

# Piston Engines for power plant applications

Sustainable Power Generation (SPG) MJ2405

*Miro Petrov*



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# Division of piston (reciprocating) engines per type of fuel and working fluid

- **Steam Engine!** → *the birth of the industrial society*
- **Internal Combustion Engines (ICE)** = open gas cycle
  - Spark Ignition (SI);
  - Compression Ignition/Diesel (CI);
  - Dual-fuel (gas-diesel) engines (DF or GD);
  - Homogeneous Charge Compression Ignition (HCCI)
- **Stirling Engine** = closed gas cycle  
(externally-heated closed-cycle piston engine)



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# Piston Engine Applications



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- **Stationary** - for driving machinery or electrical generators; or as back-up drives
- **Propulsion / transportation** - automotive, rail, airborne, marine, construction & agricultural vehicles, etc.
- **Small engines to drive hand-operated devices or appliances** - lawnmower, chainsaw, small back-up power units, etc.



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# The beginnings of thermal engineering!

## The Steam Engine...

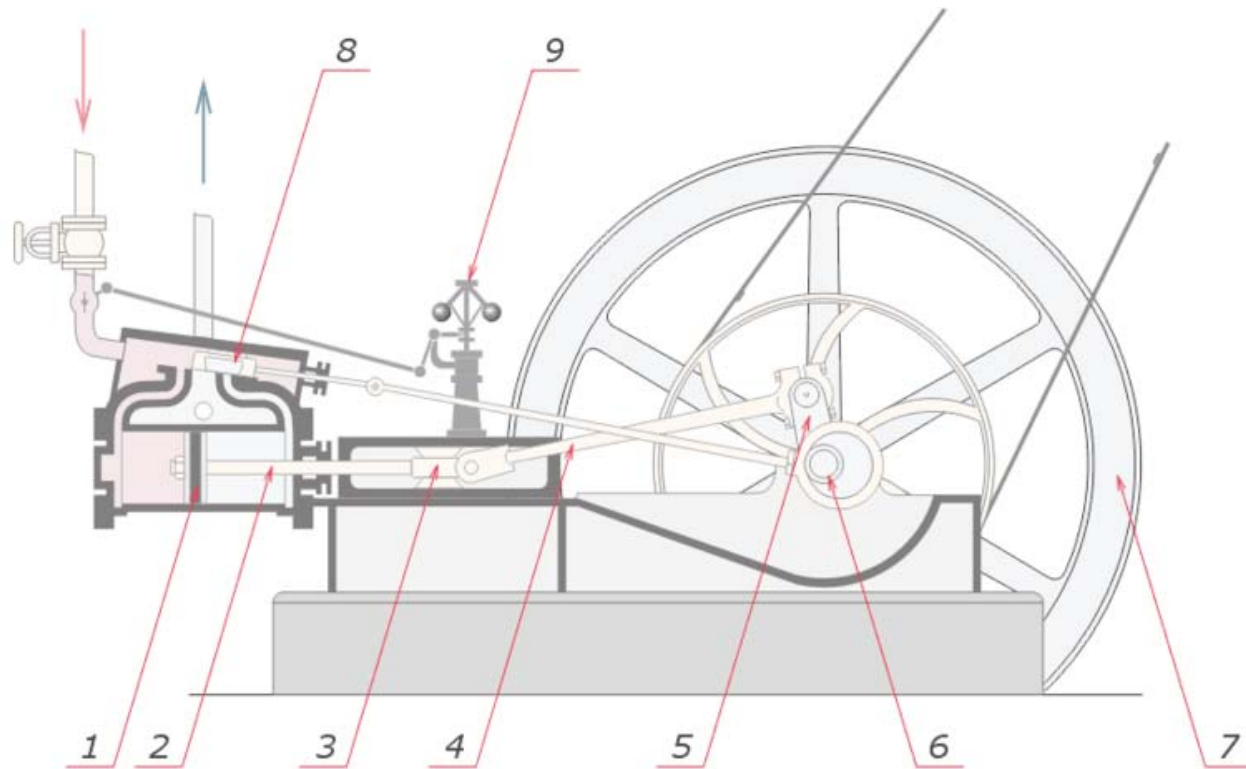
... is the first large thermal machine that humans managed to build.  
Triggered the start of modern industrialization ~250 years ago!



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Source:

[http://commons.wikimedia.org/wiki/File:Steam\\_engine\\_nomenclature.png](http://commons.wikimedia.org/wiki/File:Steam_engine_nomenclature.png)



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# Steam Locomotives: first massive machines...

**Brilliant example of early engineering... Alas quite forgotten now.**  
Might still be in use in some corners of the world. The knowledge and the craftsmanship is mostly lost nowadays.



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Source: [www.panoramio.com](http://www.panoramio.com)



# Quick Historical Review

- James Watt – the commercial steam engine in the 1780's..
- Jean Joseph Etienne Lenoir – the first commercial gas-burning engine in mid 1800's
- Nicolaus A. Otto and Eugen Langen – patented and marketed the first modern-type gasoline SI engine in 1867
- Alphonse Beau de Rochas (1861) – described theoretically the modern four-stroke SI engine before Otto
- Karl Benz, Wilhelm Maybach, Gottlieb Daimler, etc.. – further perfected various crucial components and production techniques for commercial engines
- Rudolf Diesel – patented the diesel engine in 1892
- Felix Wankel – the rotating-piston ICE in the 1950-ies
- Robert Stirling – patented the Stirling engine already in 1818



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# Reciprocating Piston Compressor/Expander

The piston-in-cylinder arrangement is by far among the most important inventions ever!

Works both as a compressor and expander in the modern reciprocating piston engine.

**Needs a connecting rod and a crankshaft to convert the reciprocating motion into a rotational motion.**

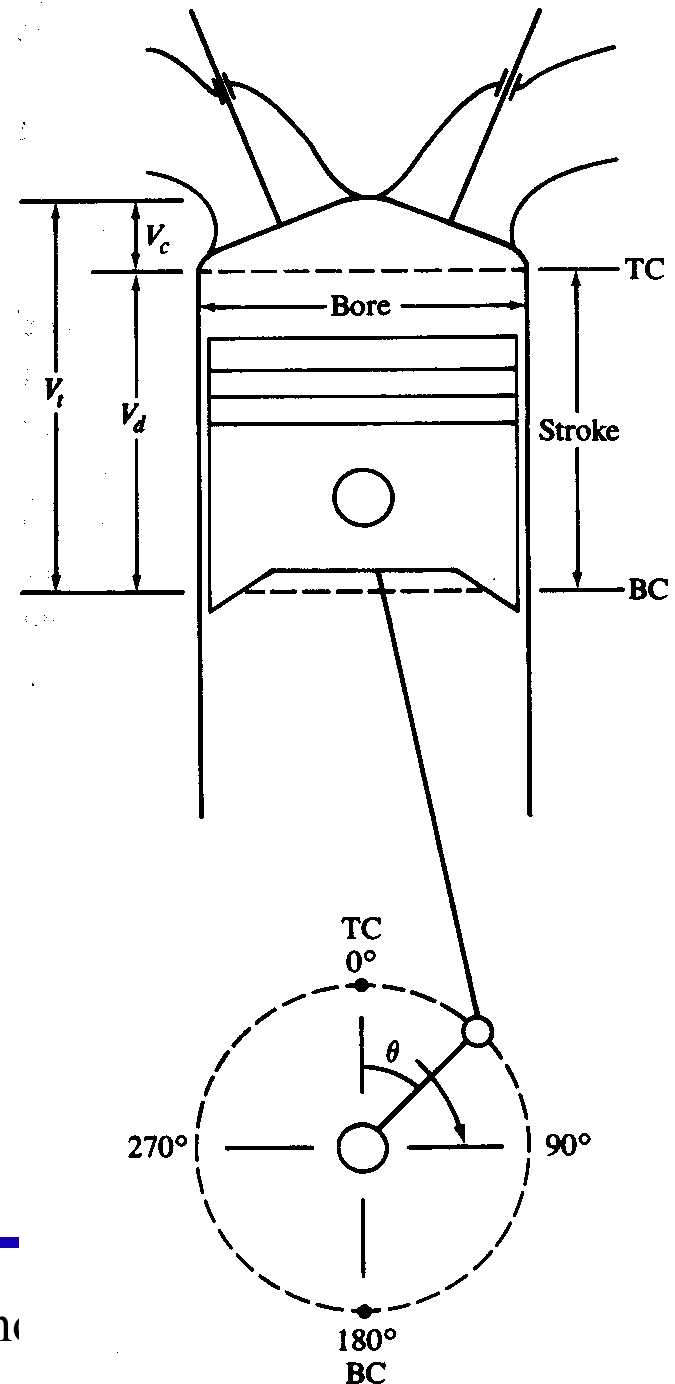
Most drawings/figures further in these slides are taken from:  
John B. Heywood, "Internal Combustion Engine Fundamentals",  
McGraw-Hill International Inc., 1988.  
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# Classification of IC Engines

