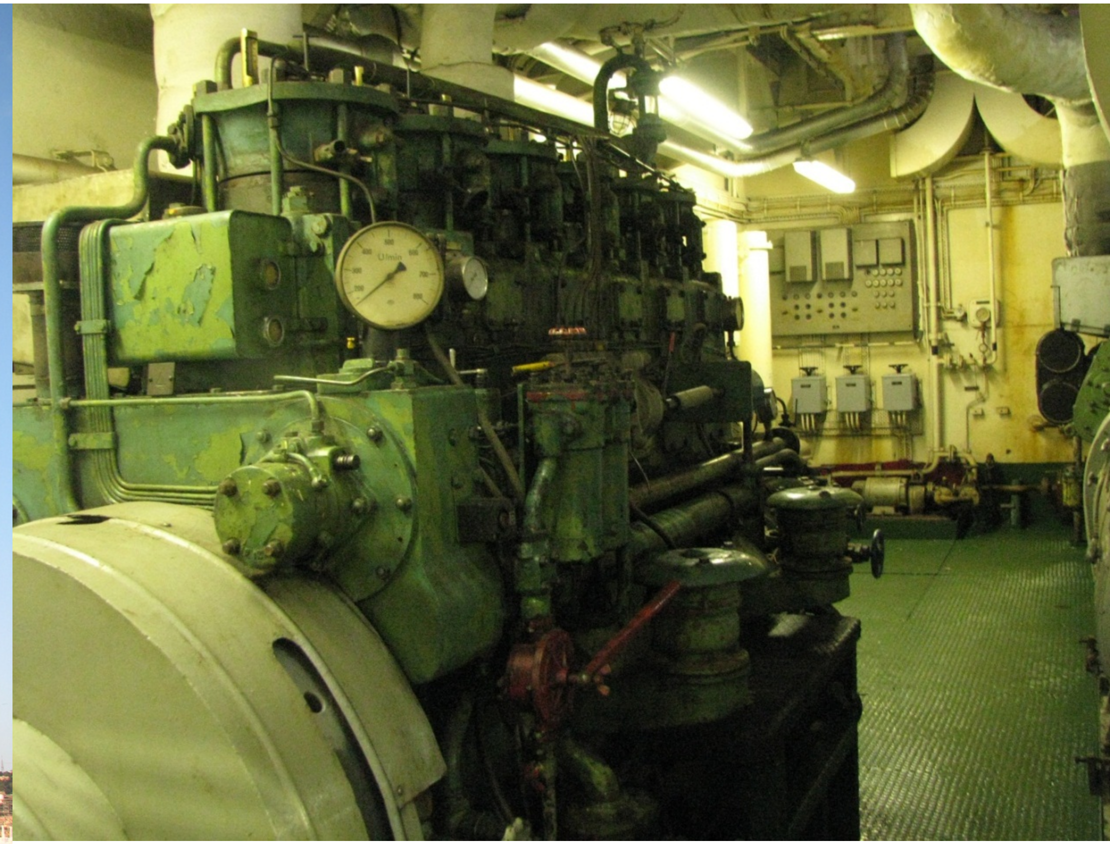
Class 14: Gas Power Cycles Reciprocating Combustion Engines



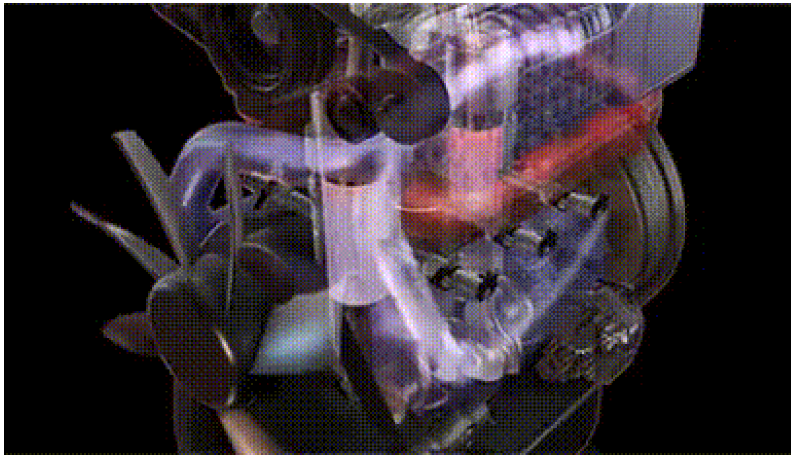
Diesel engine to power a crane (Langer Heinrich) on a platform for work on the sea

G.G.M. Stoffels

Thermal Engineering, University of Twente

Content Class 14

- In Thermo 1 in module 2 we have introduced theory and tools to study thermodynamic systems that produce power or cold (class 1 – 6)
- We have seen vapor power cycles (Rankine cycle) that produce work using a working fluid that changes phase during the cycle (class 7, 8)
- We have seen gas turbine cycles (Brayton cycle) that produce power using gas through the whole cycle as the working fluid (class 10, 11)
- We have seen refrigeration cycles that use power to transport heat from cold to hot (class 13)
- Class 14 is about gas cycles pertaining to reciprocating engines
  - Open & closed cycles
  - Air standard cycle
  - Stirling cycle (video 18a)
  - Otto cycle (video 18a)
  - Diesel cycle (video 18b)



Open and Closed Gas Power Cycles

- **Gas power cycles** use gas as working fluid (WF) throughout the cycle
- **Closed cycle**
  - Working fluid completely sealed (not exchanged with environment)
  - External "Combustion" (EC), nuclear, geothermal, solar energy possible
  - Helium common working fluid
    - Light atoms → fast motion → efficient heat transfer
    - Non-flammable (unlike H_2)
    - Low C_P → added heat efficiently converted into higher pressure
  - Example: **Stirling cycle**

A solar powered Stirling engine is an example of a closed gas power cycle

Open and Closed Gas Power Cycles

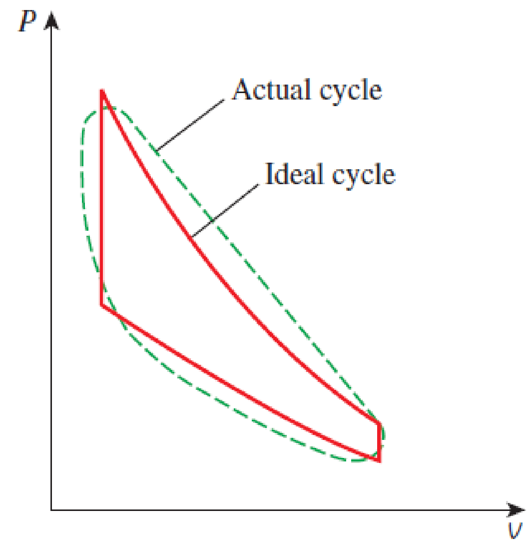
- **Gas power cycles** use gas as working fluid (WF) throughout the cycle

- **Open cycle**
  - Working fluid exchanged with environment (intake & exhaust)
  - Internal Combustion (IC) inside the system
  - Working fluid: Air + Fuel → Air + Combustion Products
  - Examples:
    - Otto
    - Diesel
    - Brayton (Gas Turbine)

The Air Standard Cycle

- The **air standard cycle** is a simplifying approximation of the real gas cycles

- This approximation is
  - Good for comparing trends
  - Good for comparing systems
  - Not good for detailed analyses

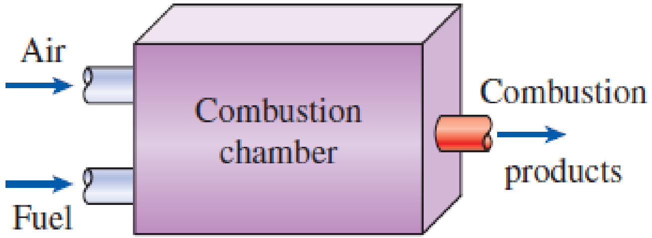


The analysis of many complex processes can be reduced to a manageable level by utilizing some idealizations

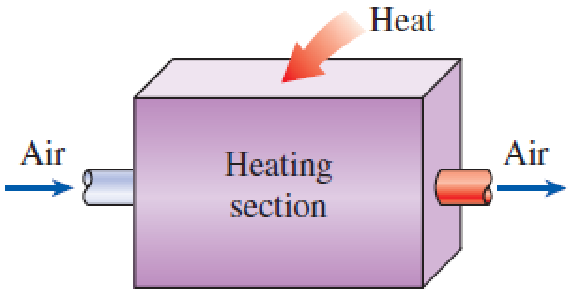
- Another assumption
  - Constant specific heats: **Ideal air standard cycle**
  - Constant specific heats at room temperature 25^{0}C: **Cold ideal air standard cycle**

The Air Standard Cycle

- Assumptions for the **air standard cycle**
- The working fluid is dry air, which continuously circulates in a closed loop and always behaves as an ideal gas ($Pv=RT$) (consequently fuel and combustion products are neglected)
- All the processes that make up the cycle are internally reversible
- The combustion process is replaced by a heat-addition process from an external source



(*a*) Actual

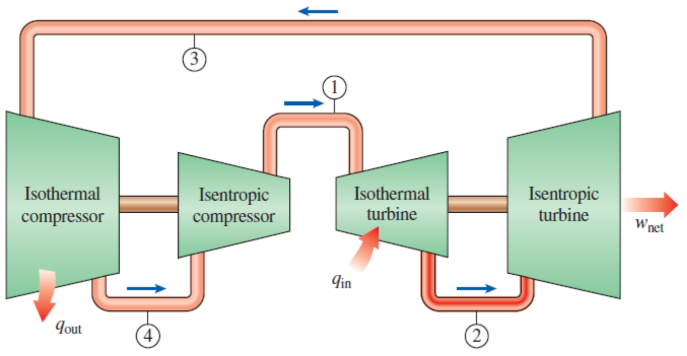


(*b*) Ideal

- The intake and exhaust processes are replaced by a heat transfer processes to the surroundings

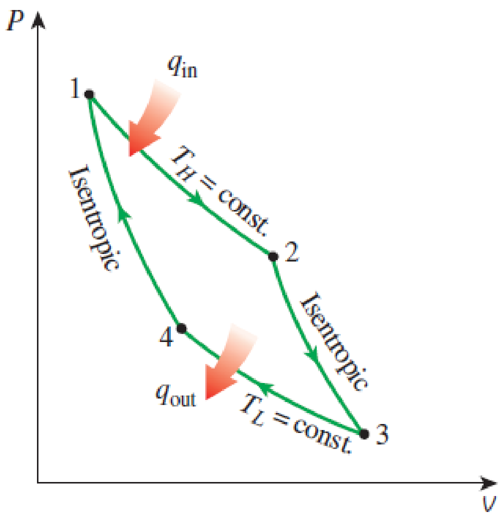
Recap Carnot Cycle

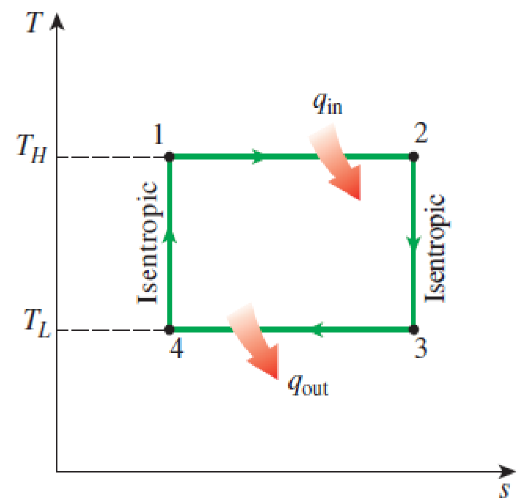
- The **Carnot cycle** is composed of four totally reversible processes:
  - isothermal heat addition
  - isentropic expansion
  - isothermal heat rejection
  - isentropic compression
- Thermal efficiency: $\eta_{CarnotT} = 1 - \frac{T_{COLD}}{T_{HOT}}$



A steady-flow Carnot engine

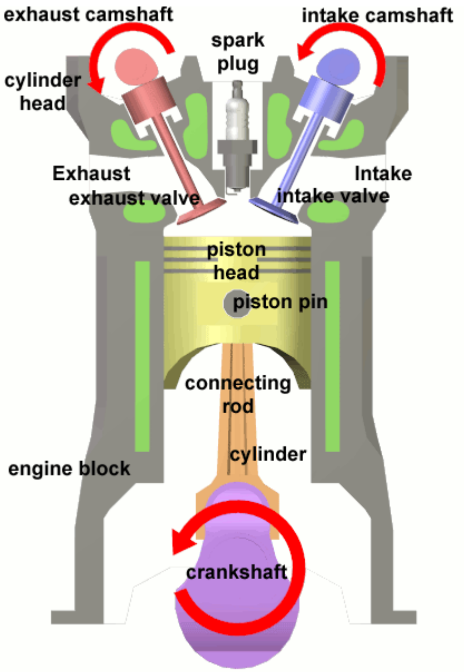
- For both ideal and actual cycles, the thermal efficiency increases with an increase in the average temperature at which heat is supplied to the system or with a decrease in the average temperature at which heat is rejected from the system





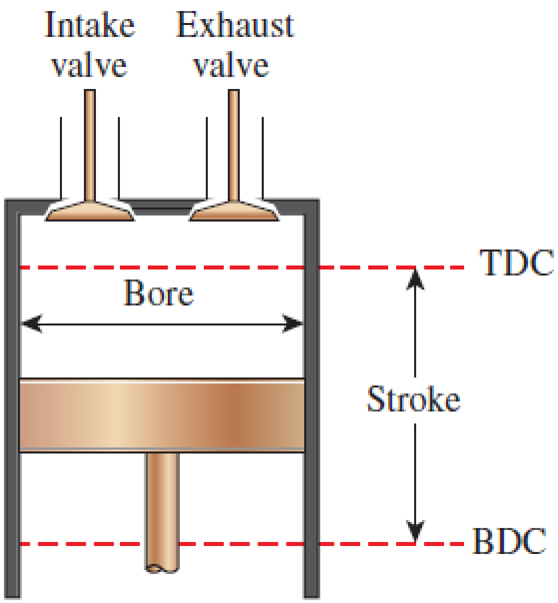
Reciprocating Engines

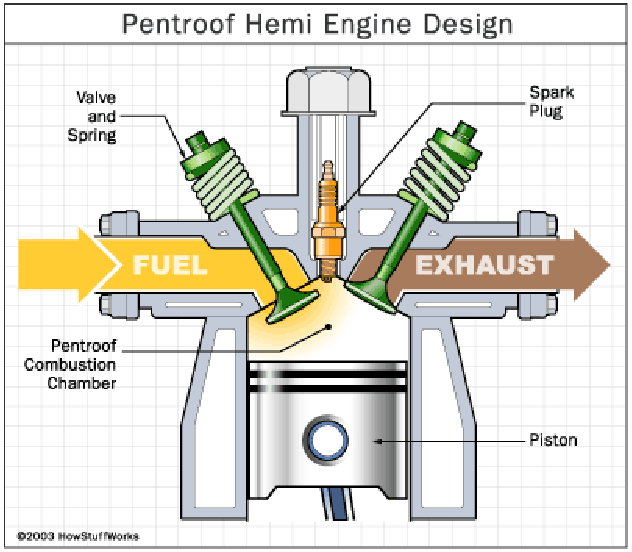
- A reciprocating engine, also known as a piston engine, is typically a heat engine that uses one or more reciprocating pistons to convert pressure into a rotating motion, the main types are:
  - the internal combustion engine, used extensively in motor vehicles
  - the steam engine, the mainstay of the industrial revolution
  - the Stirling engine, a niche application
- The last two are external combustion engines, heat is added from an external heat sources
- Internal combustion engines are classified in
  - spark-ignition (SI) engines, where the spark plug initiates the combustion (gasoline or petrol engines working on an Otto cycle)
  - compression-ignition (CI) engine, where the air within the cylinder is compressed, thus heating it, so that the heated air ignites fuel that is injected then or earlier (Diesel engines)
- The process can be executed in 2 or 4 strokes



Nomenclature Reciprocating Cycles

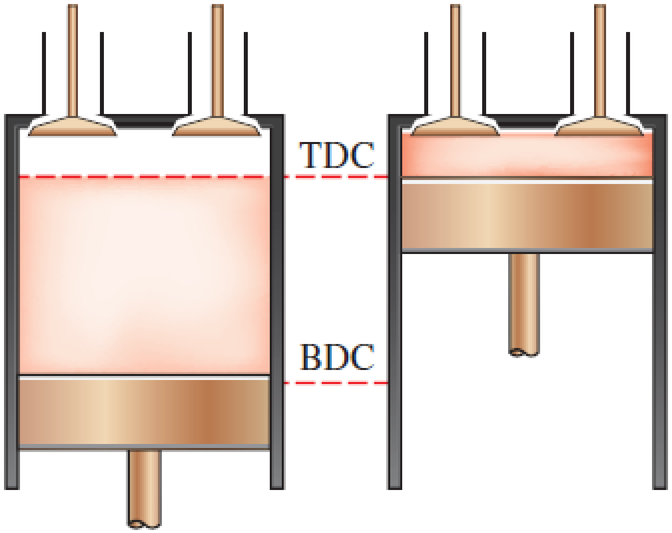
- Bore = cylinder diameter
- BDC = Bottom Dead Center, lowest position cylinder
- TDC = Top Dead Center, highest position cylinder
- Stroke = distance between TDC and BDC





