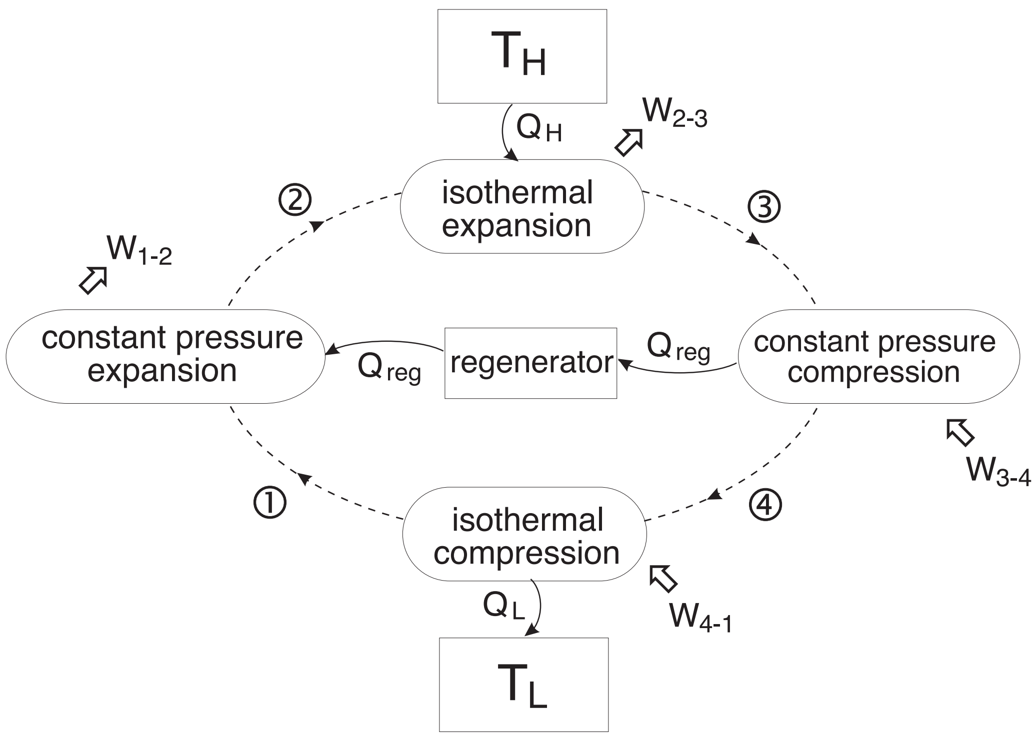

T
$Q_H$
①
②
v=const.
$Q_{reg}$
v=const.
④
③
$Q_L$
s


P
①
$T_H$= const.
②
④
$T_L$ = const.
③
v

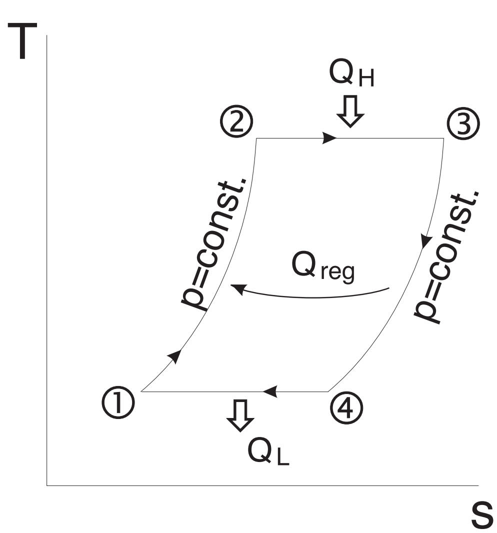
## Ericsson Cycle



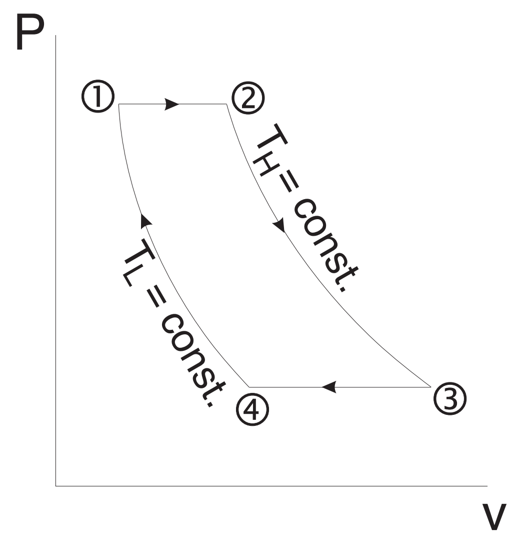

- hardware is not complicated
- but it is very difficult to operate turbines and compressors isothermally
- can approach isothermal conditions by repeated intercooling (compressor) and repeated reheating (turbines)
- $\eta_{Ericsson} = 1 - T_L/T_H$ (Carnot efficiency)



TH
QH
W2-3
isothermal expansion
②
③
W1-2
constant pressure expansion
regenerator
Qreg
Qreg
constant pressure compression
W3-4
①
④
isothermal compression
QL
W4-1
TL

T
QH
②
③
p=const.
Qreg
p=const.
①
④
QL
s

P
①
②
TH= const.
TL = const.
④
③
v