- Otto (SI) or Diesel (CI) cycle
- Four-stroke or Two-stroke
- One cylinder or Multicylinder
- Multicylinder arrangement: in-line, V-type, W-type, boxer
- Naturally-aspirated or forced-charged
- Water-cooled, Air-cooled, Oil-cooled
- Rotary ICE (rotating piston) – the Wankel engine



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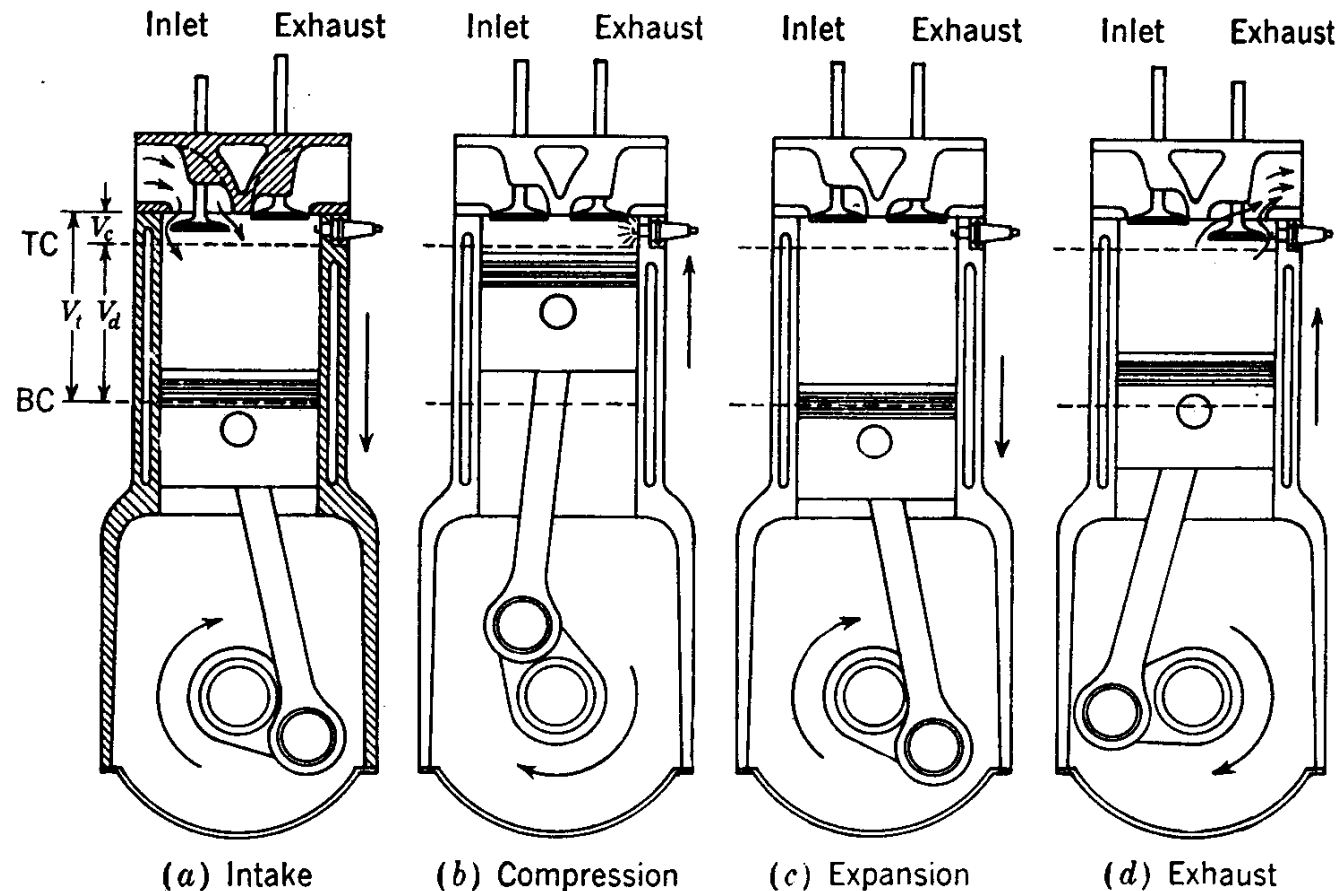


# The 4-stroke ICE

The most common engine today for most types of traction or for small power generation units



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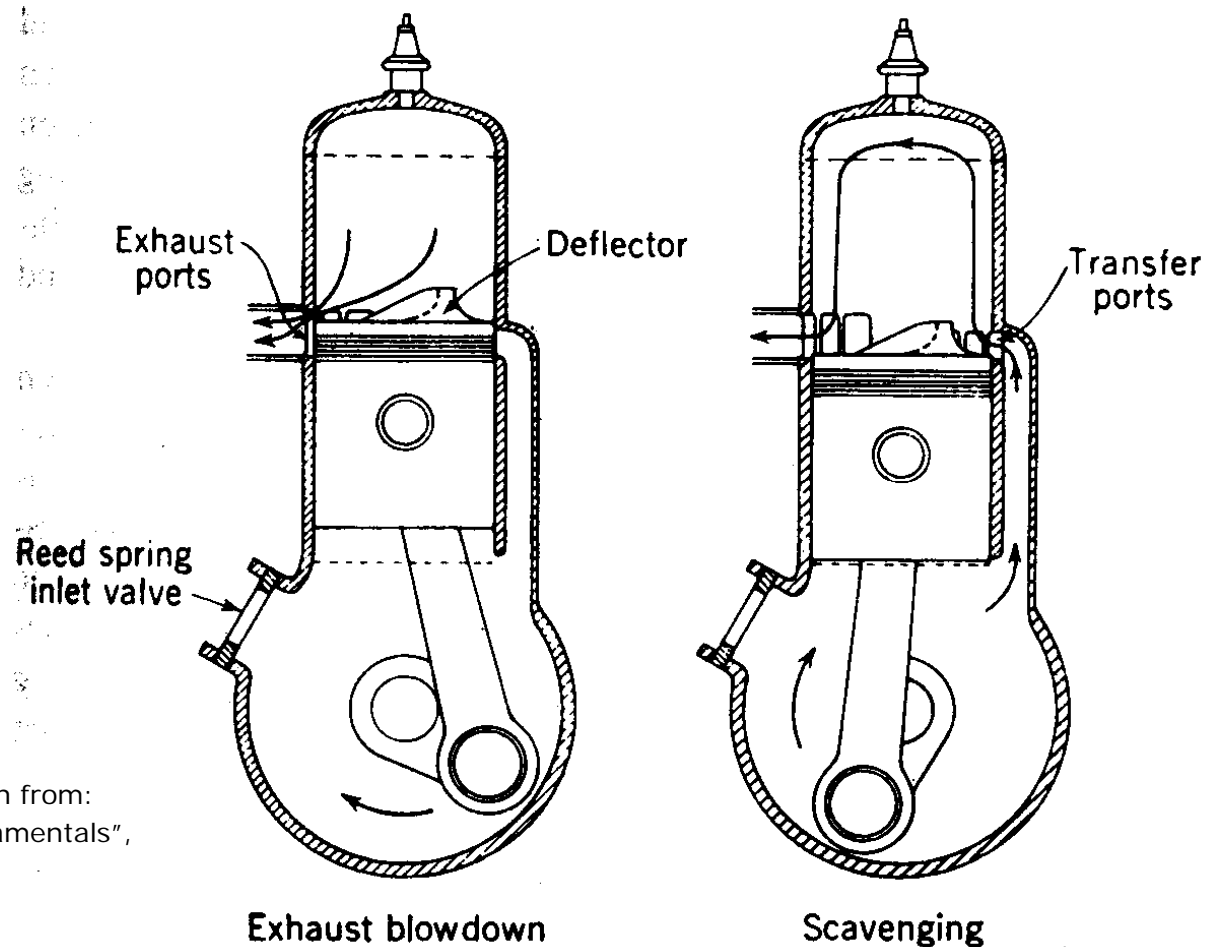
Very common in motorbikes and boats or in old small cars, typical for all small handheld devices such as a chainsaw, mower, etc.