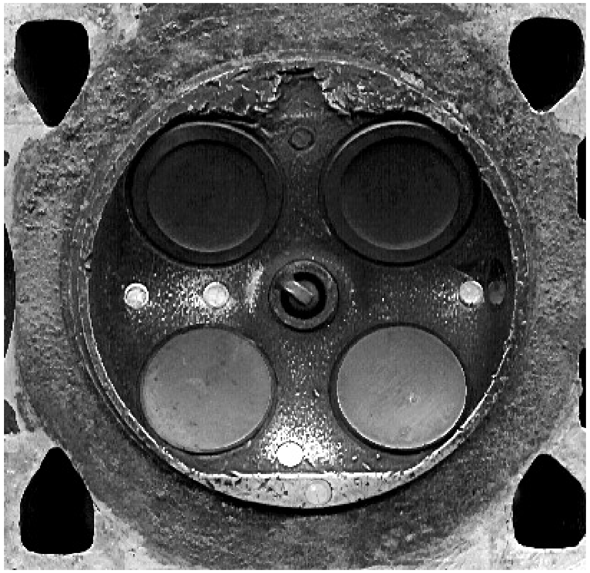
Nomenclature Reciprocating Cycles

- Swept or displacement volume = volume refreshed during a stroke
- Clearance volume = volume TDC position = minimum volume
- Maximum volume = clearance volume + swept volume



(*a*) Displacement volume

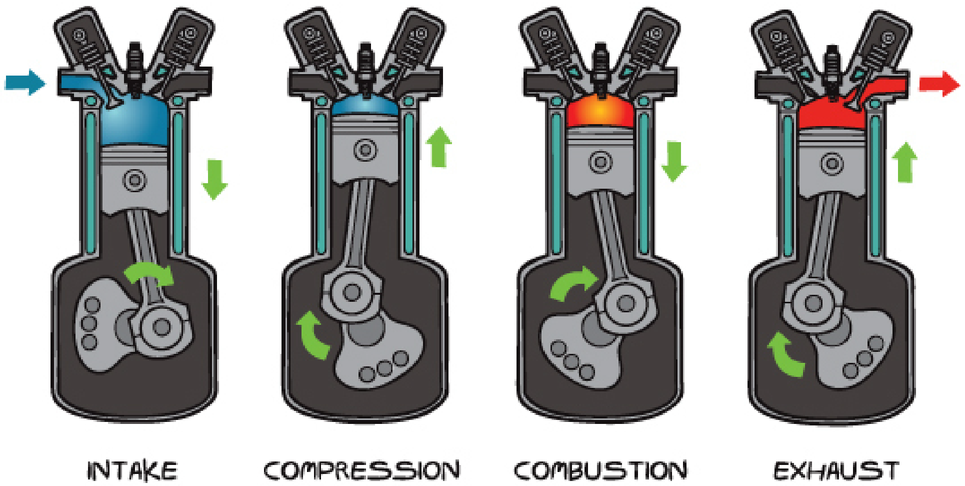
(*b*) Clearance volume



Cylinder Head Rover Twin Cam 1.6l

4 stroke internal combustion engines

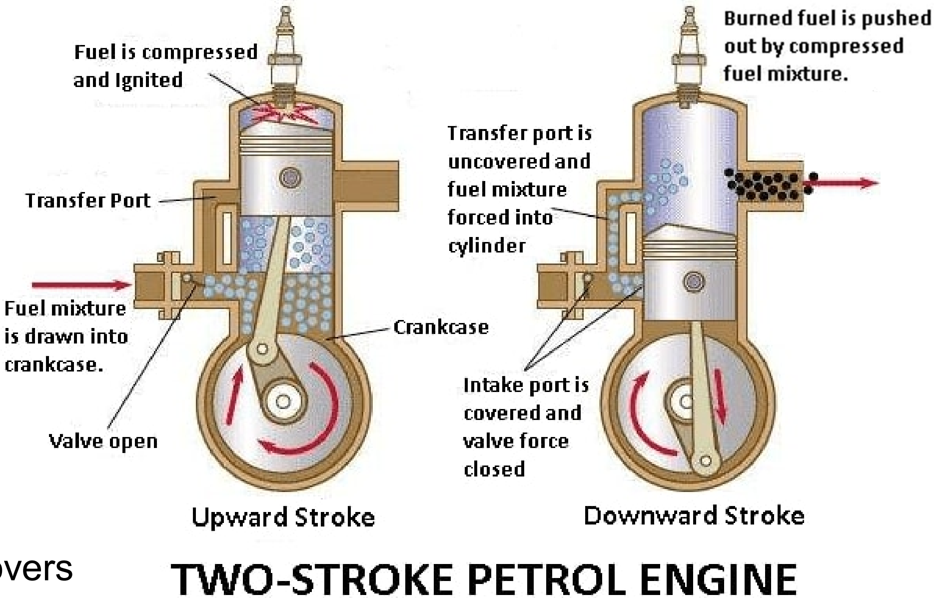
- A four-stroke engine is an internal combustion engine in which the piston completes four separate strokes while turning the crankshaft. A stroke refers to the full travel of the piston along the cylinder, in either direction. The four separate strokes are:
- **Intake:** This stroke of the piston begins at TDC and ends at BDC, the intake valve must be in the open position while the piston pulls an air-fuel mixture into the cylinder by producing vacuum pressure into the cylinder through its downward motion. The piston is moving down as air is being sucked in by the downward motion against the piston.
- **Compression:** This stroke begins at BDC, or just at the end of the intake stroke, and ends at TDC, the piston compresses the air-fuel mixture in preparation for ignition. Both the intake and exhaust valves are closed during this stage.
- **Combustion:** This is the start of the second revolution of the four stroke cycle. At this point the crankshaft has completed a full 360 degree revolution. While the piston is at TDC, the compressed air-fuel mixture is ignited, forcefully returning the piston to BDC. This stroke produces mechanical work from the engine to turn the crankshaft.
- **Exhaust:** During the exhaust stroke, the piston, once again, returns from BDC to TDC while the exhaust valve is open. This action expels the spent air-fuel mixture through the exhaust valve.



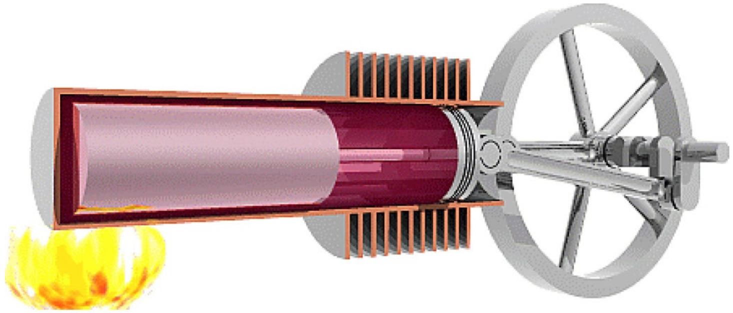
2 stroke internal combustion engines

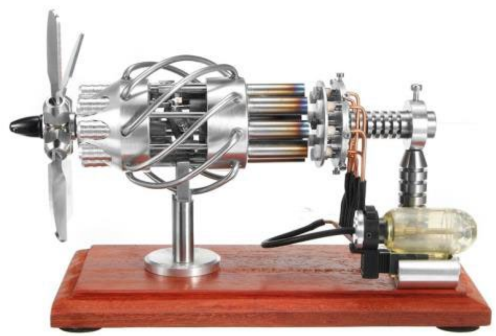
- A two-stroke engine is a type of internal combustion engine that completes a power cycle with two strokes (up and down movements) of the piston during only one crankshaft revolution
- This is in contrast to a "four-stroke engine", which requires four strokes of the piston to complete a power cycle during two crankshaft revolutions. In a two-stroke engine, the end of the combustion stroke and the beginning of the compression stroke happen simultaneously, with the intake and exhaust (or scavenging) functions occurring at the same time
- The two-stroke engines are generally less efficient than their four-stroke counterparts but they are relatively simple and inexpensive, and they have high power-to-weight and power-to-volume ratios

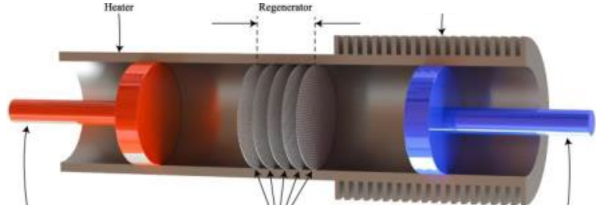
Two stroke engines are commonly used in motorcycles and lawn movers



The Stirling Cycle

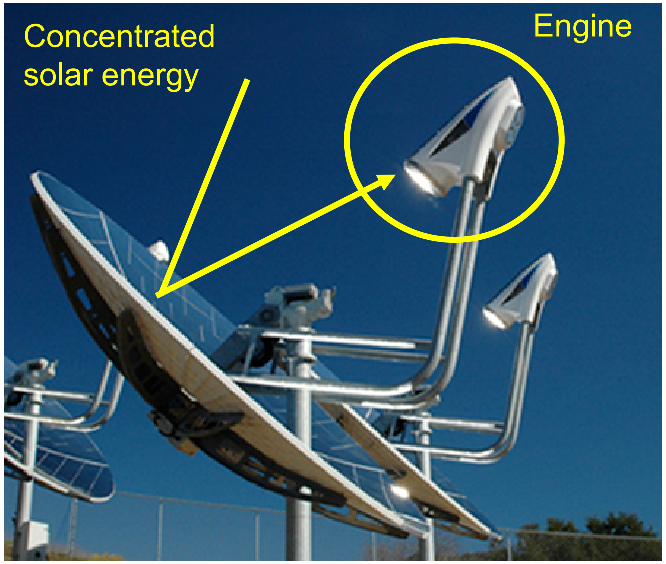






The Stirling Cycle

- The Stirling cycle is the oldest gas cycle
- It is developed by Robert Stirling in 1816
- It is a closed cycle → external heating
- It consists of 2 isochoric processes and 2 isothermal processes
- It uses a regenerator to recover heat from the exhaust gasses



Solar powered Stirling engine

- It is very efficiency, as the processes are reversible, in the ideal case its efficiency is the Carnot efficiency

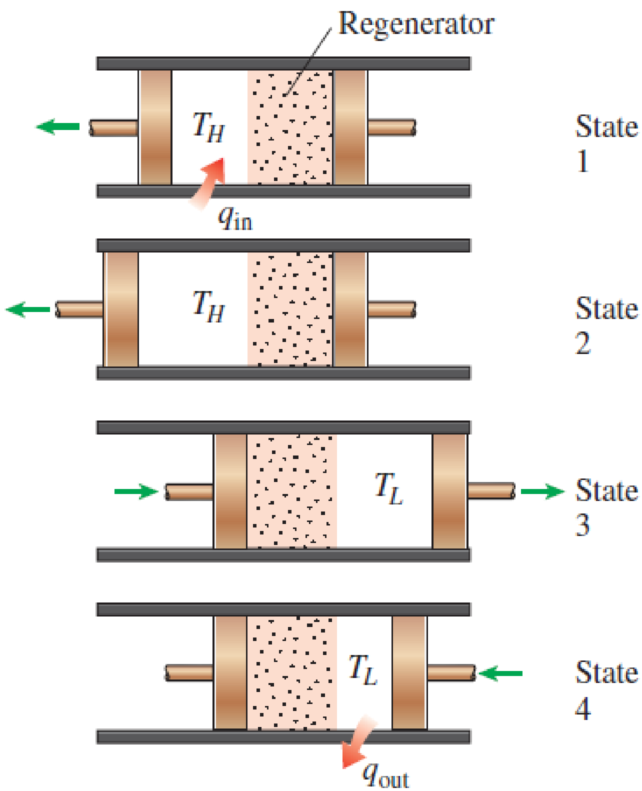
$$\eta_{Stirling,rev} = \eta_{CarnotT} = 1 - \frac{T_{COLD}}{T_{HOT}}$$

- However, it is difficult to manufacture in practice
- There are different configurations, for example one or two cylinders

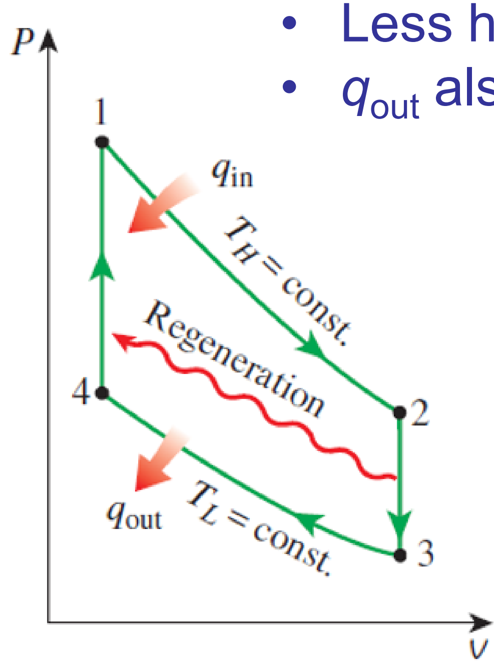

Robert Stirling

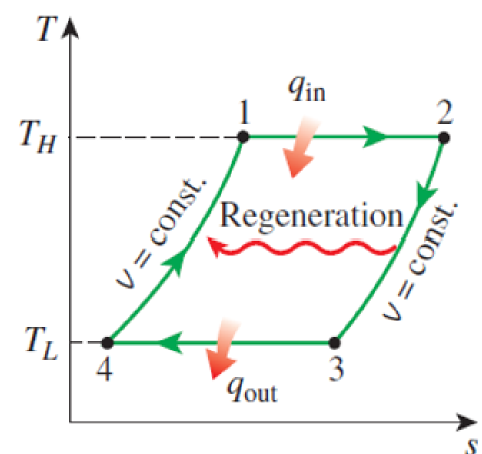
Principle of the Stirling Cycle

1 → 2 Isothermal expansion (heat addition fro external source)
2 → 3 Isochoric heat rejection (internal heat transfer from the working fluid to the regenerator)
3 → 4 Isothermal compression (heat rejection to the external sink)
4 → 1 Isochoric heat addition (internal heat transfer from the regenerator back to the working fluid)



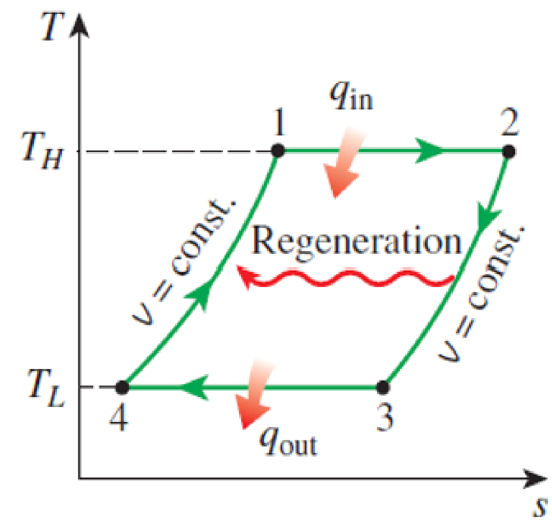
Regenerator:
- Less heat q_{in} required ($q_{in} - q_R$)
- q_{out} also reduced ($q_{out} - q_R$)





Stirling Cycle Analysis

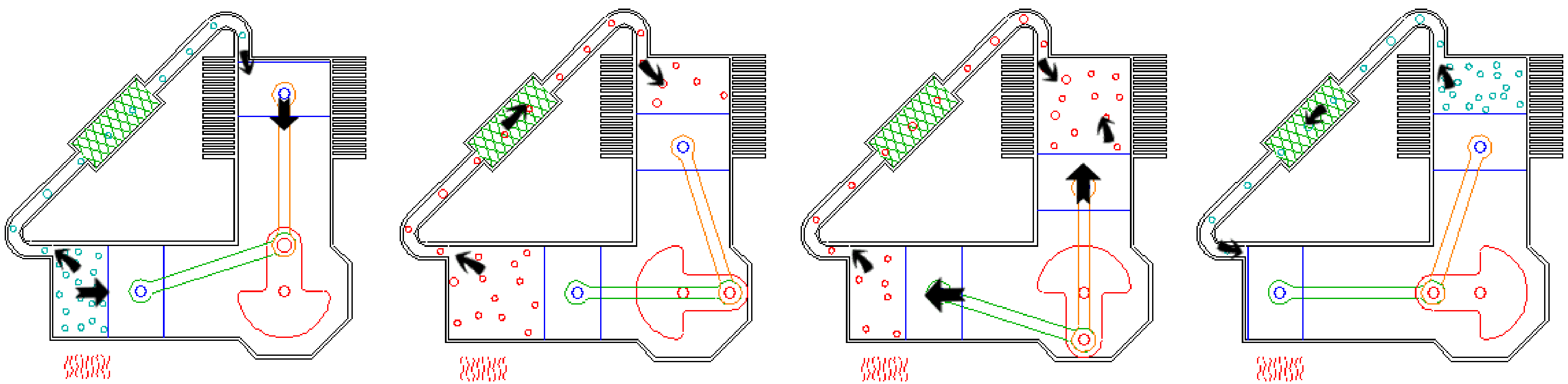
- Compression ratio: $r_V = v_{max}/v_{min} = v_2/v_1$
- Ideal gas: $Pv = RT$
- Regeneration
  - Use waste heat from 2 → 3 as input for 4 → 1
  - Reduces q_{IN} and q_{OUT} by same amount q_R
  - Increases the efficiency: $1 - \frac{q_{out} - q_R}{q_{in} - q_R} = \frac{q_{in} - q_{out}}{q_{in} - q_R}$



Process	q	w	Const Prop	Other Relations
1 ⟶ 2	q_{IN}	w_{OUT}	T $(T_1 = T_2)$	$q_{IN} = w_{OUT}$ and $\delta w_{OUT} = Pdv$
2 ⟶ 3	$q_{REGEN,OUT}$	0	v $(v_2 = v_3)$	$q_{REGEN,OUT} = q_{REGEN,IN}$
3 ⟶ 4	q_{OUT}	w_{IN}	T $(T_3 = T_4)$	$q_{OUT} = w_{IN}$ and $\delta w_{IN} = -Pdv$
4 ⟶ 1	$q_{REGEN,IN}$	0	v $(v_4 = v_1)$	-

Two Cylinder Stirling Engine

- The Stirling is a very simple engine, and was often billed as a safe alternative to steam, since there's no risk of a boiler explosion.
- It enjoyed some success in industrial applications, and also in small appliances like fans and water pumps, but it was eclipsed by the advent of inexpensive electric motors
- However, because it can run on any source of heat, it now holds promise for alternative fuel engines, solar power, geothermal power, etcetera
- Stirling engines feature a completely closed system in which the working gas (usually air but sometimes helium or hydrogen) is alternately heated and cooled by shifting the gas to different temperature locations within the system
- In the two-cylinder (or *alpha configured*) Stirling, one cylinder is kept hot while the other is kept cool. In this illustration, the lower-left cylinder is heated by burning fuel. The other cylinder is kept cool by air circulating through a heat sink (a.k.a. cooling fins). The Stirling cycle can be thought of as four different phases: expansion, transfer, contraction, and transfer



1: Expansion
Most of the gas in the system has just been driven into the hot cylinder. The gas heats and expands driving both pistons inward.