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John B. Heywood, "Internal Combustion Engine Fundamentals",  
McGraw-Hill International Inc., 1988.  
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## The 2-stroke ICE



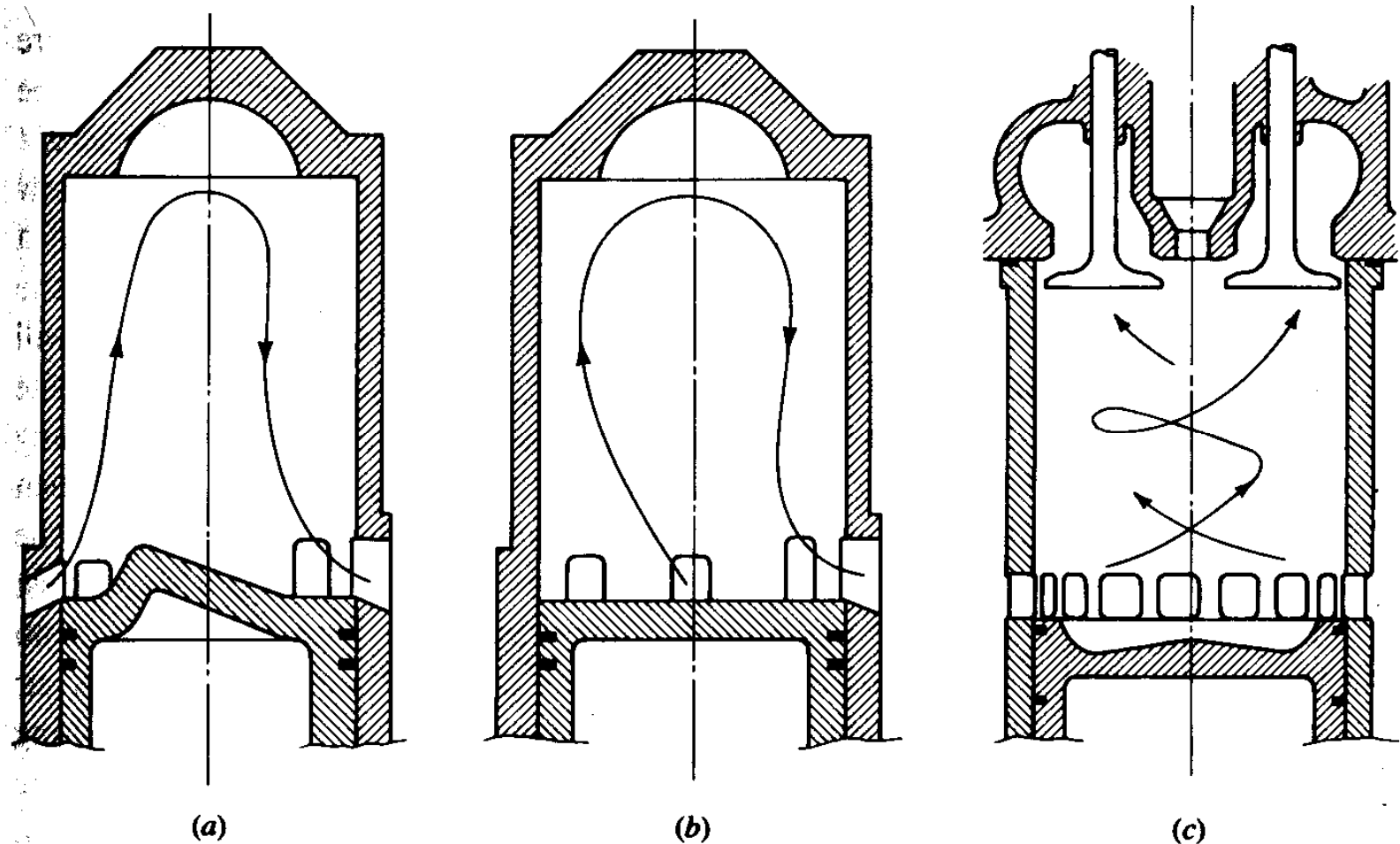
Major problem for  
2-stroke gas  
engines:

To properly replace  
the exhaust  
gases with new  
air-gas mixture  
in the cylinder..



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## 2-stroke cylinder scavenging



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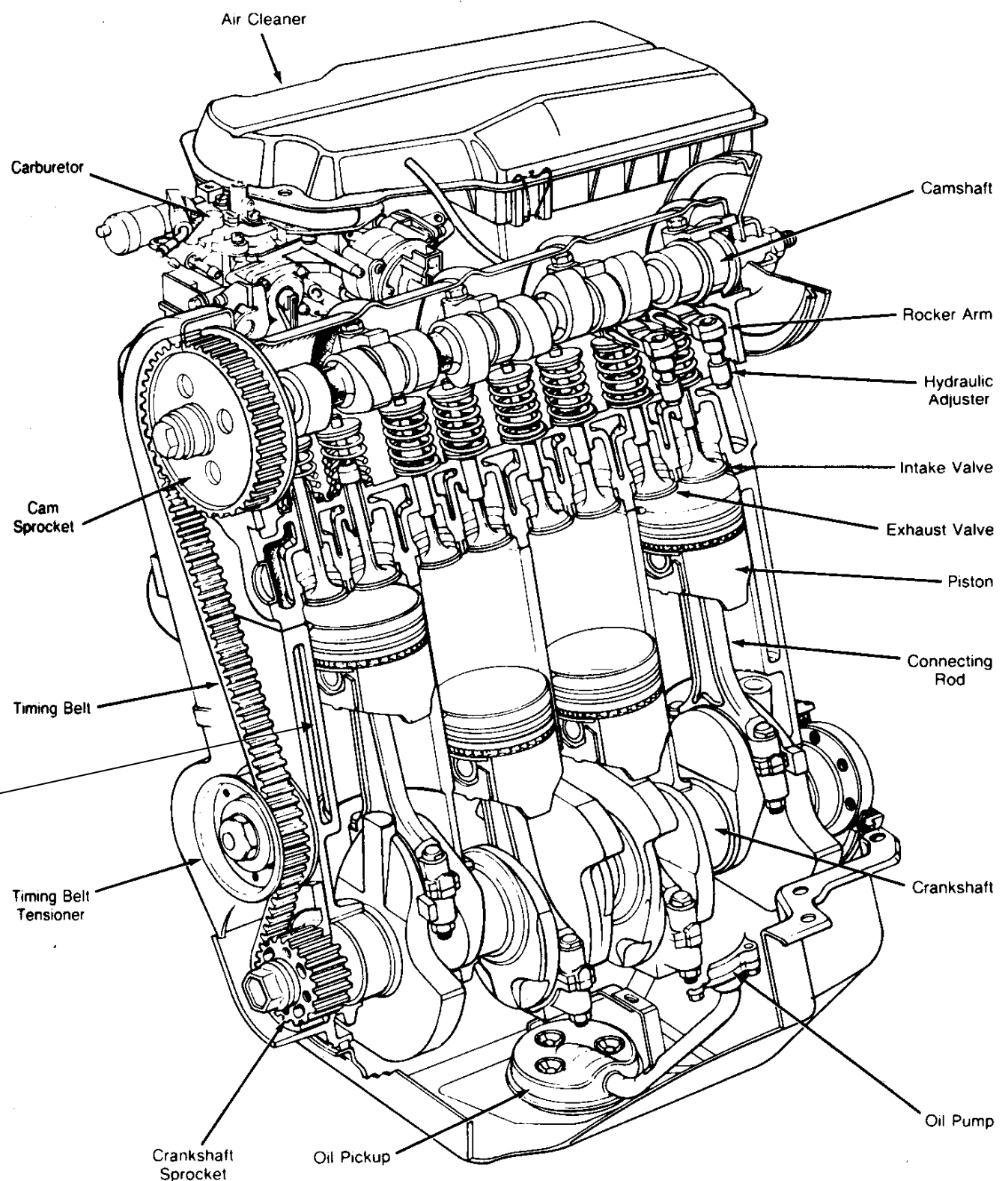
# Typical ICE

The typical car engine:  
4-stroke, 4-in-line cylinders,  
overhead camshaft..



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Channels for cooling  
water (jacket water)



# Main parameters of reciprocating engines

- **Cylinder displacement** (cylinder volume = combustion chamber volume)
- **Number of cylinders**
- **Rotational speed** (revolutions per minute – rpm – also defining the number of work strokes per minute)
- **Number of work strokes per cycle (2 or 4)**
- **Compression ratio**
- **Mean Effective Pressure (break mean effective pressure)**



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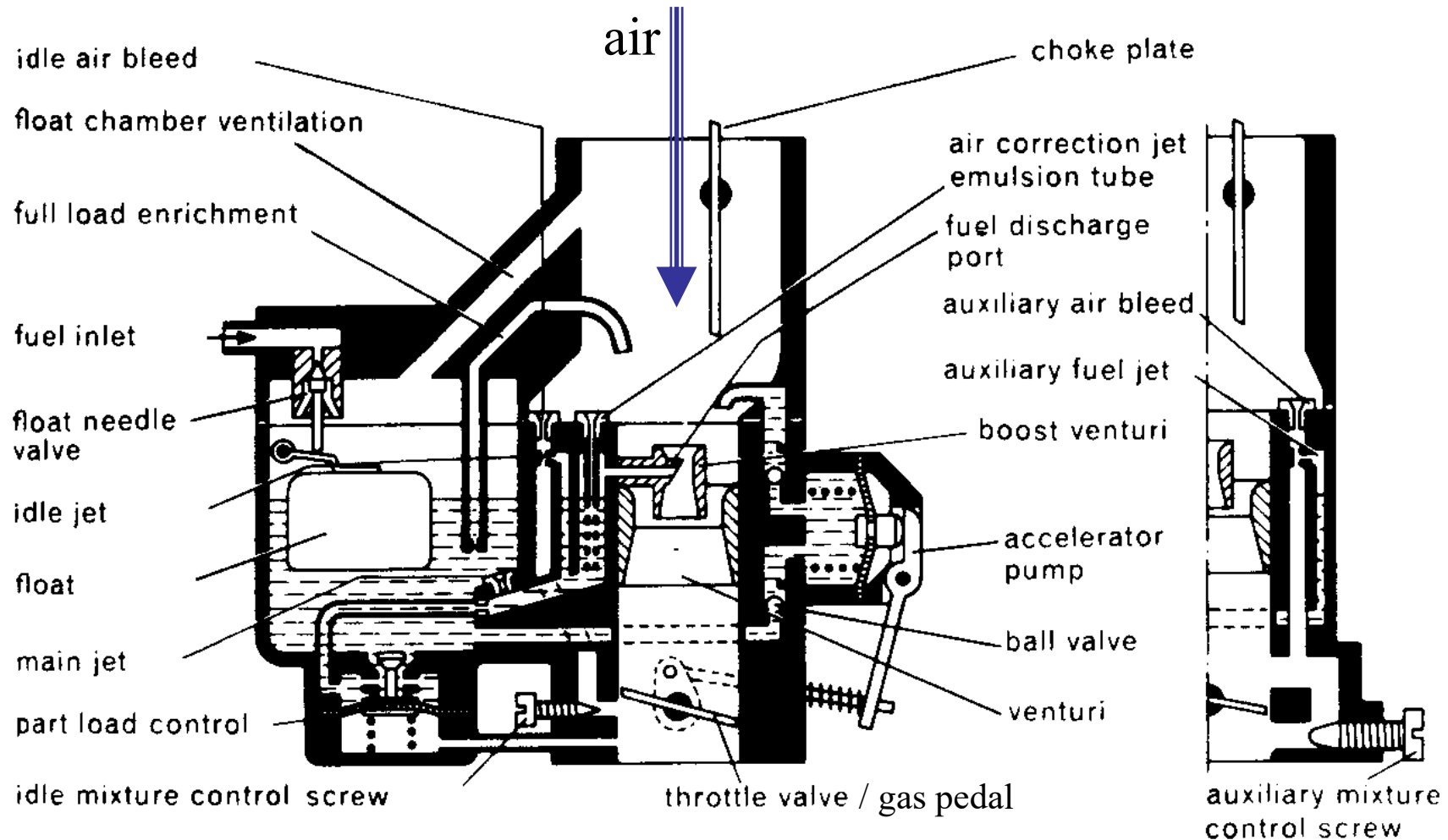
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# The carburetor for old SI engines

Producing the air-fuel mixture for the SI engine. Fumes of fuel vaporized in the intake air flow.



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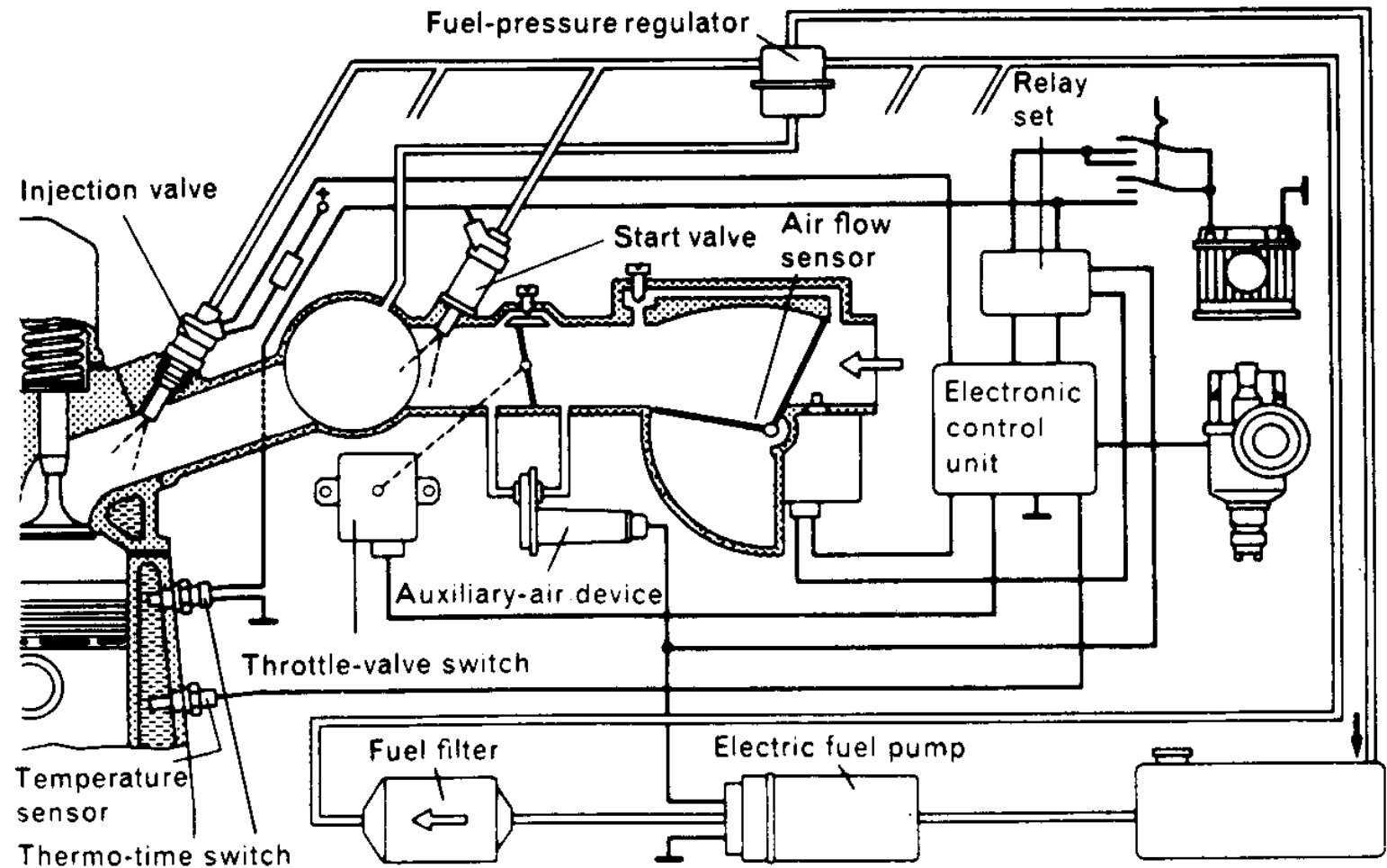


# Fuel Injection for modern SI engines

All SI engines nowadays use fuel injection in the air intake channel. The fuel should vaporize before reaching the cylinder.