2: Transfer
The gas has expanded (about 3 times in this example). Most of the gas (about 2/3) is still located in the hot cylinder. Flywheel momentum carries the crankshaft the next 90 degrees, transferring the bulk of the gas to the cool cylinder.

3: Contraction
The majority of the expanded gas has shifted to the cool cylinder. It cools and contracts, drawing both pistons outward.

4: Transfer
The contracted gas is still located in the cool cylinder. Flywheel momentum carries the crank another 90 degrees, transferring the gas to back to the hot cylinder to complete the cycle.

Not for the exam

An animation can be found on: http://www.animatedengines.com/vstirling.html

Single Cylinder Stirling Engine

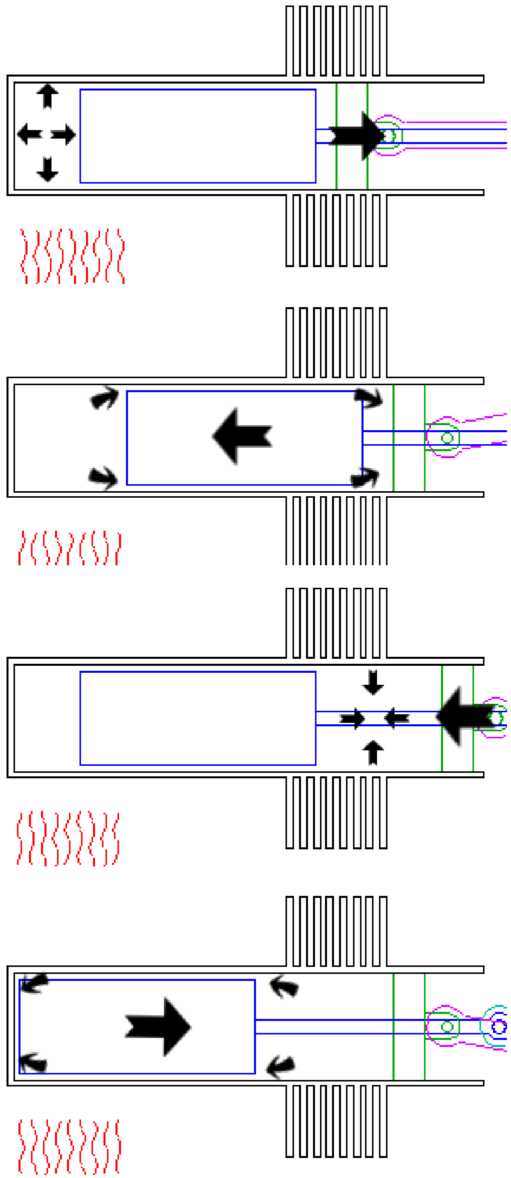
- This type of Stirling engine, known as the beta configuration, features just one cylinder with a hot end and a cool end.
- The working gas is transferred from one end of the cylinder to the other by a device called a displacer (illustrated in blue).
- The displacer resembles a large piston, except that it has a smaller diameter than the cylinder, thus its motion does not change the volume of gas in the cylinder—it merely transfers the gas around within the cylinder.
- The same four phases of the Stirling cycle are at work in this engine

1: Expansion
Most of the gas in the system has just been driven to the hot end of the cylinder. The gas heats and expands, driving the piston outward.

2: Transfer
The gas has expanded. Most of the gas is still located in the hot end of the cylinder. Flywheel momentum carries the crankshaft the next quarter turn. The bulk of the gas is transferred around the displacer to the cool end of the cylinder.

3: Contraction
The majority of the expanded gas has shifted to the cool end. The gas cools and contracts, drawing the piston inward.

4: Transfer
The contracted gas is still located near the cool end of the cylinder. Flywheel momentum carries the crank another quarter turn, moving the displacer and transferring the bulk of the gas back to the hot end of the cylinder

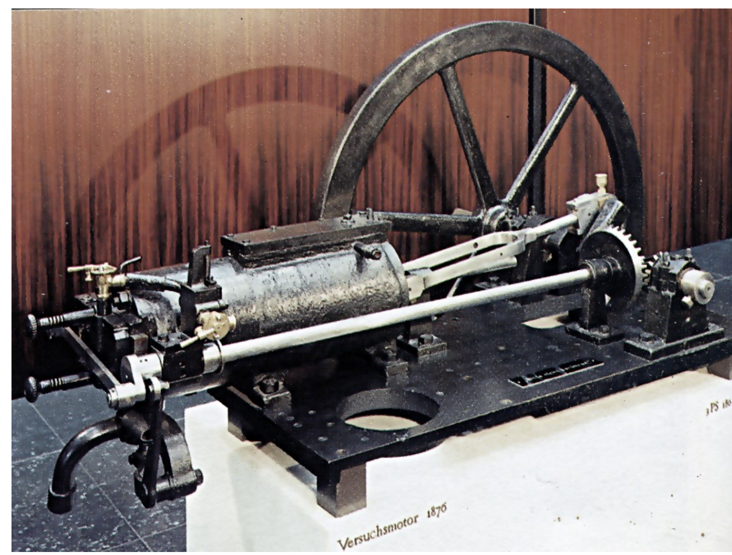


An animation can be found on: http://www.animatedengines.com/stirling.html

Not for the exam

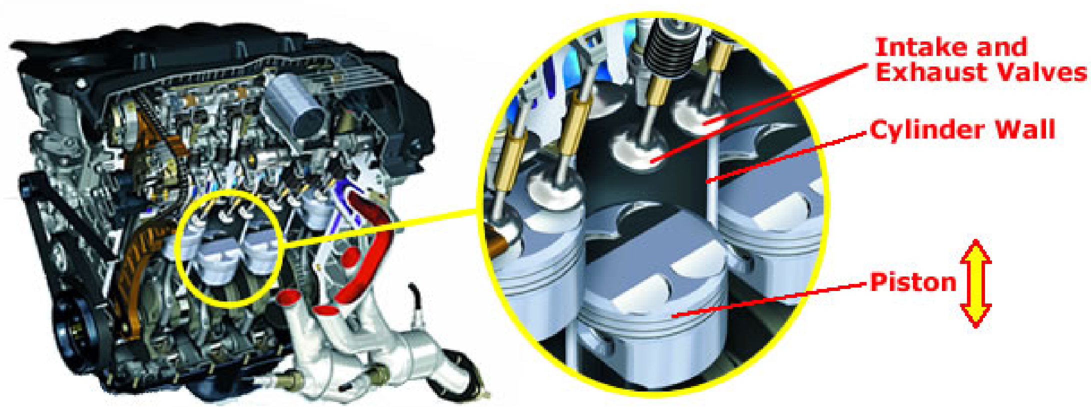
The Otto Cycle

Nicolaus Otto & his 1876 four cycle engine



The Otto Cycle

- **The Otto cycle**
  - It is an idealization of the internal combustion gasoline engine cycle developed by Nikolaus August Otto (around 1878)
  - It is executed in a reciprocating piston-cylinder device
  - In practice it is an open cycle gas powered internal combustion engine, however it is modeled as a closed cycle
  - It consists of 2 constant volume and 2 constant entropy processes
  - The combustion starts using spark ignition
  - It can be a 2 or 4 stroke process

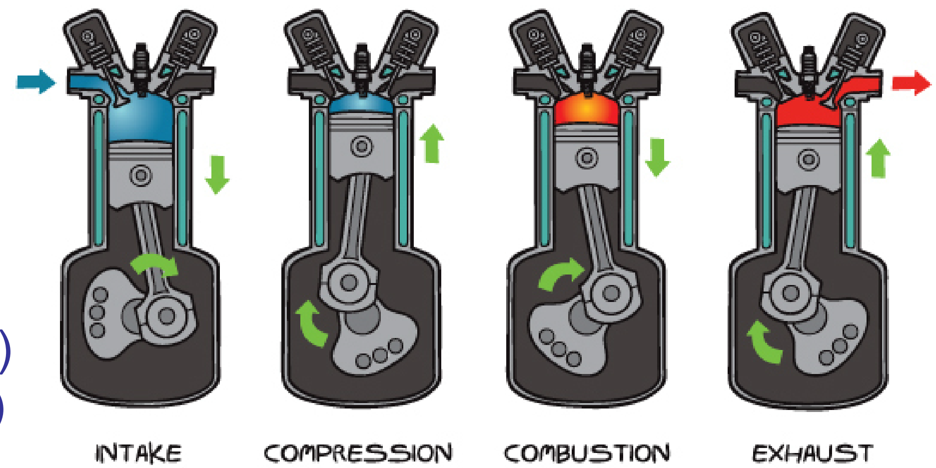


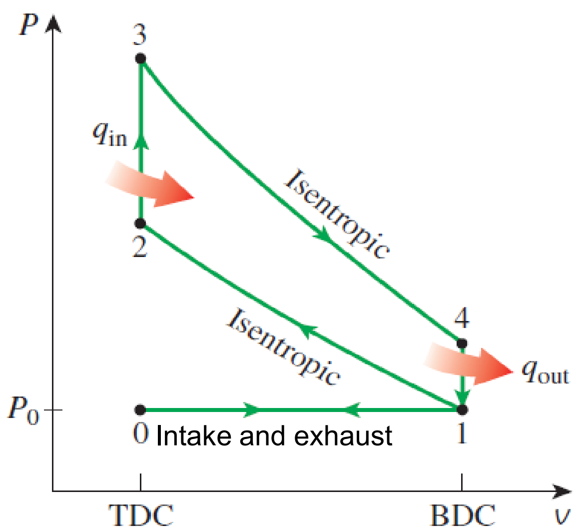
Cutaway view of 4-Cylinder Gasoline Engine (Image Courtesy BMW)

ThermoNet: Wiley

Principle of the Otto Cycle

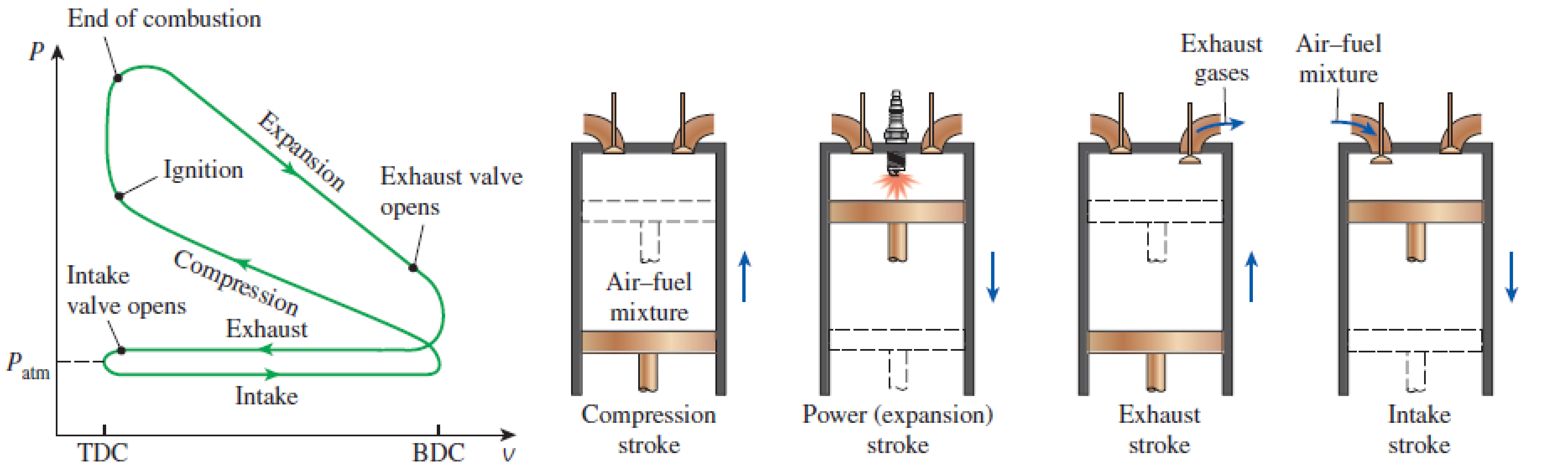
- **Stroke 1, intake**
  - $0 \rightarrow 1$ inlet fresh air
- **Stroke 2, compression**
  - $1 \rightarrow 2$ isentropic compression (w_{in})
  - $2 \rightarrow 3$ isochoric heat addition (q_{in})
- **Stroke 3, combustion**
  - $3 \rightarrow 4$ isentropic expansion (w_{out})
  - $4 \rightarrow 1$ isochoric heat rejection (q_{out})
- **Stroke 4, exhaust**
  - $1 \rightarrow 0$ outlet air-fuel mixture



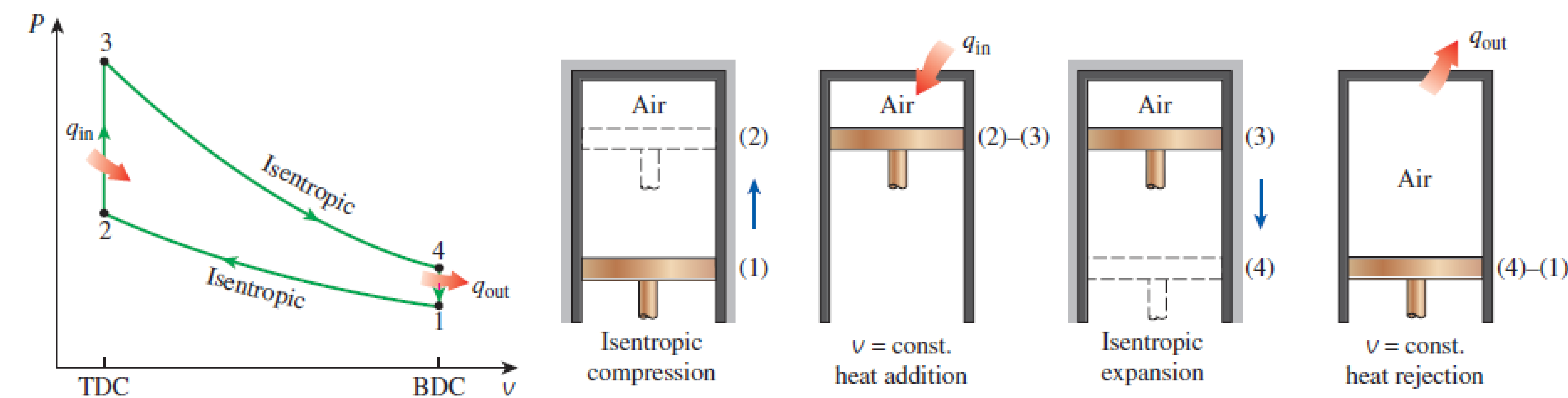


- **Stroke 1 and 4**
- Work interactions during intake and exhaust cancel each other, and thus inclusion of the intake and exhaust processes has no effect on the net work output from the cycle
- In modeling they are ignored, however, when calculating the power output from the cycle during, we must consider the fact that the ideal cycle has four strokes just like the actual four-stroke engine