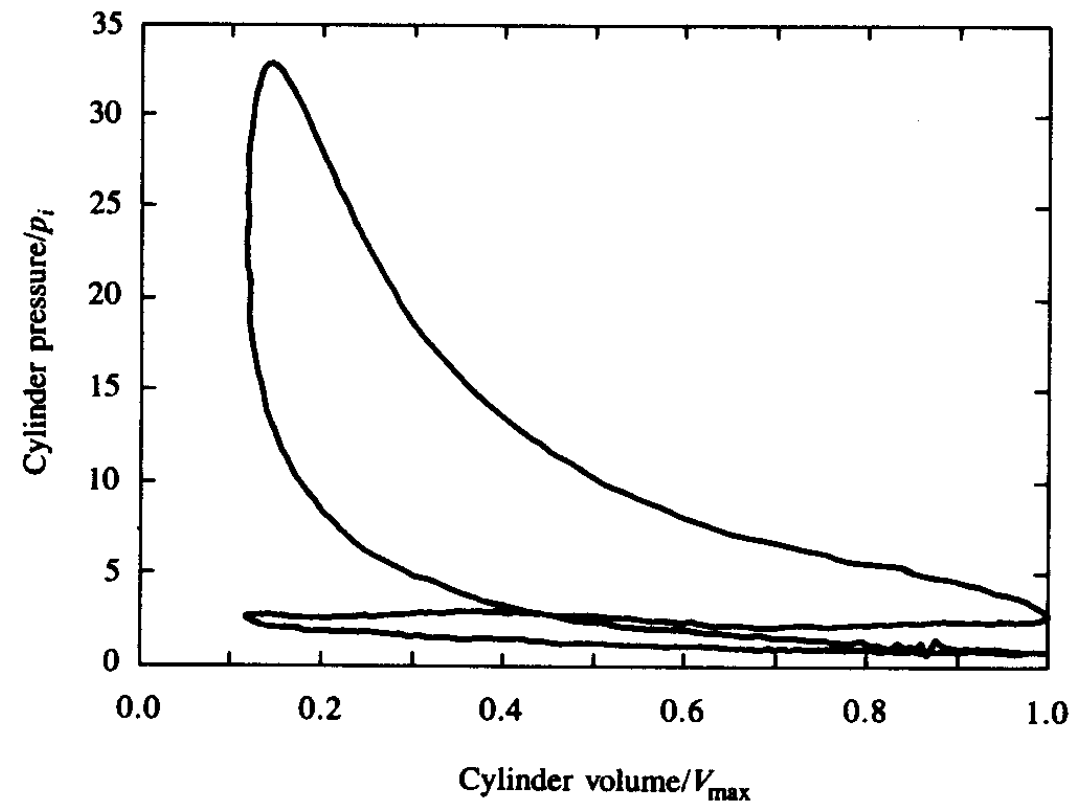
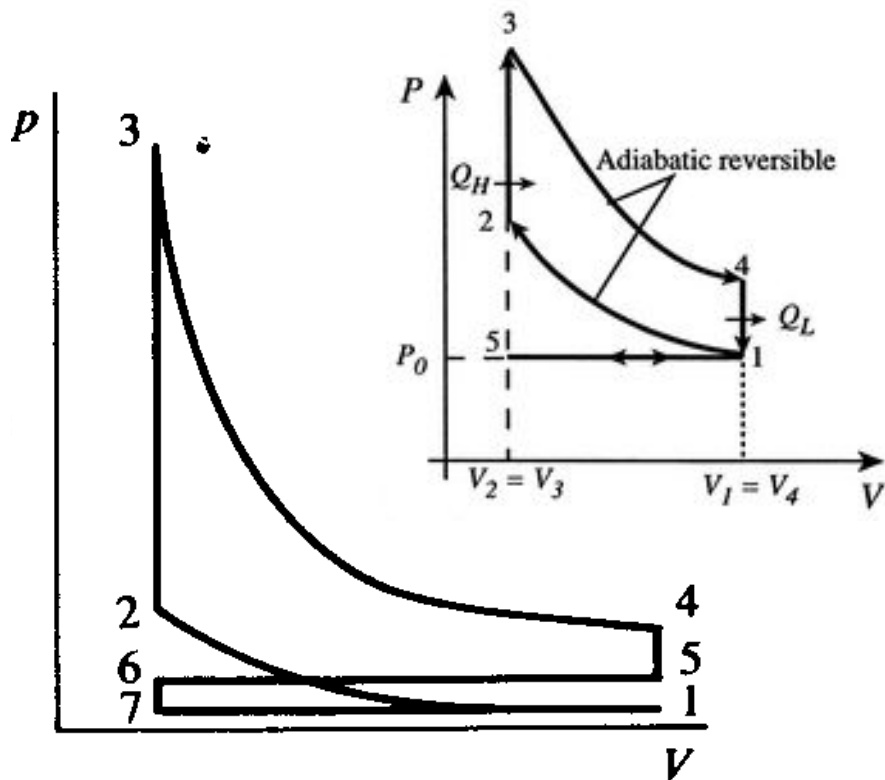


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# SI (gasoline) Engine Thermodynamics

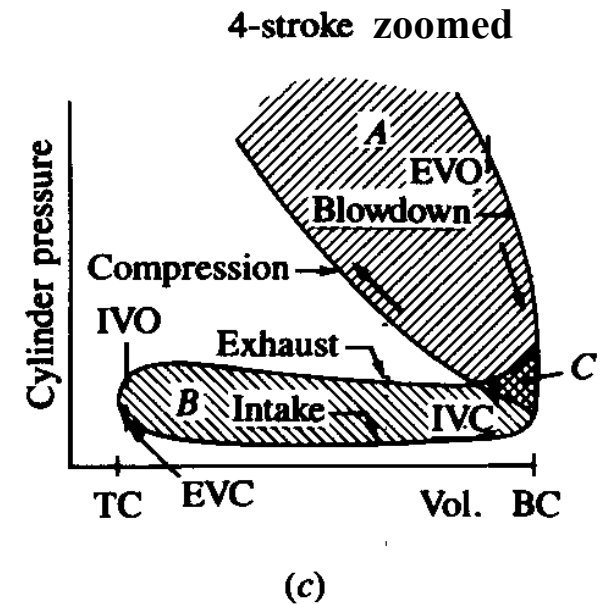
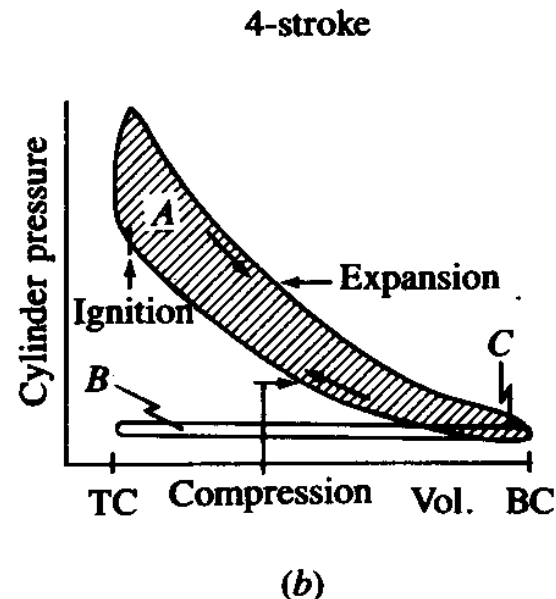
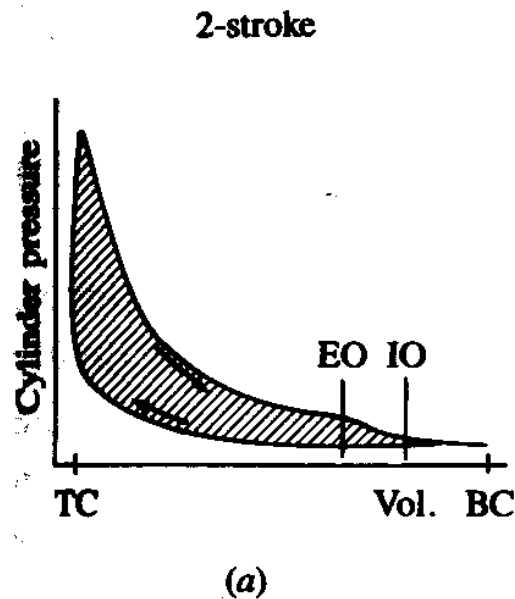
Ideal (left) and real (right) cycle for a 4-stroke SI engine in a p-v diagram. Aspiration losses (cylinder scavenging) clearly seen in the cycle chart below right.



# Real SI Engine Cycles



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Examples of  $p$ - $V$  diagrams for (a) a two-stroke cycle engine, (b) a four-stroke cycle engine; (c) a four-stroke cycle spark-ignition engine exhaust and intake strokes (pumping loop) at part load.



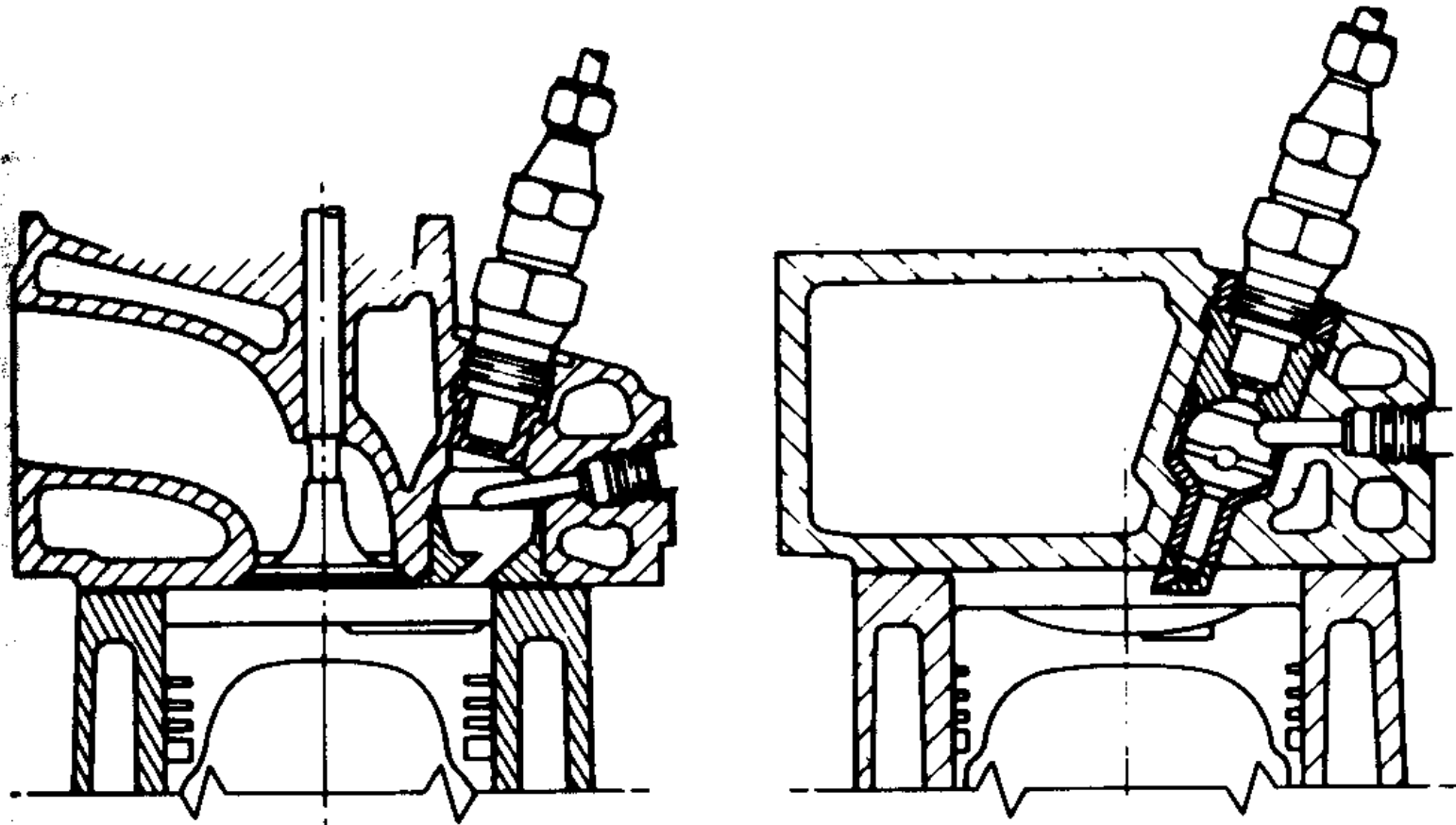
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# Pre-chamber (Indirect Injection) Diesel Engines

Early diesels



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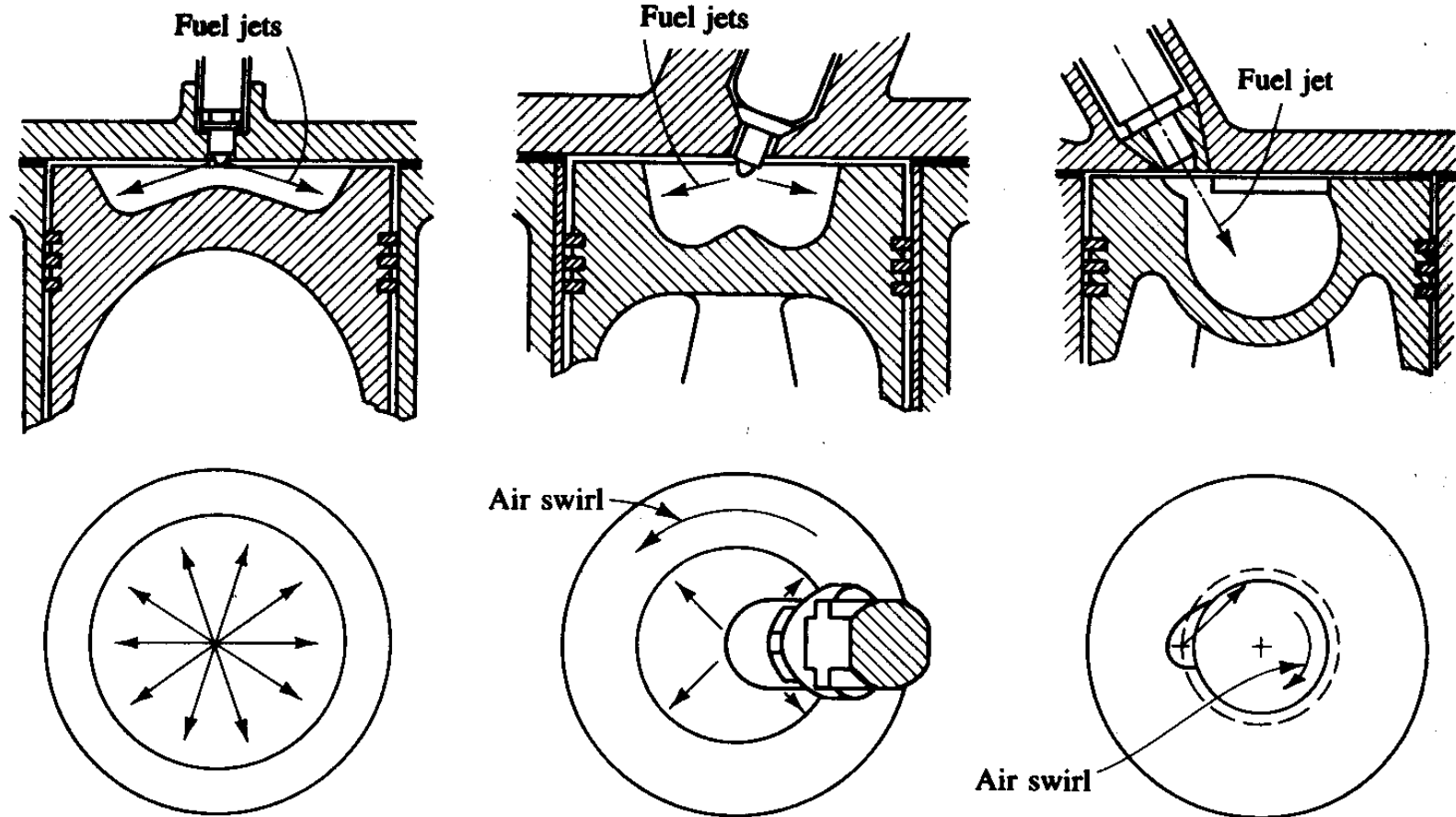
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# Direct Injection Diesel Engines