The Actual and Ideal Otto Cycle



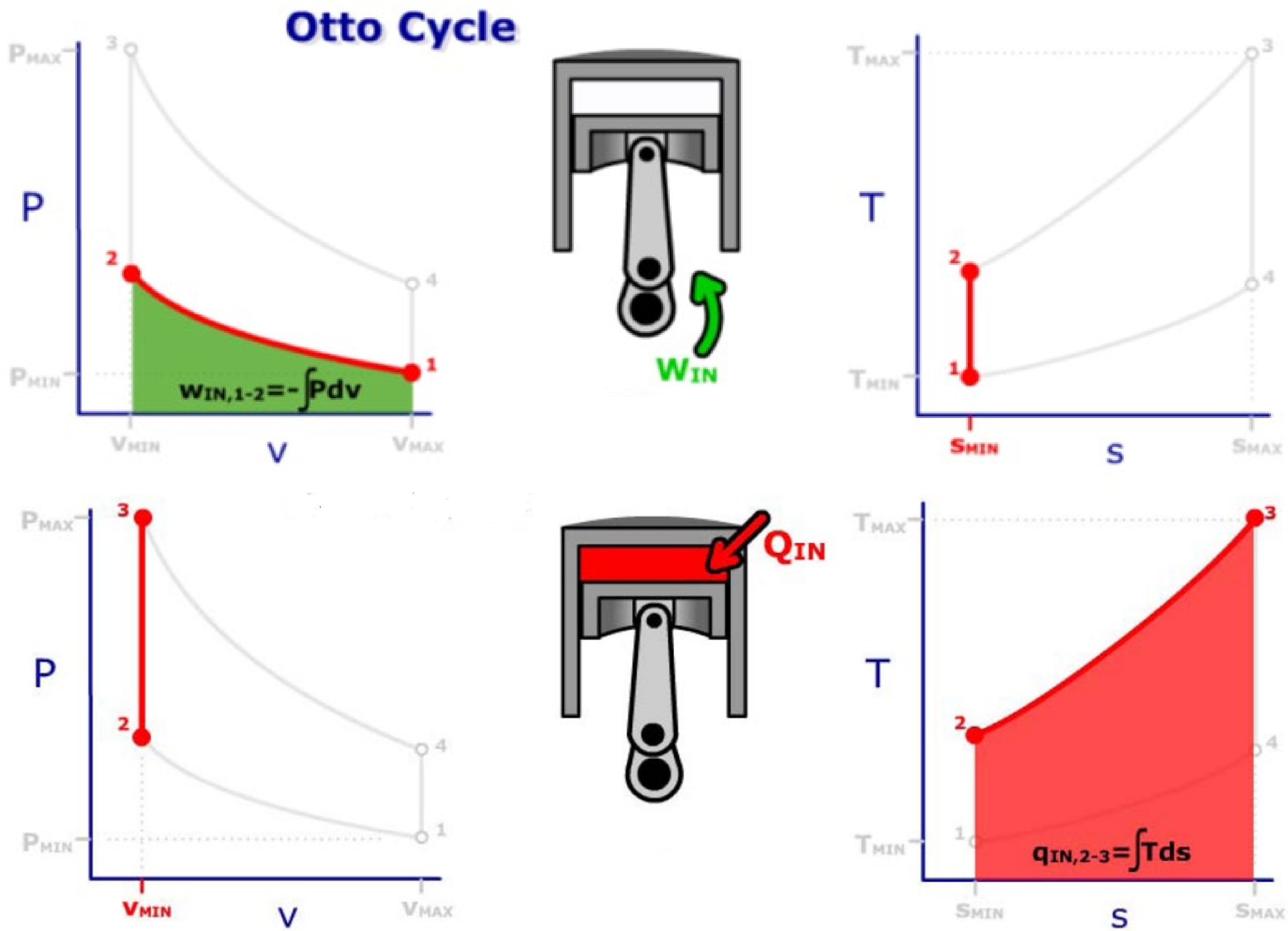
(*a*) Actual four-stroke spark-ignition engine



(*b*) Ideal Otto cycle

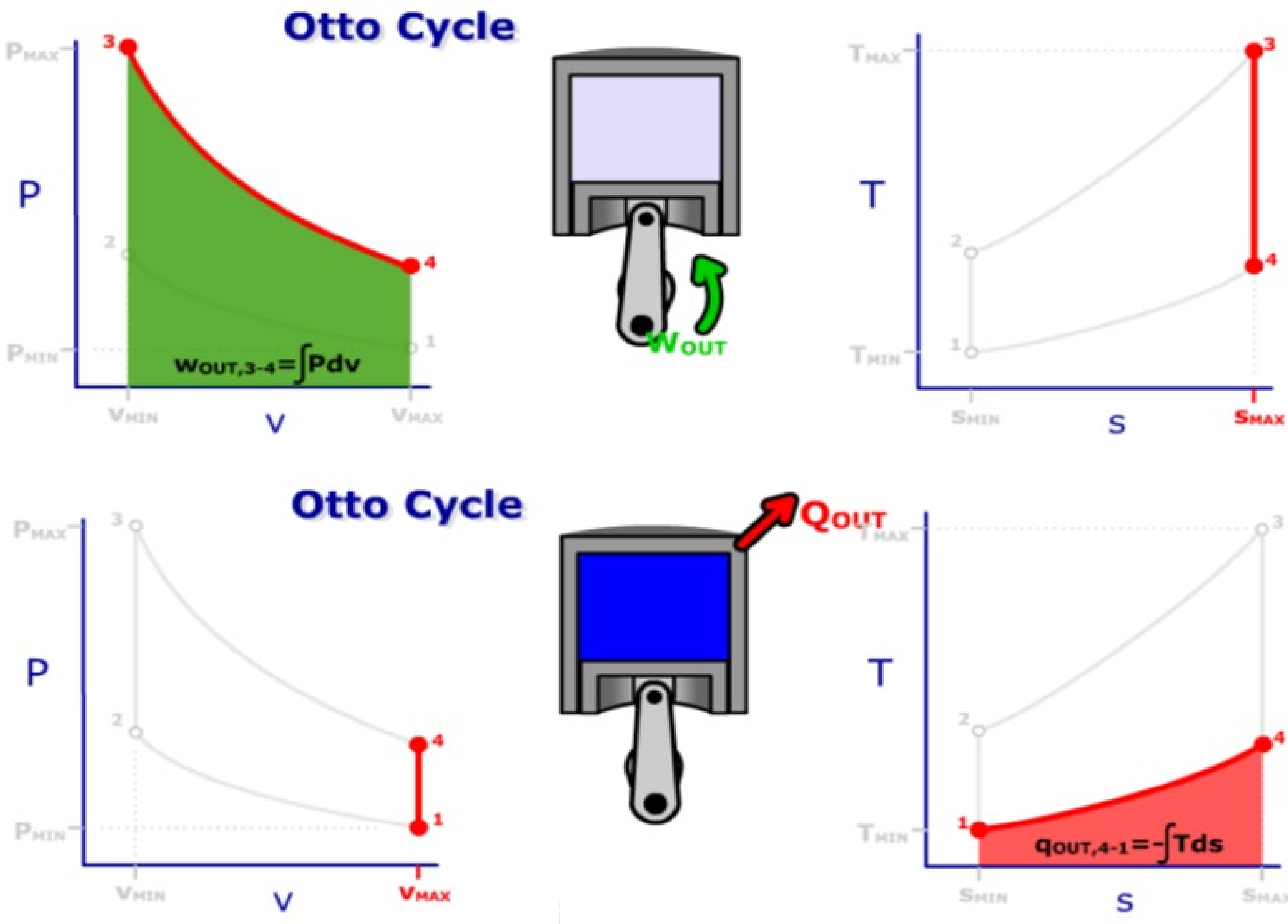
In the analysis the intake and exhaust stroke are neglected

The Otto Cycle



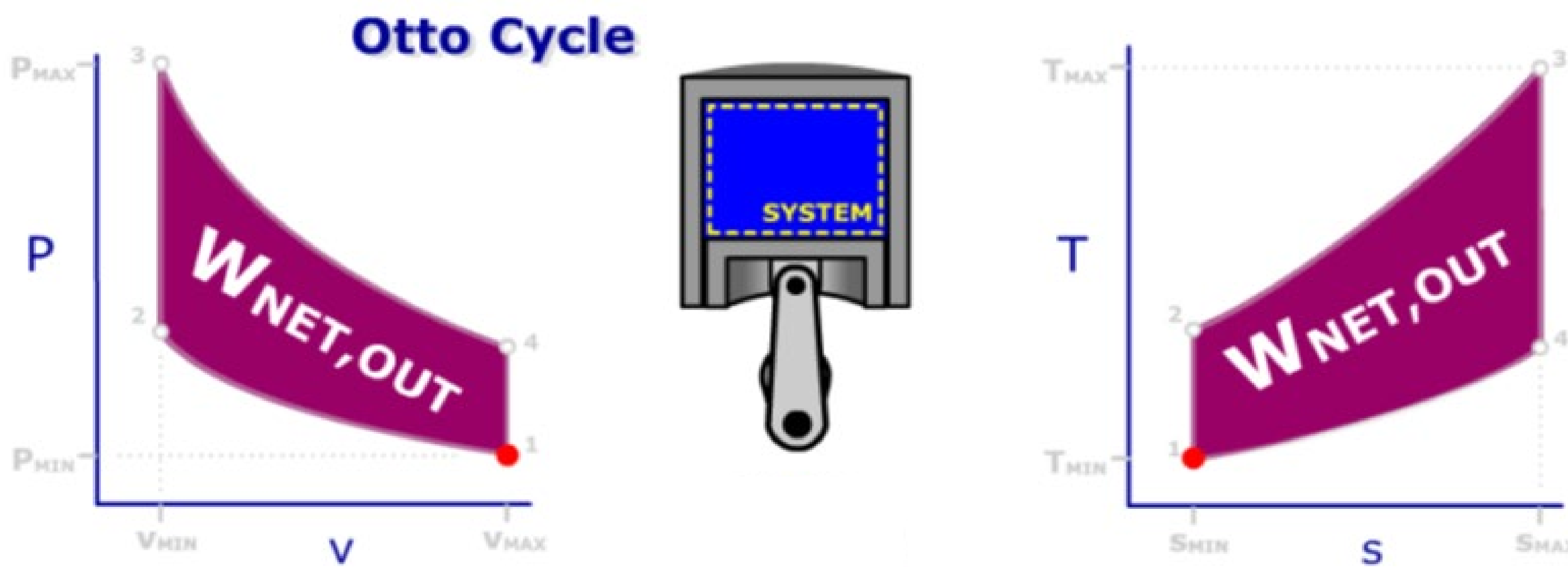
The area below the Pv diagram indicates the work input during compression and the area below the Ts diagram indicates the heat input

The Otto Cycle



The area below the Pv diagram indicates the work output during expansion and the area below the Ts diagram indicates the heat output

The Otto Cycle



Process	Q	W	Type
1 → 2	0	W_{IN}	Isentropic
2 → 3	Q_{IN}	0	Isometric
3 → 4	0	W_{OUT}	Isentropic
4 → 1	Q_{OUT}	0	Isometric

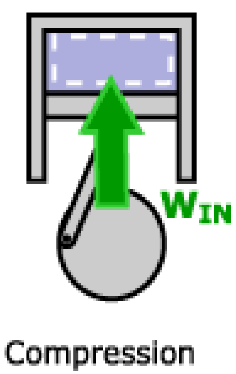
State	T	P	v	s
1	T_{MIN}	P_{MIN}		
2				$s_2=s_1$
3	T_{MAX}	P_{MAX}	$v_3=v_2$	
4			$v_4=v_1$	$s_4=s_3$

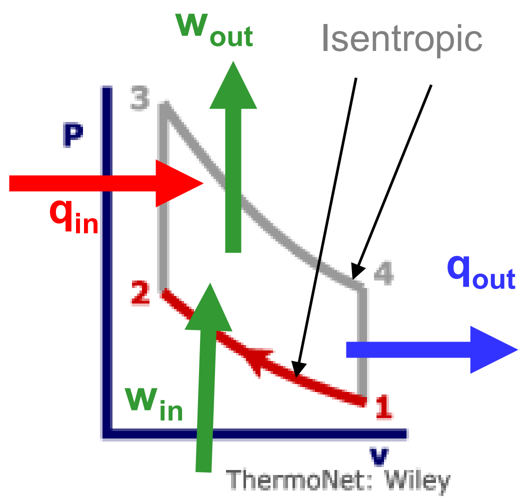
The area enclosed in the the Pv diagram indicates the net work output and the area enclosed in the Ts diagram indicates the net heat input of the cycle

For a cycle these are the same: $w_{net} = q_{net}$

Otto Cycle Analysis

- Otto cycle modeled as a closed ideal air standard cycle
- **Important formulas (our tools)**
  - Ideal gas: $Pv = RT$ (for all processes)
    - For example: $P_3T_2 = P_2\,T_3$
  - Isentropic processes (1 - 2 and 3 - 4):
    - $Pv^k = constant \quad (k=c_p/c_v)$
      - For example: $P_1v_1^k = P_2v_2^k$
    - $Tv^{(k-1)} = constant$
    - $TP^{(1-k)/k} = constant$





Isentropic relations:
See Class 9, and Çengel 7.9

  - First law closed system: $\Delta u = (q_{in} - q_{out}) + (w_{out} - w_{in})$
  - $\Delta u = c_v\Delta T$
    - For example: $w_{in} = w_{(1\text{-}2)} = \Delta u_{(1\text{-}2)} - q_{(1\text{-}2)} = u_2 - u_1 = c_v(T_2 - T_1)$
  - Compression ratio: $r_V = v_{max}/v_{min} = v_1/v_2 = v_4/v_3$
  - $P_{max} = P_3$, $P_{min} = P_1$ and $T_{max} = T_3$, $T_{min} = T_1$

Work and Heat Otto Cycle

- Work in- and output Otto cycle: Ideal air standard analysis

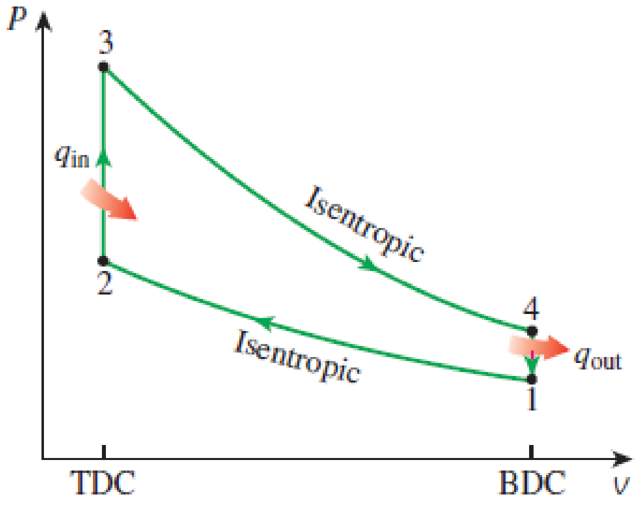
- The **work input** is between point 1 and 2
- $w_{in} = w_{1\text{-}2}$, for this process the heat is zero: $q_{1\text{-}2} = 0$
- The first law states: $\Delta u_{a\text{-}b} = q_{a\text{-}b} + w_{a\text{-}b}$
- Therefore: $w_{in} = w_{1\text{-}2} = u_2 - u_1 = c_v(T_2 - T_1)$

- The **work output** is between point 3 and 4
- $w_{out} = w_{3\text{-}4}$ the heat is also zero: $q_{3\text{-}4} = 0$
- Similar, the work output is:

$$w_{out} = w_{3\text{-}4} = u_3 - u_4 = c_v(T_3 - T_4)$$

- The **net work output** is: $w_{net} = w_{3\text{-}4} - w_{1\text{-}2}$

$$w_{net} = c_v(T_3 - T_4) - c_v(T_2 - T_1)$$



Heat in- and output Otto Cycle

- Heat in- and output Otto cycle: Ideal air standard analysis

- The **heat input** is between point 2 and 3
- $q_{in} = q_{2\text{-}3}$, for this process the work is zero as $v = constant$, $w_{2\text{-}3} = 0$
- The first law states: $\Delta u_{a\text{-}b} = q_{a\text{-}b} + w_{a\text{-}b}$
- Therefore: $q_{in} = q_{2\text{-}3} = u_3 - u_2 = c_v(T_3 - T_2)$

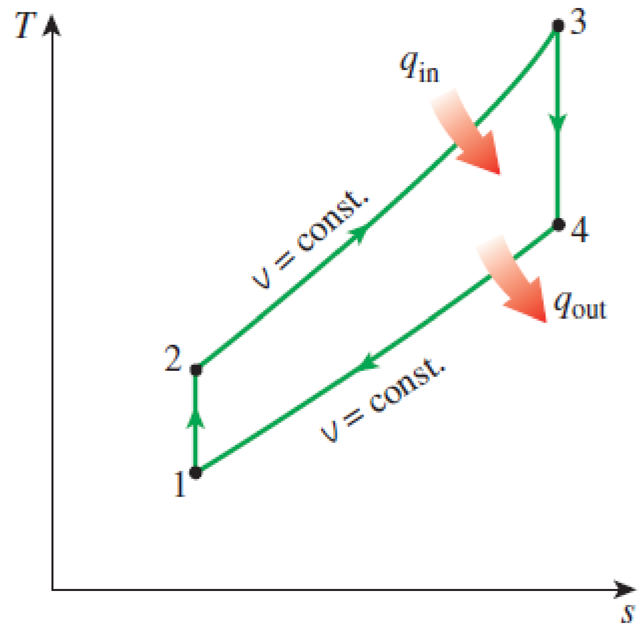
- The **heat output** is between point 4 and 1
- $q_{out} = q_{4\text{-}1}$ the work is also zero:, $w_{4\text{-}1} = 0$
- Similar, the heat output is:

$$q_{out} = q_{4\text{-}1} = u_4 - u_1 = c_v(T_4 - T_1)$$

- The **net heat input** is $q_{net} = q_{2\text{-}3} - q_{4\text{-}1}$

$$q_{net} = c_v(T_3 - T_2) - c_v(T_4 - T_1)$$

- This is equal to the net work output

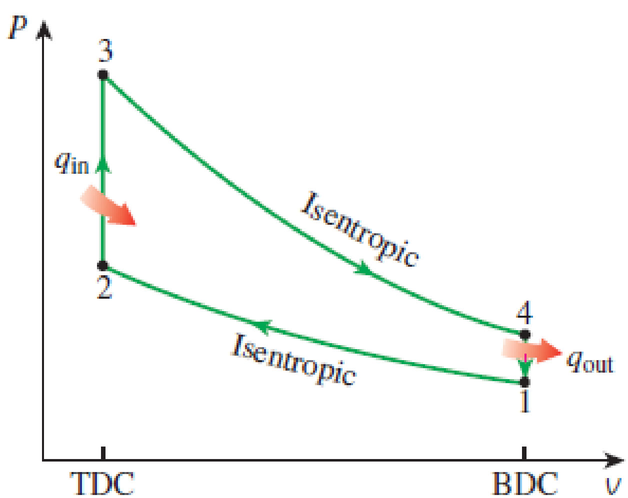


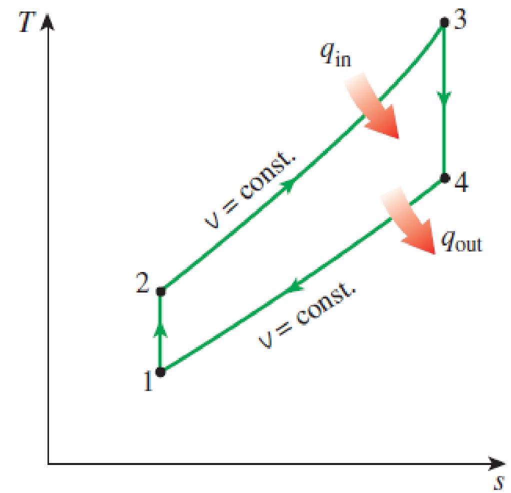
Net Work Output and Heat Input Otto Cycle