Modern diesels



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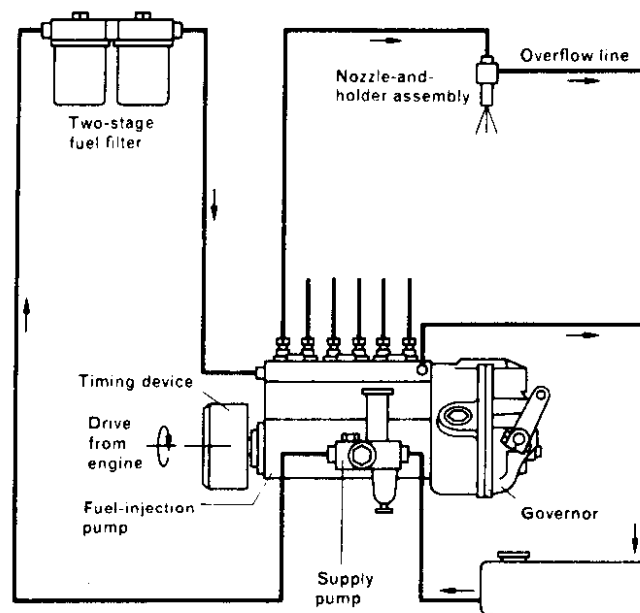


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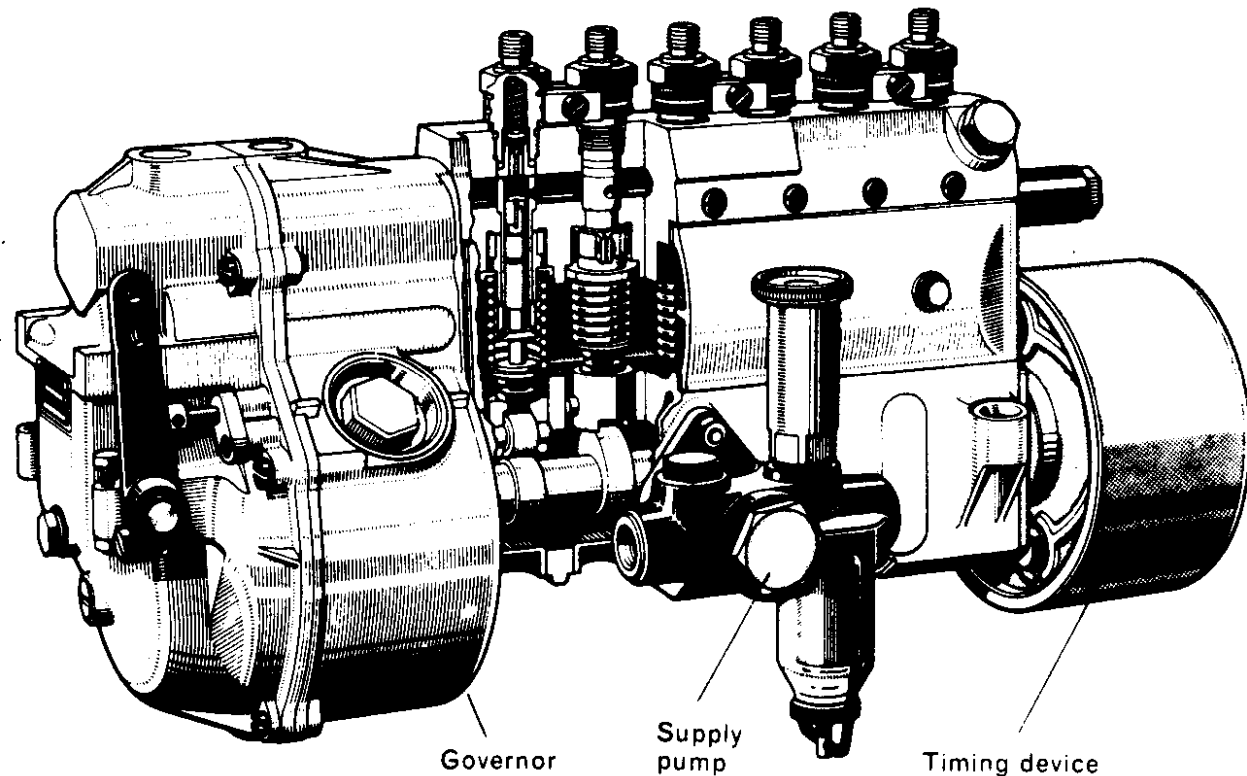
# Diesel Fuel Supply & Injection Pump



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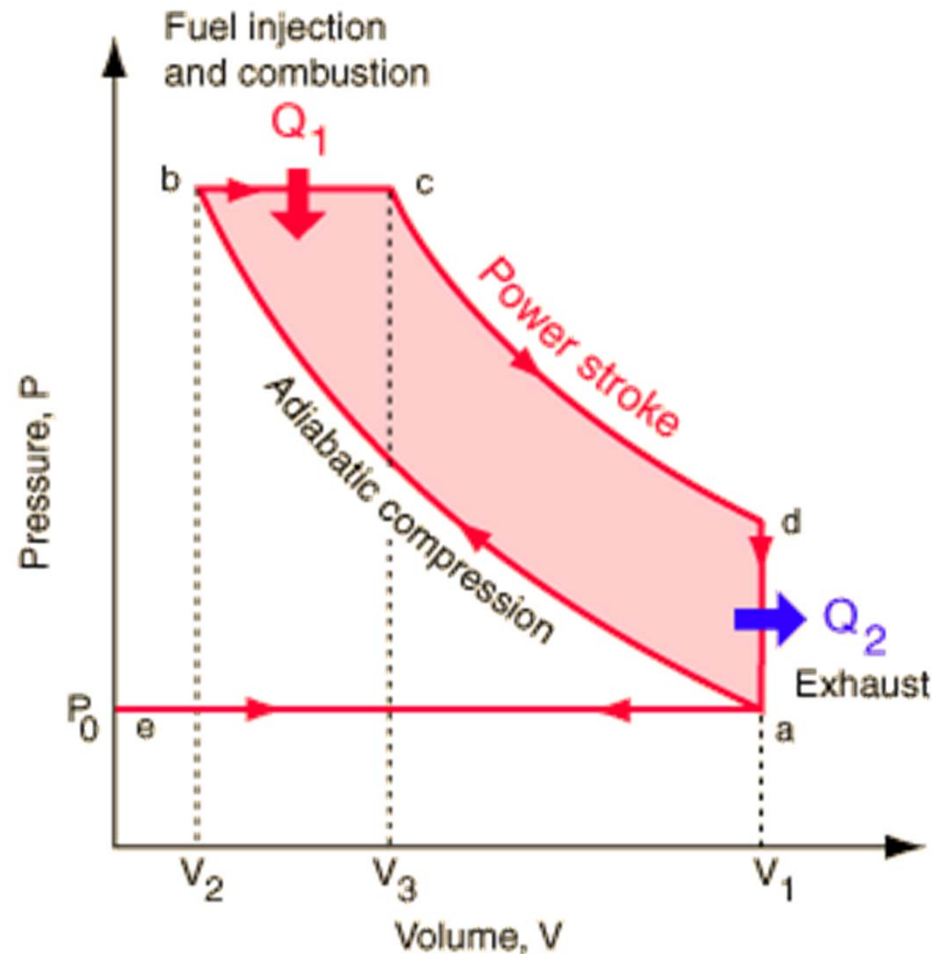


Fuel is delivered and injected at very high pressure into the cylinder – the fuel pump is a very important and vulnerable part of the diesel engine.