- **Net work output Otto cycle:** Ideal air standard analysis
  - $w_{net} = c_v(T_3 - T_4) - c_v(T_2 - T_1)$ [kJ/kg]

- **Heat input Otto cycle:** Ideal air standard analysis
  - $q_{in} = q_{2\text{-}3} = u_3 - u_2 = c_v(T_3 - T_2)$ [kJ/kg]

- These expressions give specific energies for one stroke only





Power Output Otto Cycle

- **What is the power output of an Otto engine?**

- A 4-stroke engine has 4 strokes and two turnings of the crank
- Only in one stroke and one turning power is delivered
- An Otto engine has many revolutions per minute (RPM)

- Therefore, the specific power is: $\dot{w}_{net} = w_{net} \frac{1}{2} \frac{RPM}{60} \quad [\mathrm{kJ/skg} = \mathrm{kW/kg}]$

- Otto engines mostly have more than 1 cylinder, the total mass of the gas in all cylinders should be considered to calculate the power

$$\dot{W}_{net} = m\dot{w}_{net} = mw_{net} \frac{1}{2} \frac{RPM}{60} \quad [\mathrm{kJ/s} = \mathrm{kW}]$$

Otto Cycle Efficiency

- The **efficiency of the Otto cycle** (Ideal air standard):

$$\eta_{\text{Otto, ias}} = \frac{\text{Wanted}}{\text{Payed for}} = \frac{w_{net}}{q_{in}} = \frac{w_{out} - w_{in}}{q_{in}} =$$

$$\frac{(u_3 - u_4) - (u_2 - u_1)}{(u_3 - u_2)} = \frac{c_v(T_3 - T_4) - c_v(T_2 - T_1)}{c_v(T_3 - T_2)}$$

- Which can be written as:

$$\eta_{\text{Otto, ias}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_4}{T_3} = 1 - \left(\frac{v_3}{v_4}\right)^{k-1} = 1 - \frac{1}{r_v^{k-1}}$$

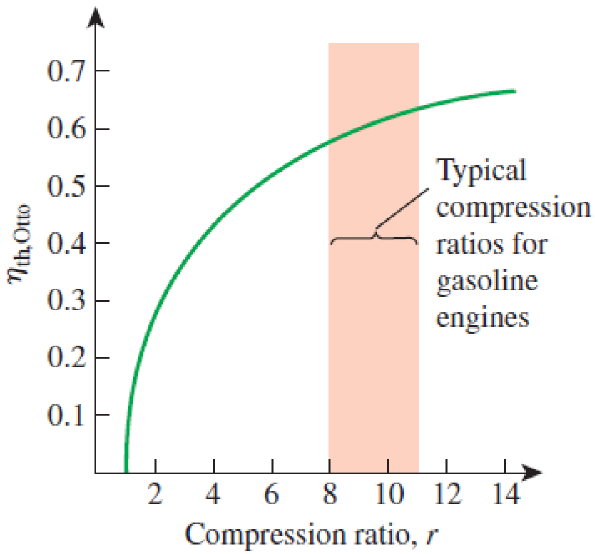
- The efficiency of **an ideal air-standard cycle** depends only on the compression ratio

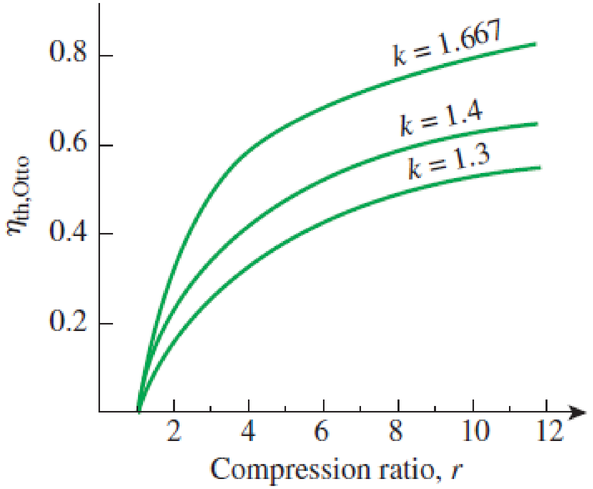
- Compare with the Carnot efficiency: $\eta_{CARNOT} = 1 - \frac{T_{COLD}}{T_{HOT}} = 1 - \frac{T_1}{T_3}$

- The Otto cycle efficiency is lower because heat addition and rejection are not reversible and isothermal

Efficiency of an Ideal Otto Cycle

- Efficiency of the ideal Otto cycle as a function of the compression ratio (top) and as a function of the specific heat ratio *k* of the working fluid (bottom)

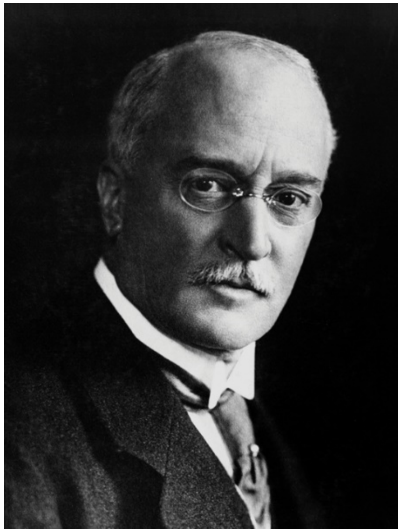




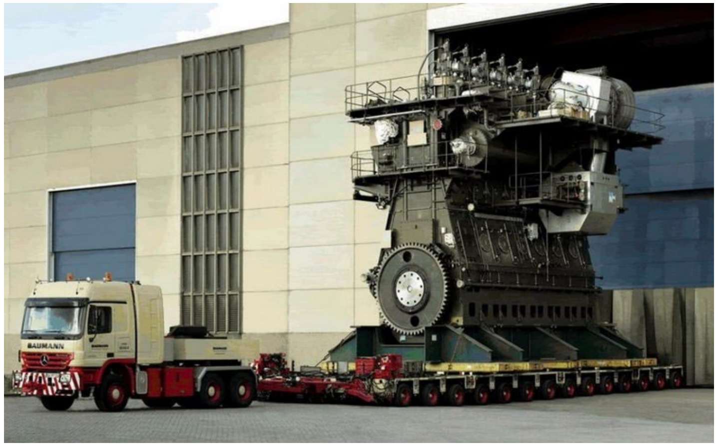
$$\eta_{\text{Otto, ias}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{1}{r_v^{k-1}}$$

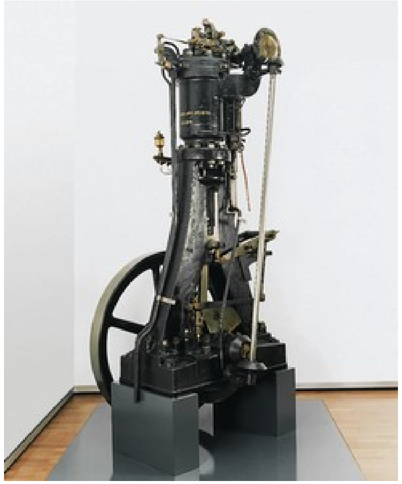
- Here:
  - $r_v = \frac{v_{max}}{v_{min}} = \frac{v_1}{v_2}$ (Compression ratio)
  - $k = \frac{c_p}{c_v}$
- The top figure shows that the efficiency of a gasoline engine, undergoing the Otto cycle, increase with a higher compression ratio
- The bottom figure shows that the efficiency increases with a higher specific heat ratio *k*, so with a larger difference in c_p and c_v

Diesel Cycle



Rudolph Diesel and the first Diesel engine

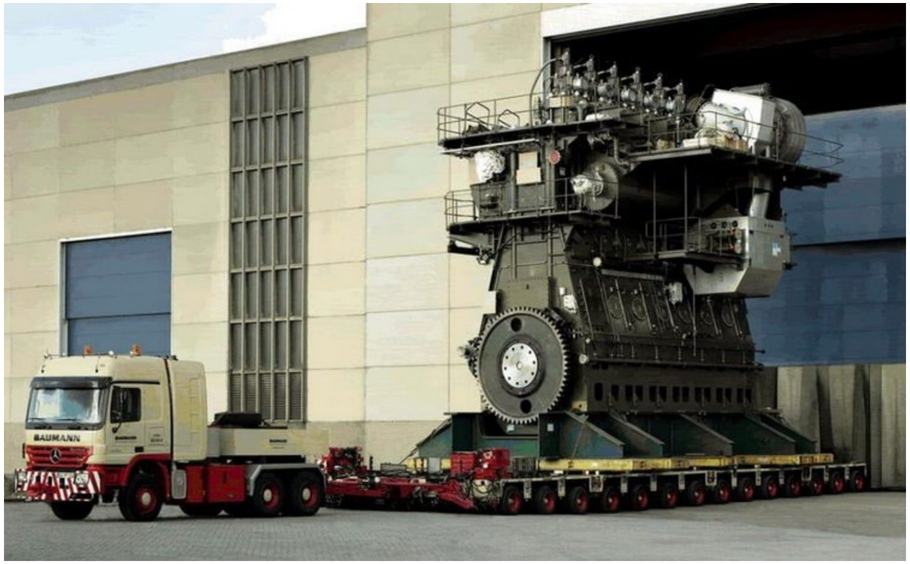




Wärtsilä-Sulzer RTA96-C

- We have seen the analysis of
  - the Stirling cycle, an external combustion reciprocating cycle
  - the Otto cycle, an internal combustion reciprocating cycle used in gasoline (petrol) engines
- Before we continue to the Diesel cycle an example to show how large they can be
- The Wärtsilä-Sulzer RTA96-C designed for large container ships that run on heavy fuel oil is the largest reciprocating engine in the world

Wärtsilä-Sulzer RTA96-C (right) used to power container ship Emma Maersk (above)



Wärtsilä-Sulzer RTA96-C

The engine has 14 massive cylinders and a huge camshaft. Its specs are given in the table

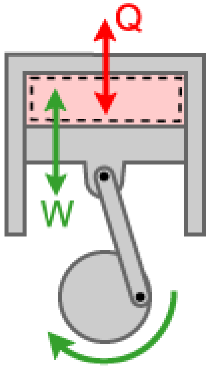
Technical data (as of 2008)

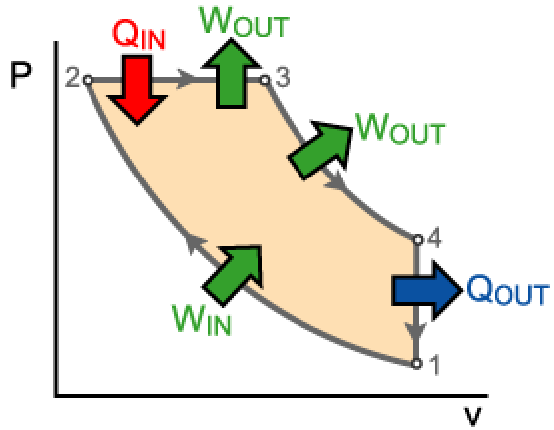
Configuration	Turbocharged two-stroke diesel straight engine, 6 to 14 cylinders
Bore	960 mm (38 in)
Stroke	2,500 mm (8.2 ft)
Displacement	1810 litres (110450 CI) per cylinder
Engine speed	22–120 RPM
Mean effective pressure	1.96 MPa @ full load, 1.37 MPa @ maximum efficiency (85% load)
Mean piston speed	8.5 meters per second
Best specific fuel consumption	160 g/(kW·h)[3][a]
Power	Up to 5,720 kW per cylinder, 34,320–80,080 kW (46,020–107,390 bhp) total
Torque	Up to 7,603,850 N·m (5,608,310 lbf·ft) @ 102 rpm
Power density	29.6–34.8 kW (39.7–46.7 bhp) per tonne, 2300 tonnes for the 14-cylinder version
Mass of fuel injected per cylinder per cycle	~160 g (5.6 oz) @ full load (Whole engine uses up to 250 tons of fuel per day.)
Crankshaft weight	300 t (660,000 lb)[1]
Piston weight	5.5 t (12,000 lb)
Piston height	6 m (20 ft)

https://en.wikipedia.org/wiki/W%C3%A4rtsil%C3%A4-Sulzer_RTA96-C

The Diesel Cycle

- **The Diesel cycle**
  - It is an idealization of the internal combustion Diesel engine cycle developed by Rudolph Diesel (1893)
  - It is executed in a reciprocating piston-cylinder device
  - It is an open cycle oil-fueled internal combustion engine, however it is modeled as a closed cycle
  - It consists of 2 constant entropy processes, 1 constant pressure and 1 constant volume process
  - Auto-ignition occurs due to high P & T

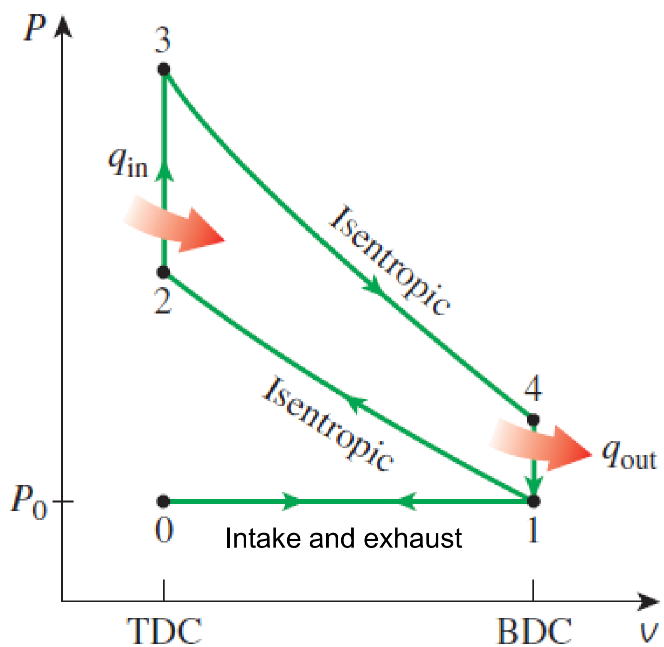


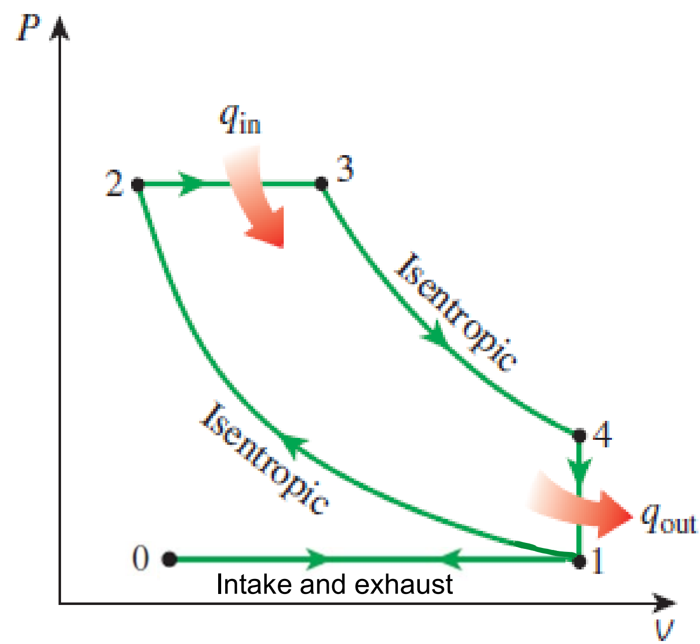


Diesel Cycle

Principle of the Diesel Cycle

- **The Diesel cycle** was developed in an attempt to approach the Carnot efficiency more closely, its principle is very much alike the Otto Cycle
- The main difference with the Otto cycle is the process between 2 and 3
  - In a **Diesel engine auto-ignition** occurs when fuel is injected at high pressure and temperature at constant pressure
  - In the **Otto engine** the gas is **ignited by a spark** at constant volume

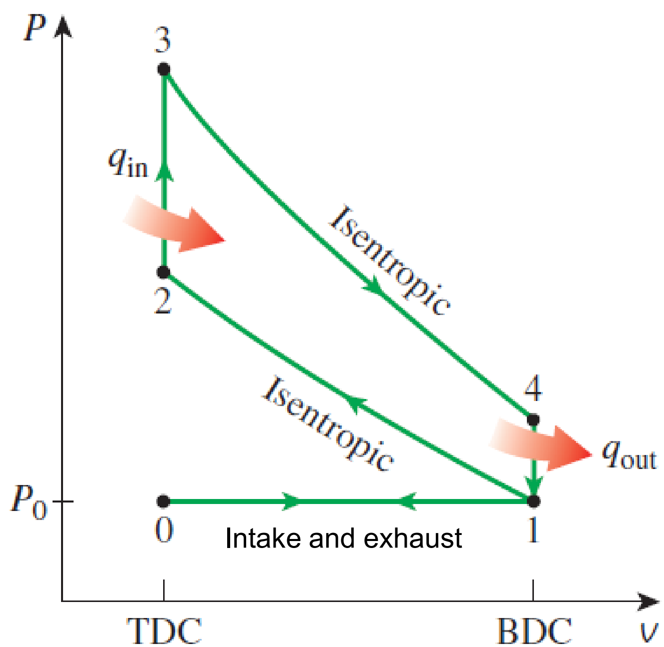


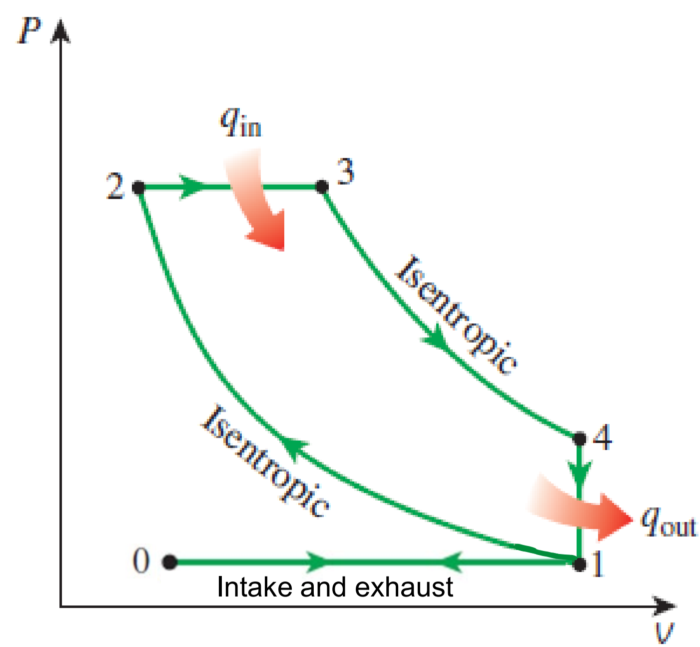


Principle of the Diesel Cycle

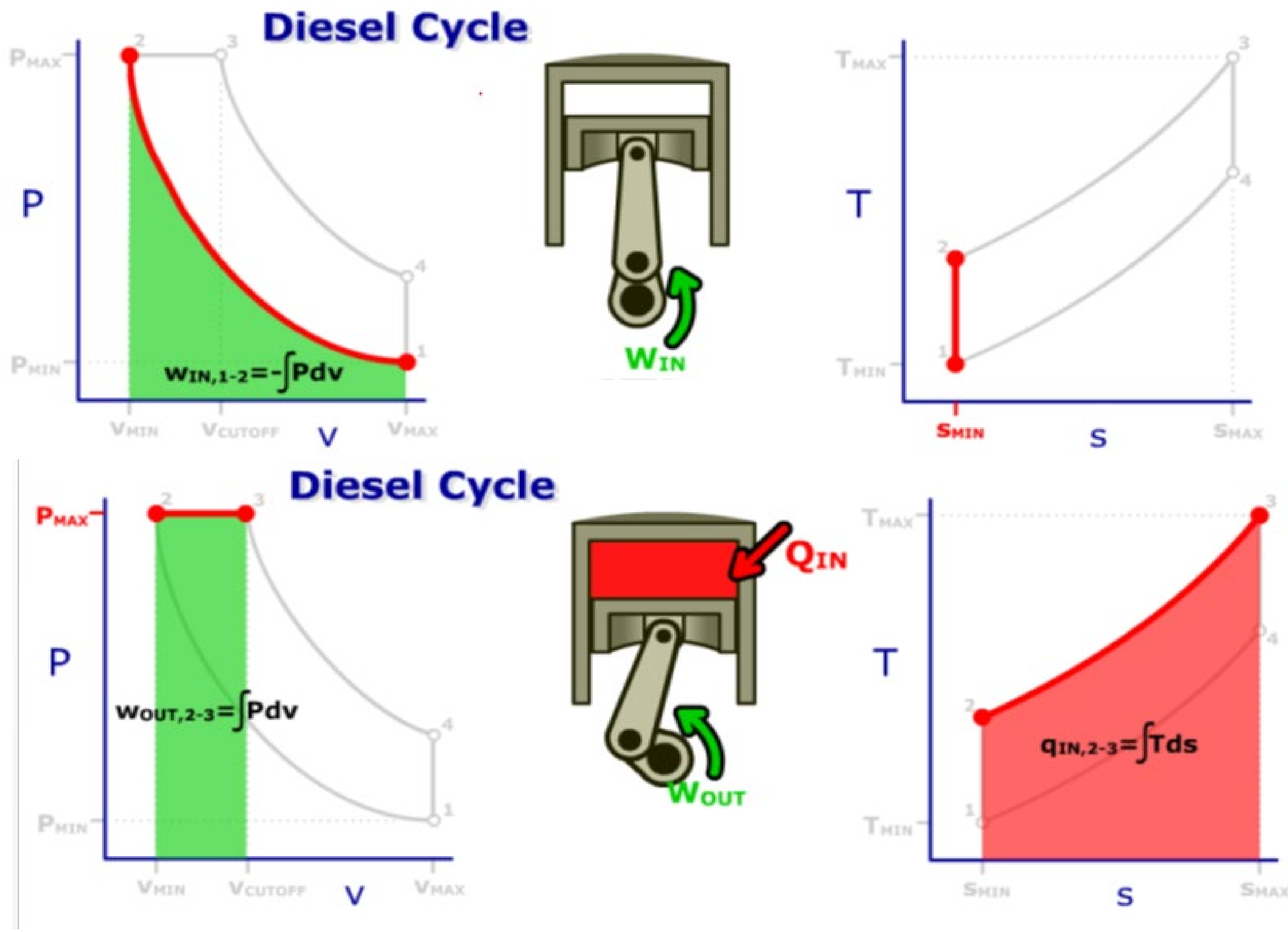
- **The Diesel cycle** was developed in an attempt to approach the Carnot efficiency more closely, its principle is very much alike the Otto Cycle

Cycle	Compression	Ignition	Combustion
Otto	Air + Fuel	Spark	Isochoric
Diesel	Air	Compression	Isobaric



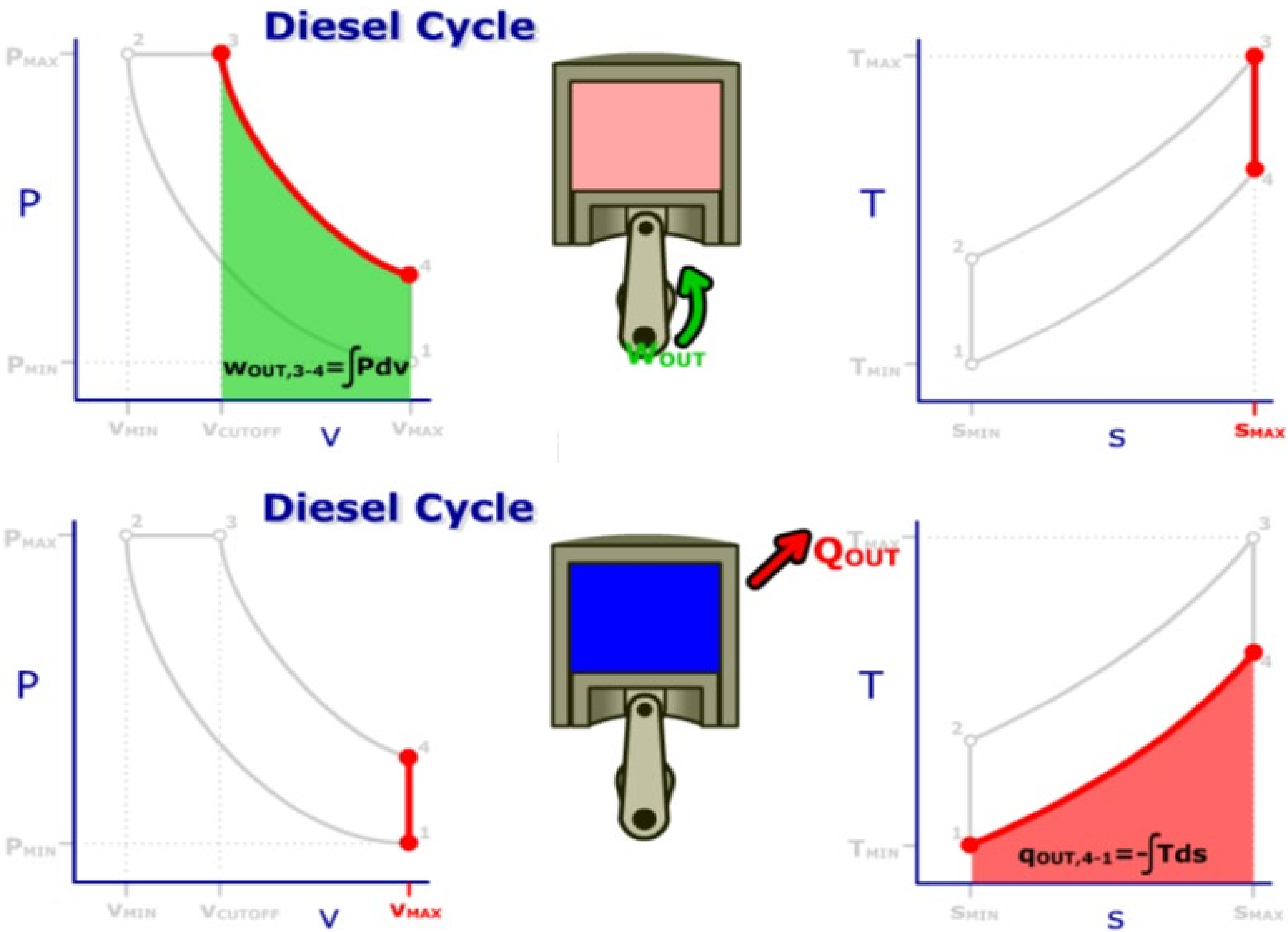


The Diesel Cycle



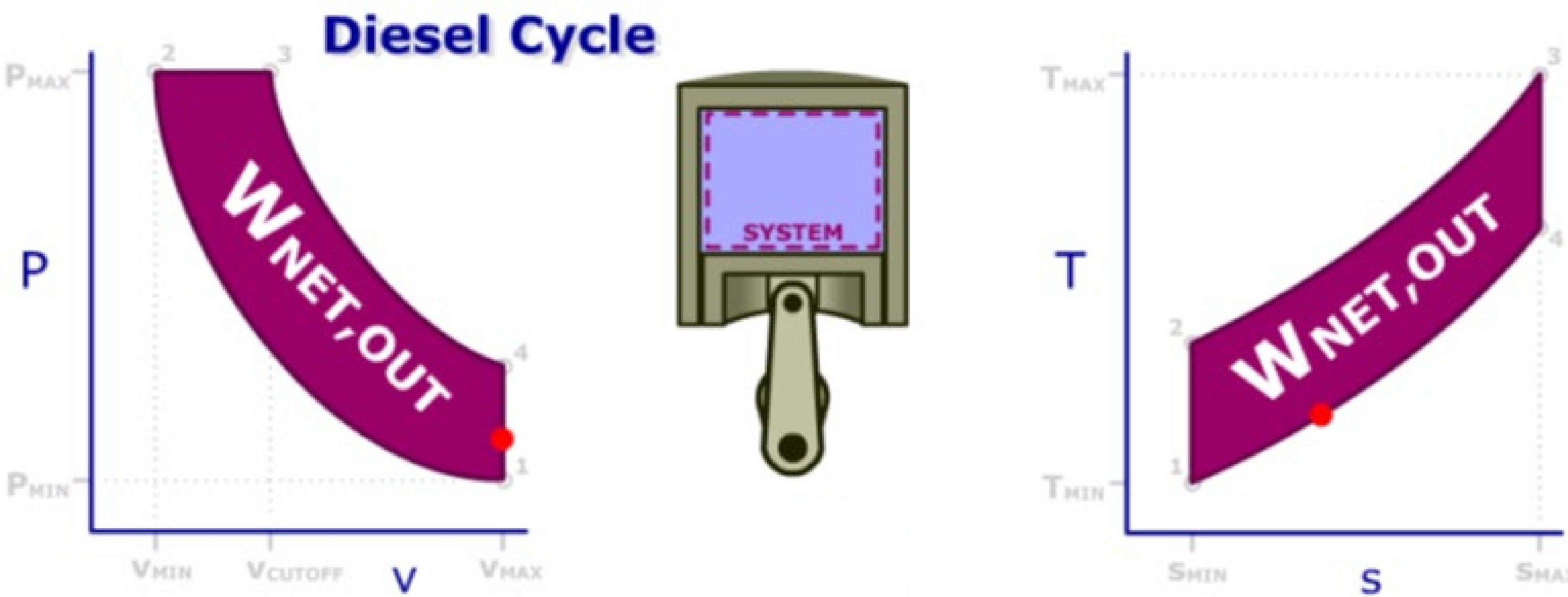
The area below the upper Pv diagram indicates the work input during compression. The lower Pv diagrams shows the work output during combustion. The area below the Ts diagram indicates the heat input. A

The Diesel Cycle



The area below the Pv diagram indicates the work output during expansion and the area below the Ts diagram indicates the heat output

The Diesel Cycle



Process	Q	W	Type
1 → 2	0	W_{IN}	Isentropic
2 → 3	Q_{IN}	W_{OUT}	Isobaric
3 → 4	0	W_{OUT}	Isentropic
4 → 1	Q_{OUT}	0	Isometric

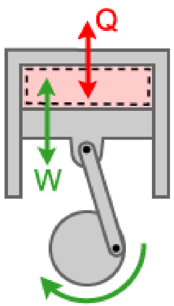
State	T	P	v	s
1	T_{MIN}	P_{MIN}		
2		P_{MAX}		$s_2=s_1$
3	T_{MAX}	$P_3=P_2$		
4			$v_4=v_1$	$s_4=s_3$

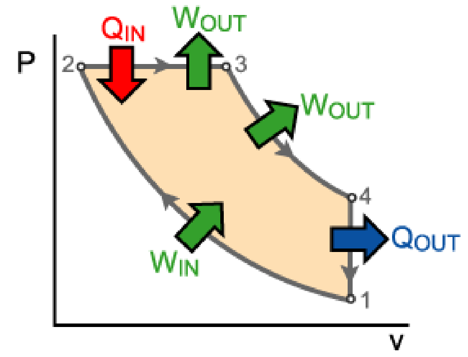
The area enclosed in the the Pv diagram indicates the net work output and the area enclosed in the Ts diagram indicates the net heat input of the cycle

For a cycle these are the same: $w_{net} = q_{net}$

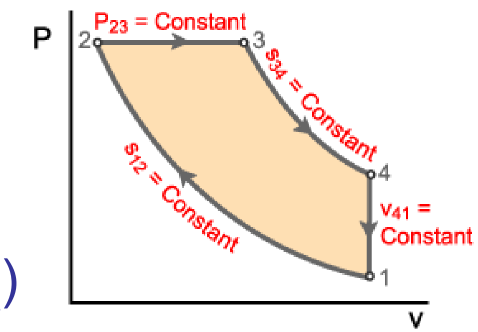
Diesel Cycle Analysis

- Diesel cycle modeled as a closed ideal air standard cycle
- **Important formulas**
  - Ideal gas: $Pv = RT$
    - For example: $v_3 T_2 = v_2\, T_3$
  - Isentropic processes (1-2 and 3-4):
    - Pv^k = constant $(k = c_p/c_v)$
      - For example: $P_1 v_1^{\,k} = P_2 v_2^{\,k}$
    - $Tv^{(k\text{-}1)}$ = constant
    - $TP^{(1\text{-}k)/k}$ = constant





Isentropic relations:
See ET Class 9,
and Çengel 7.9



Diesel Cycle

  - First law closed system: $\Delta u = (q_{in} - q_{out}) + (w_{in} - w_{out})$
  - $\Delta u = c_v \Delta T$ and $\Delta h = c_p \Delta T$, for example:
    - $q_{in}=q_{(2\text{-}3)}=\Delta u_{(2\text{-}3)}+w_{(2\text{-}3)}=u_3 - u_2+(P_3v_3 - P_2v_2)= h_3 - h_2=c_p(T_3 - T_2)$
  - Compression ratio: $r_V = v_{max}/v_{min} = v_1/v_2 = v_4/v_2$
  - Cut-off ratio: $r_{cut\text{-}off} = v_3/v_2$ (plays no role in Otto Cycle)
  - $P_{max} = P_2 = P_3$, $P_{min} = P_1$ and $T_{max} = T_3$, $T_{min} = T_1$

Work and Heat Diesel Cycle

- Work in- and output Diesel cycle: Ideal air standard analysis

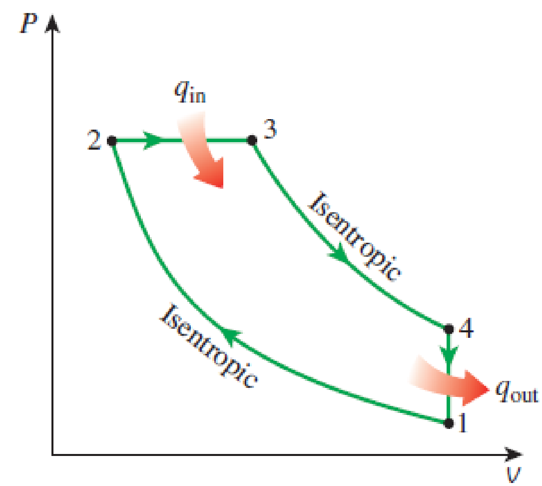
- The **work input** is between point 1 & 2 (like the Otto cycle)
- $w_{in} = w_{1\text{-}2}$, for this process the heat is zero: $q_{1\text{-}2} = 0$
- The first law states: $\Delta u_{a\text{-}b} = q_{a\text{-}b} + w_{a\text{-}b}$ and therefore: $w_{in} = w_{1\text{-}2} = u_2 - u_1$

- The **work output** is between point 3 & 4 and **point 2 & 3**: $w_{out} = w_{3\text{-}4} + w_{2\text{-}3}$
- With $q_{3\text{-}4} = 0$ follows from the first law: $w_{3\text{-}4} = u_3 - u_4$
- From $\delta w = Pdv$ with $P_2 = P_3 = constant$ follows: $w_{2\text{-}3} = P_3v_3 - P_2v_2$
- Therefore: $w_{out} = w_{3\text{-}4} + w_{2\text{-}3} = u_3 - u_4 + P_3v_3 - P_2v_2$

- The **net work output** is:

$$w_{net} = w_{out} - w_{in} = w_{3\text{-}4} + w_{2\text{-}3} - w_{1\text{-}2}$$
$$= u_3 - u_4 + P_3v_3 - P_2v_2 - (u_2 - u_1)$$
$$= u_3 + P_3v_3 - u_2 - P_2v_2 - u_4 + u_1$$
$$= h_3 - h_2 + u_1 - u_4 = c_p(T_3 - T_2) - c_v(T_4 - T_1)$$

- Note: this is different from the Otto cycle net work

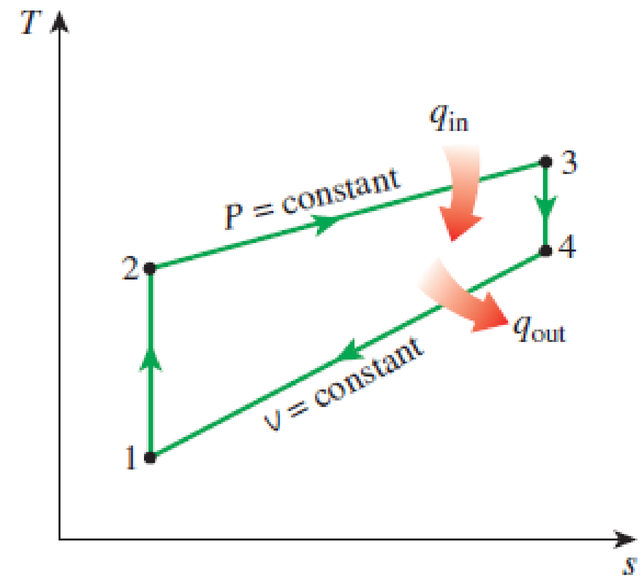


Work and Heat Diesel Cycle

- Heat in- and output Diesel cycle: Ideal air standard analysis

- The **heat input** is between point 2 and 3
- $q_{in} = q_{2\text{-}3}$, for this process the work is: $w_{2\text{-}3} = P_3v_3 - P_2v_2$
- The first law states: $\Delta u_{a\text{-}b} = q_{a\text{-}b} + w_{a\text{-}b}$
- Therefore: $q_{in} = q_{2\text{-}3} = u_3 - u_2 + P_3v_3 - P_2v_2$

$$= u_3 + P_3v_3 - u_2 - P_2v_2$$
$$= h_3 - h_2 = c_p(T_3 - T_2)$$



- The **heat output** is between point 4 and 1
- $q_{out} = q_{4\text{-}1}$ the work is also zero: $w_{4\text{-}1} = 0$
- From the first law follows:

$$q_{out} = q_{4\text{-}1} = u_4 - u_1 = c_v(T_4 - T_1)$$

- The **net heat input** is $q_{net} = q_{2\text{-}3} - q_{4\text{-}1}$

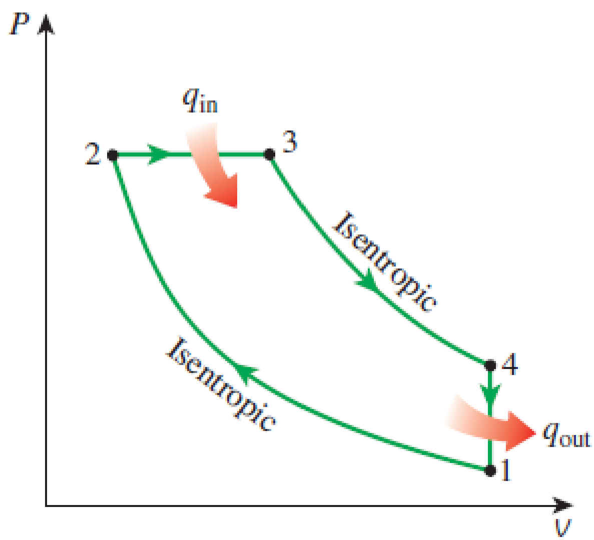
$q_{net} = c_p(T_3 - T_2) - c_v(T_4 - T_1)$, this is equal to the net work output

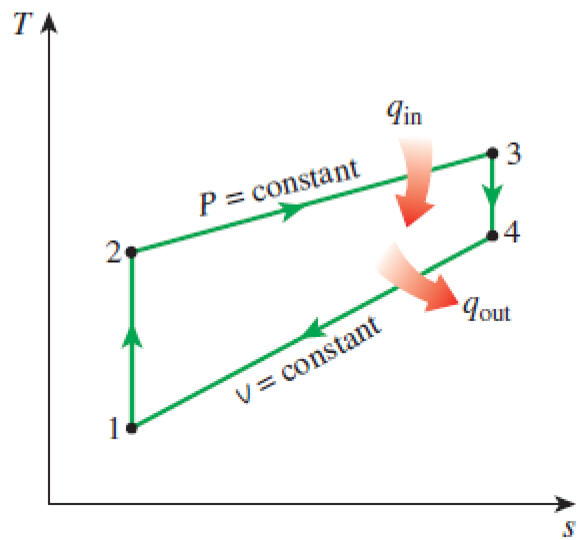
Net Work Output and Heat Input Diesel Cycle

- **Net work output Diesel cycle:** Ideal air standard analysis
  - $w_{net} = c_p(T_3 – T_2) - c_v(T_4 – T_1)$ [kJ/kg]

- **Heat input Diesel cycle:** Ideal air standard analysis
  - $q_{in} = q_{2\text{-}3} = u_3 – u_2 = c_p(T_3 – T_2)$ [kJ/kg]

- These expressions give specific energies for one stroke only





Power Output Diesel Cycle

- **What is the power of a Diesel engine?**

- A 4-stroke engine has 4 strokes and two turnings of the crank
- Only in one stroke and one turning power is delivered
- A Diesel engine has many revolutions per minute (RPM)

- Therefore, the specific power is: $\dot{w}_{net} = w_{net}\frac{1}{2}\frac{RPM}{60}$ $[\mathrm{kJ/skg{=}kW/kg}]$

- Diesel engines have more than 1 cylinder, the total mass of the gas in all cylinders should be considered to calculate the power

$$\dot{W}_{net} = m\dot{w}_{net} = m w_{net}\frac{1}{2}\frac{RPM}{60}\ [\mathrm{kJ/s{=}kW}]$$

Diesel Cycle Efficiency

- The Diesel cycle is a bit more complicated than the Otto cycle, because of **cut off ratio** that plays a role in the Diesel cycle, and not in the Otto
- The cut off ratio is the ratio between the volume before and after the heat addition: $r_{Cutoff} = \frac{v_3}{v_2} = \frac{T_3}{T_2}$ and $\frac{T_4}{T_1} = \frac{P_4}{P_1} = \left(r_{Cutoff}^k\right)_{IAS}$
- The efficiency of the Diesel cycle (Ideal air standard):

$$\eta_{\text{Diesel,ias}} = \frac{\text{Wanted}}{\text{Payed for}} = \frac{w_{netto}}{q_{in}} = \frac{w_{out} - w_{in}}{q_{in}} = \frac{w_{23} + w_{34} - w_{12}}{q_{in}} =$$

$$\frac{(P_3V_3 - P_2V_2) + (u_3 - u_4) - (u_2 - u_1)}{(u_3 - u_2) + (P_3V_3 - P_2V_2)} = \frac{(h_3 - h_2) - (u_4 - u_1)}{(h_3 - h_2)} = \frac{c_p(T_3 - T_2) - c_v(T_4 - T_1)}{c_p(T_3 - T_2)}$$

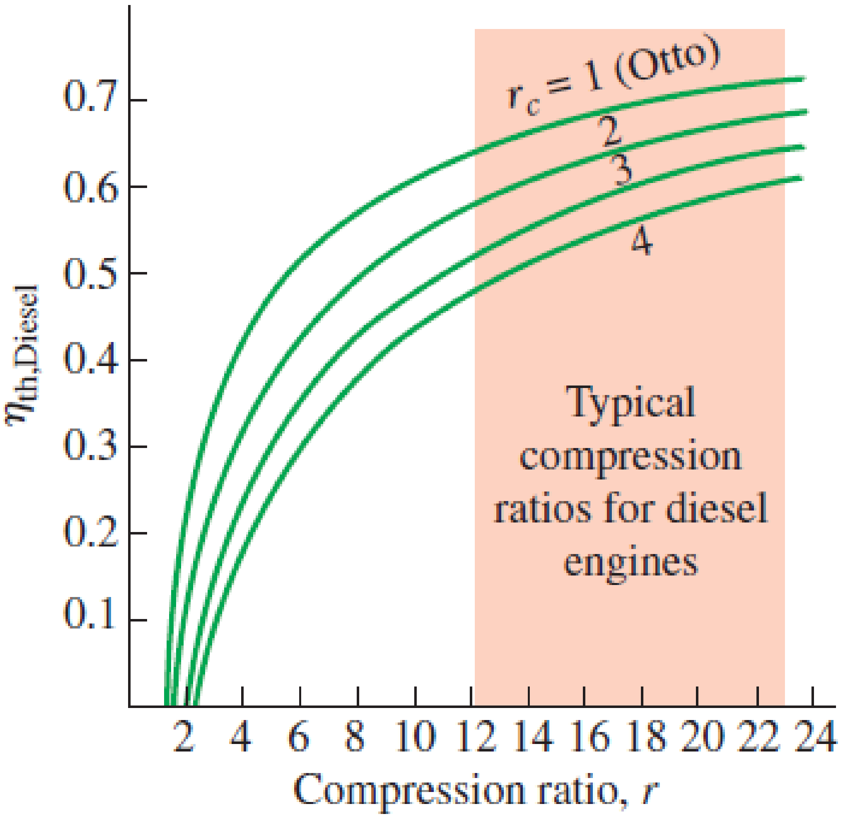
- Which can be rewritten as:

$$\eta_{\text{Diesel,ias}} = 1 - \frac{c_v(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{kT_2(T_3/T_2 - 1)} = 1 - \frac{1}{k}\left(\frac{1}{r_v}\right)^{k-1} \frac{\left(r_{cutoff}^k - 1\right)}{\left(r_{cutoff} - 1\right)}$$

Efficiency of the Ideal Diesel Cycle

- Efficiency of the ideal Diesel cycle as a function of the compression ratio

$$\eta_{\text{Diesel, ias}} = 1 - \frac{C_v(T_4 - T_1)}{C_p(T_3 - T_2)} = 1 - \frac{1}{k}\left(\frac{1}{r_v}\right)^{k-1} \frac{\left(r_{cutoff}^{k} - 1\right)}{\left(r_{cutoff} - 1\right)}$$



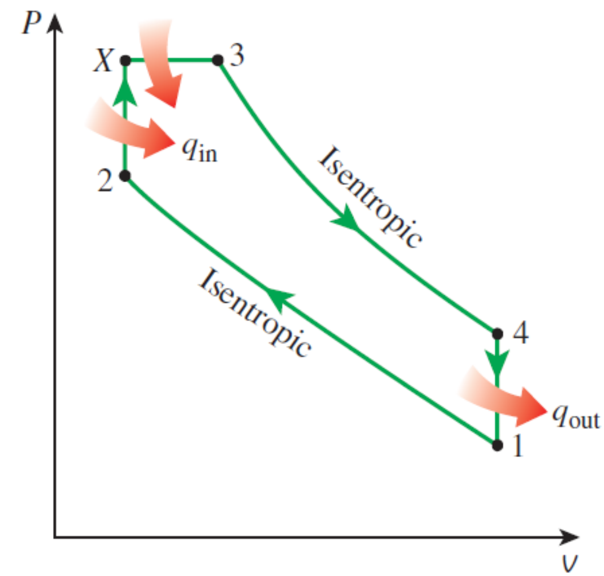
- Note: in a Diesel cycle the cut off ratio, $r_c = \frac{v_3}{v_2}$ plays a role
- If $r_c = 1$ the Diesel cycle approaches the Otto cycle
- $r_v = \frac{v_1}{v_2}$ compression ratio

- The figure shows that the efficiency of a Diesel engine increases with a higher compression ratio and a lower cut off ratio

Other Piston Engine Cycles: Dual Cycle

- In modern high-speed compression ignition engines, fuel is injected into the combustion chamber much sooner compared to the early diesel engines
- Fuel starts to ignite late in the compression stroke, and consequently part of the combustion occurs almost at constant volume
- Fuel injection continues until the piston reaches the top dead centre, and combustion of the fuel keeps the pressure high well into the expansion stroke
- Thus, the entire combustion process can better be modelled as the combination of constant-volume and constant-pressure processes, the dual cycle

- The **dual cycle** is a hybrid between an Otto and a Diesel cycle and comes closer to a real cycle
  - If $v_3 = v_x \rightarrow$ Otto Cycle
  - If $P_x = P_2 \rightarrow$ Diesel Cycle
- Volume compression ratio: $r_1 = \frac{v_1}{v_2}$
- Volume expansion ratio: $r_2 = \frac{v_4}{v_3}$
- Efficiency dual cycle: $\eta_{DUAL,IAS} = 1 - \frac{\left(\frac{1}{r_1^{k-1}}\right)\left[\left(\frac{P_x}{P_2}\right)\left(\frac{r_1}{r_2}\right)^k - 1\right]}{\left(\frac{P_x}{P_2}\right) - 1 + k\left[\left(\frac{r_1}{r_2}\right) - 1\right]}$

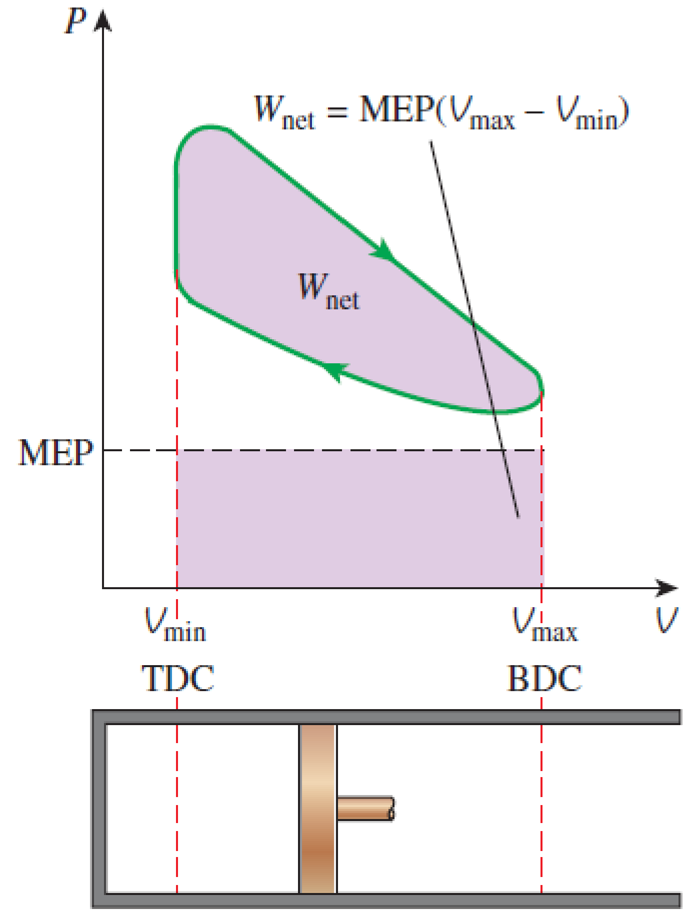


Not for the exam

Mean Effective Pressure

- The mean effective pressure (P_{ME}) is a convenient measure of the practicality of an Otto or Diesel cycle

- This is a mean pressure which multiplied by the maximum volume change gives the net cycle work output



- Definition (P_{ME})

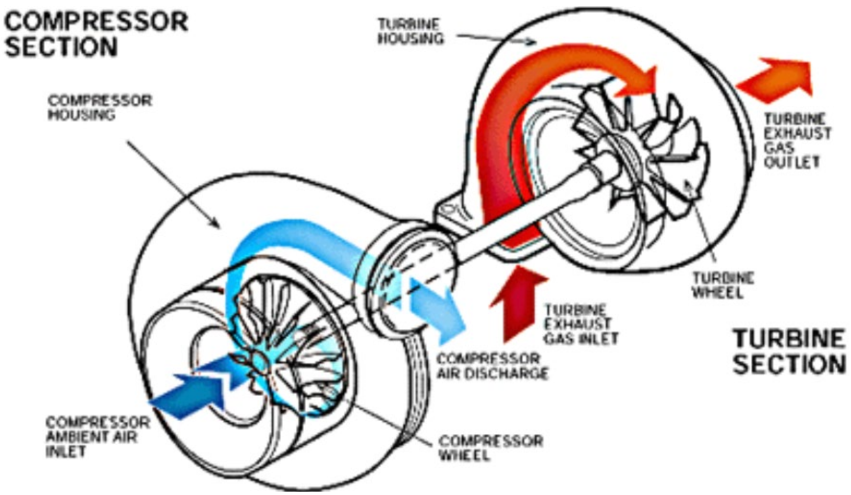
$$w_{out} - w_{in} = \oint P\mathrm{d}v$$

$$= P_{ME}(v_{max} - v_{min})$$

- ($v_{max} - v_{min}$) is proportional to size of engine
- Engines with larger P_{ME} produce more work per unit volume
- Engines with larger P_{ME} tend to be more practical

Turbo Charging

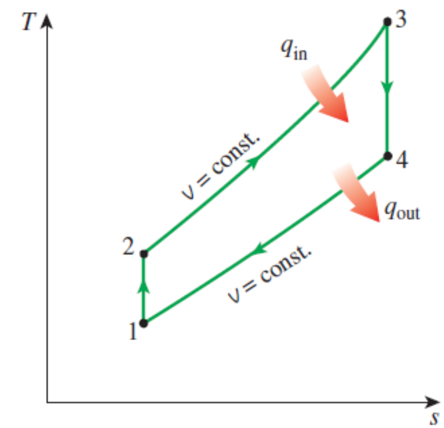
- Turbo charging is used to enhance the output power of the Diesel engine
- A turbo charger consists of a compressor connected to a turbine to drive the compressor
- The compressor is placed before the cylinder inlet and compresses the inlet air before it enters the cylinder
- This results in a higher density of the air in the cylinder and therefore the mass of air and oxygen is higher
- At a constant air/fuel ratio more fuel can be injected to the cylinder resulting in a higher power output
- The turbine of the turbo charger is placed after the cylinder outlet and powered by the combustion gases leaving the cylinder at high pressure



Not for the exam

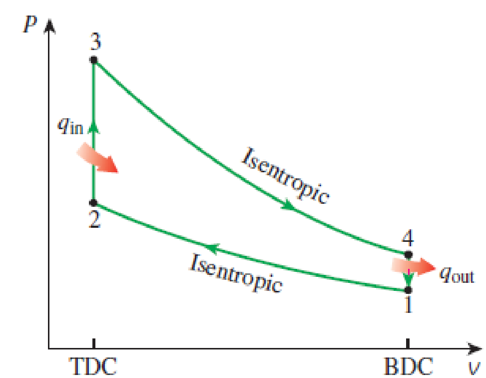
Example Otto Cycle

- Given is an ideal standard air Otto cycle with compression ratio 8
  - Inlet conditions T_1 = 300 K, P_1 = 100 kPa
  - Maximum pressure is 3.0 MPa
- Determine the net power output and the heat transferred to the engine per kg air and the thermal efficiency (k = 1.4, c_v at 300K)



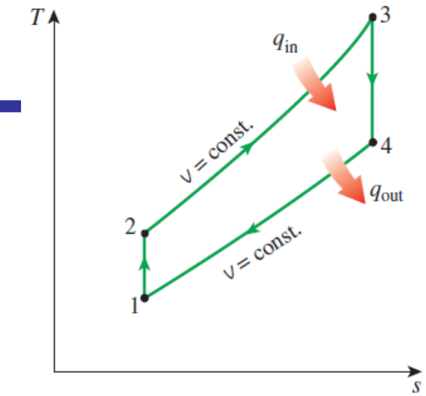
- **Solution:**
  - P_3 is the maximum pressure = 3.0 MPa
  - Compression ratio of 8 means $r_v = v_1 / v_2 = 8 = v_4 / v_3$
  - Heat transferred to the engine is: $q_{in} = c_v(T_3 - T_2)$
  - Net power output is: $w_{net} = c_v(T_3 - T_4) - c_v(T_2 - T_1)$
  - The thermal efficiency is:

$$\eta_{Otto,ias} = \frac{c_v(T_3 - T_4) - c_v(T_2 - T_1)}{c_v(T_3 - T_2)}$$

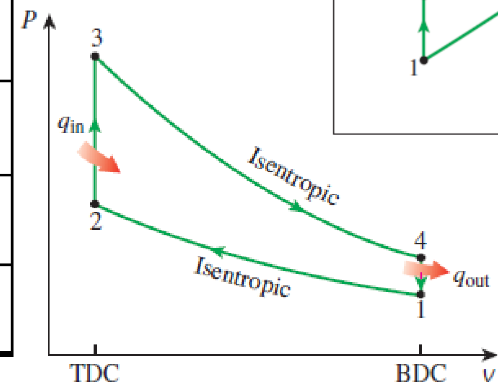


- For this we need the temperatures on the points 1 to 4
- Therefore, we must find all the temperatures

Example Otto cycle



	T(K)	P(MPa)	Volume	Entropy
1	300	0.1	v_1	
2	689	1.84	$v_2 = v_1 / 8$	$s_2 = s_1$
3	1123	3.0	$v_3 = v_2$	
4	489	0.16	$v_4 = 8v_3 = v_1$	$s_4 = s_3$



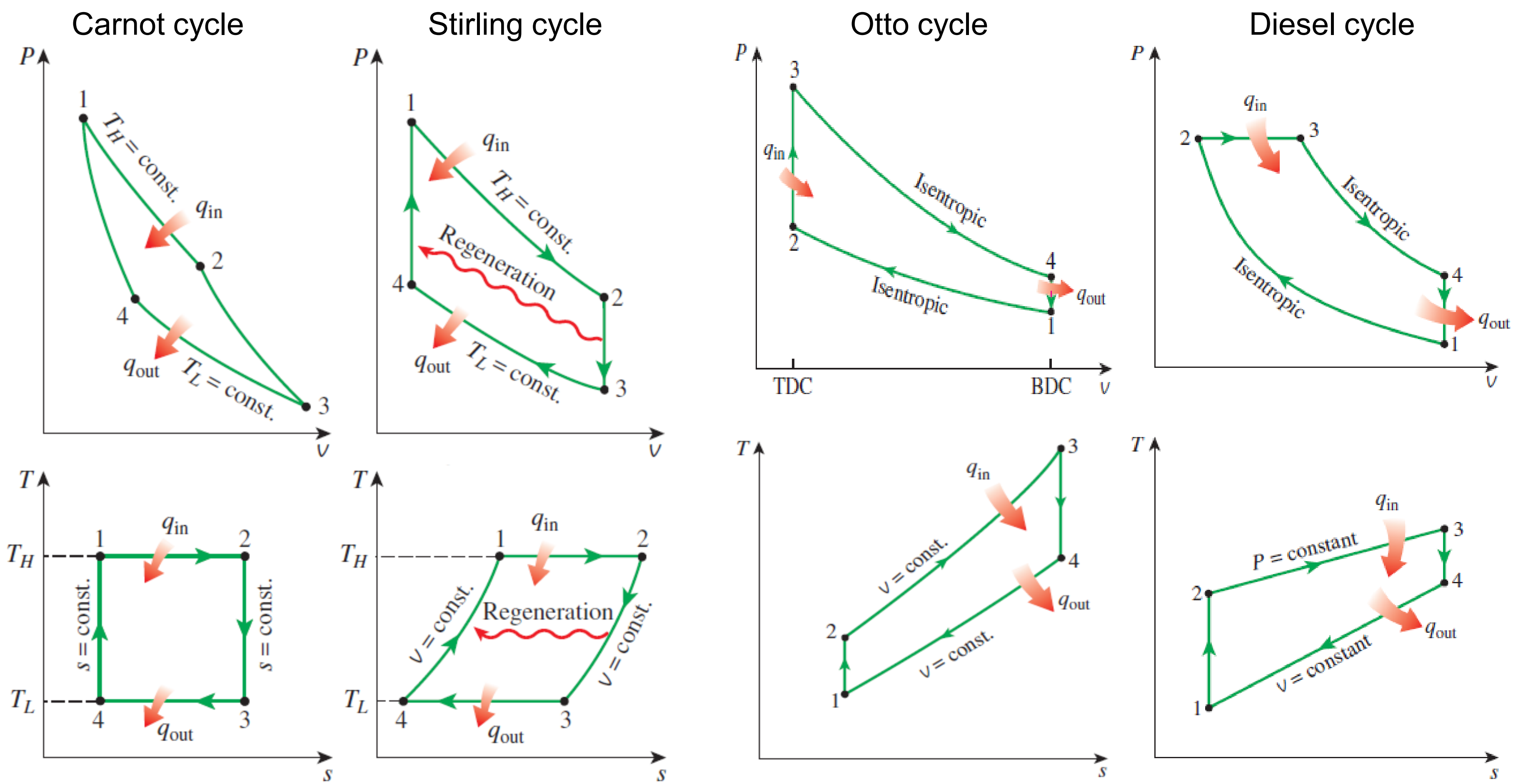
- $1 \rightarrow 2$ isentropic: $P_2 = P_1\,(v_1/v_2)^k \rightarrow P_2 = 1.84$ MPa
- $T_2 = P_2\, v_2 / R = (P_2\, T_1) / (8P_1) = 689$ K $(v_2 = v_1 / 8 = RT_1 / 8P_1)$
- $T_3 = ((v_3 P_3) / (v_2 P_2))\, T_2 = 1123$ K $(v_2 = v_3)$
- $3 \rightarrow 4$ isentropic: $P_4 = P_3\,(v_3/v_4)^k \rightarrow P_4 = 0.16$ MPa
- $T_4 = P_4\, v_4 / R = (8P_4\, T_3) / P_3 = 489$ K $(v_4 = 8v_3 = 8RT_3 / P_3)$

  All temperatures lead to:
- $q_{in} = c_v(T_3 - T_2) = 312$ kJ/kg
- $w_{net} = c_v(T_3 - T_4) - c_v(T_2 - T_1) = 176$ kJ/kg

$$\eta_{Otto,ias} = \frac{(T_3 - T_4) - (T_2 - T_1)}{(T_3 - T_2)} = 0.56$$

Recapitulate Class 14

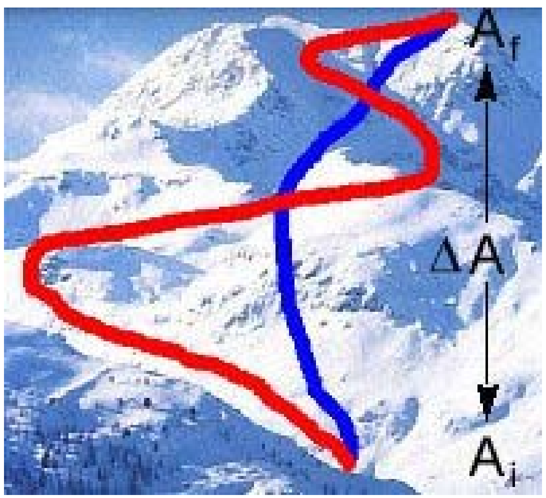
- Reciprocating engine cycles, **gas power cycles,** executed in a piston cylinder device undergoing an air standard cycle are analyzed
- Stirling cycle, Otto cycle, Diesel cycle



Next Classes 15, 16 & 17: Math Background

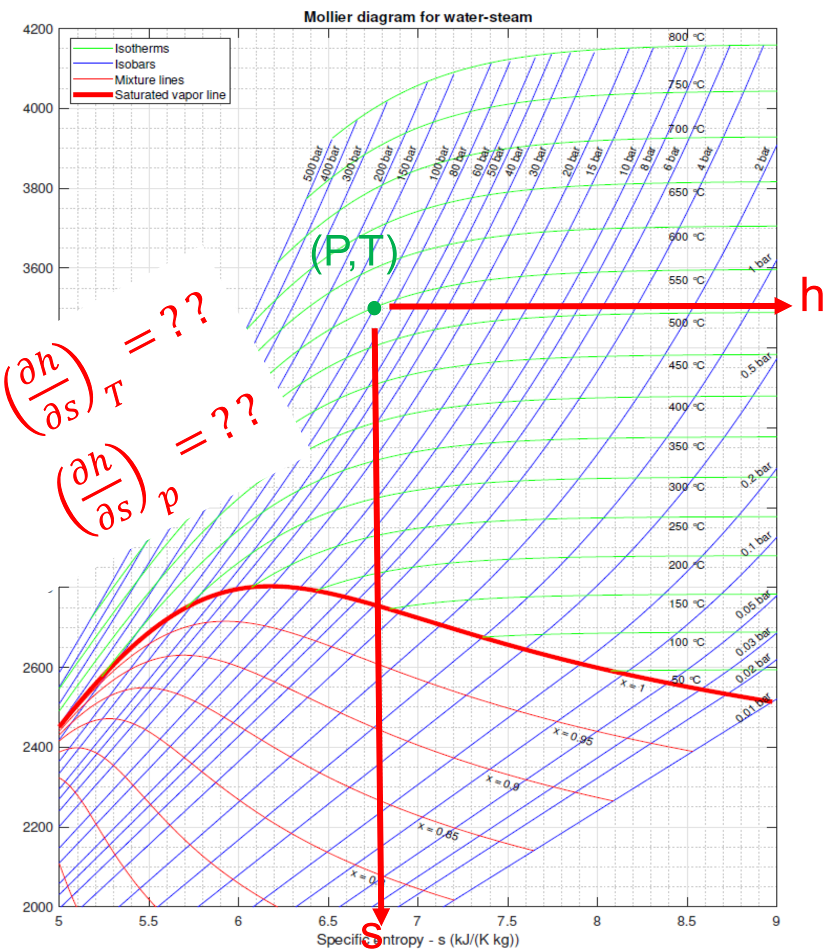
- How are tables and diagrams composed?
- How can unknow properties that can not be measured be determined from a set of limited available data?

- **Class 15** → State postulate, thermodynamics and partial derivatives, state and path functions



$$dv(P,T) = \left(\frac{\partial v}{\partial T}\right)_p dT + \left(\frac{\partial v}{\partial P}\right)_T dP$$

- Isotherms: $\left(\frac{\partial h}{\partial s}\right)_T = ??$
- Isobars: $\left(\frac{\partial h}{\partial s}\right)_p = ??$



Keep in mind: Important Formulas

- Specific volume $v = V/m$ [m^3/kg] and density $\rho = 1/v = m/V$ [kg/m^3]
- Volume work $\delta w = Pdv$
- Enthalpy $h = u + Pv$, (u internal energy, P pressure, v volume)
- Thermal efficiency $\eta_{thermal} = \frac{Net\ electrical\ power\ output}{Rate\ of\ fuel\ energy\ input} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$
- Mixture fraction $x = \frac{v - v_l}{v_v - v_l} \rightarrow v = v_l + x(v_v - v_l)$
- Ideal gas law $Pv = RT$, $c_p - c_V = R$
- For an ideal gas $du = c_V dT$ and $dh = c_p dT$
- Conservation of mass $m_{in} = m_{out}$, mass flow rate $\dot{m} = \rho v A$
- Conservation of energy, first law of thermodynamics
  - Closed system $du = \delta w - \delta q \rightarrow \Delta u = w - q$
  - Open system $q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$
- S increases, second law $ds_{total} = ds_{system} + ds_{surroundings} = \delta s_{gen} \geq 0$
- Inequality of Clausius $ds \geq \frac{\delta q_{net}}{T_{res}}$ (= for reversible process)
- Reversible heat transfer $\delta q_{net,rev} = Tds$, irreversible $\delta q_{net,irrev} < Tds$
- Gibbs equations $Tds = du + Pdv$ and $Tds = dh - vdP$
- Isentropic efficiencies $\eta_{INPUT,S} = \frac{w_{IN,S}}{w_{IN,A}}$, $\eta_{OUTPUT,S} = \frac{w_{OUT,A}}{w_{OUT,S}}$
- Isentropic processes ideal gas Pv^k = constant, Tv^{k-1} = constant, $P^{(k-1)/k}/T$ = constant
- Thermal efficiency power cycles $\eta_{he} = \frac{w_{out} - w_{in}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$ Carnot efficiency $\eta_{carnot} = 1 - \frac{T_{cold}}{T_{hot}}$

- Phase diagrams