# CI (Diesel) Engine Thermodynamics



The Diesel engine is more efficient than the SI one – but is bulky and heavy.



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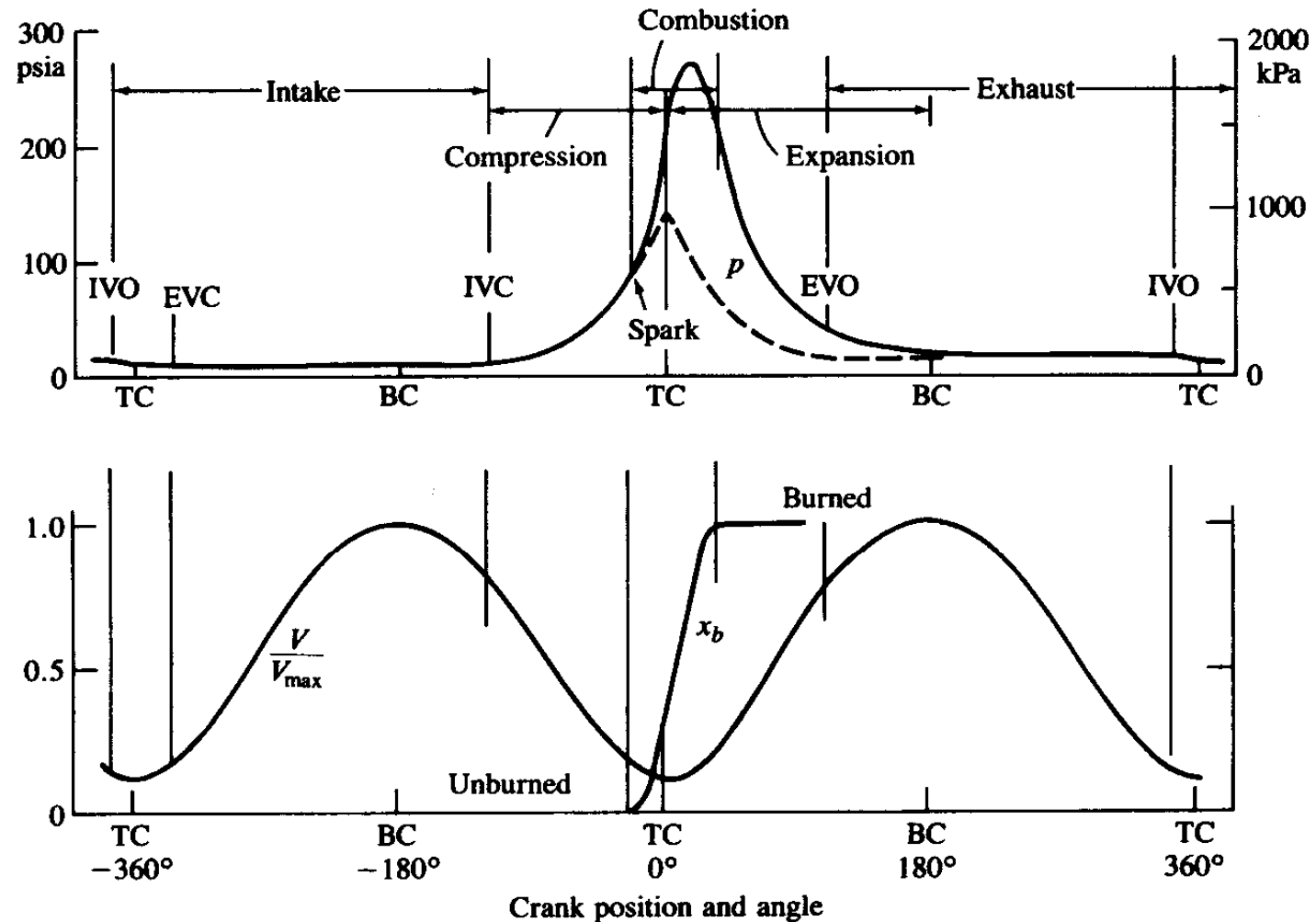
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# Combustion Process & Timing

The proper timing for ignition and for opening/closing the valves is crucial.



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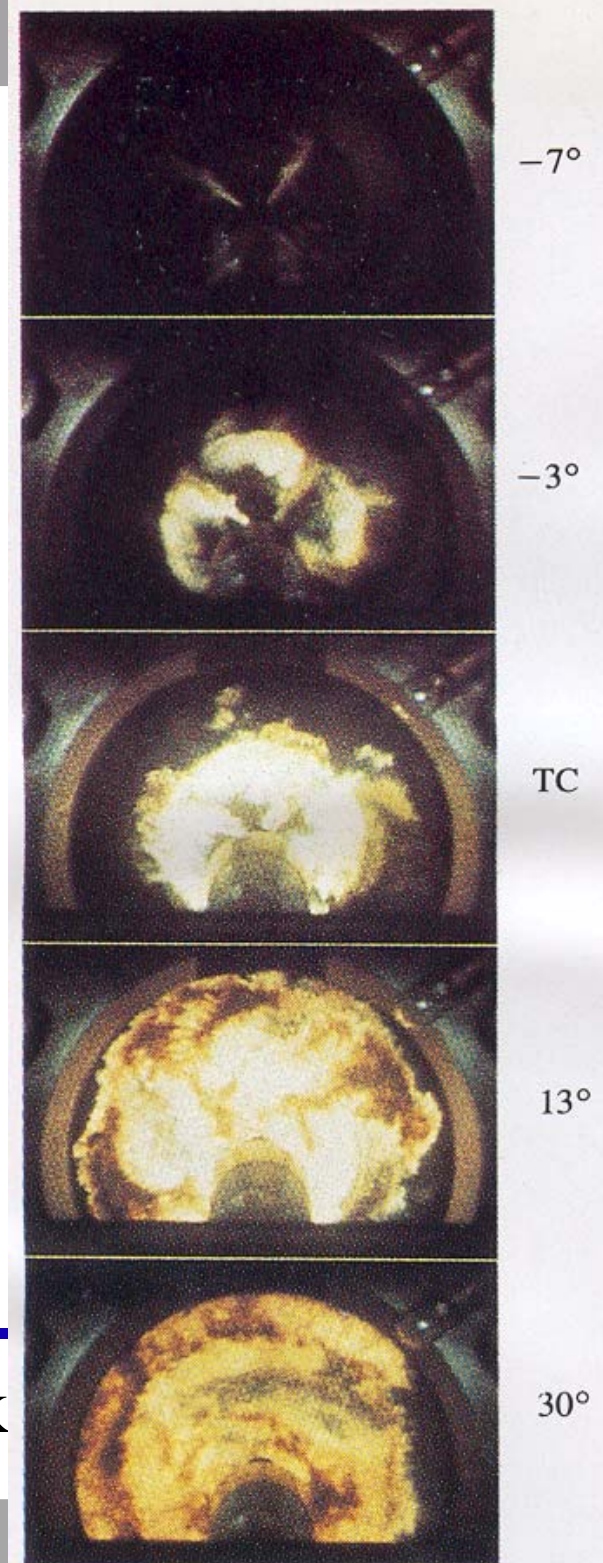
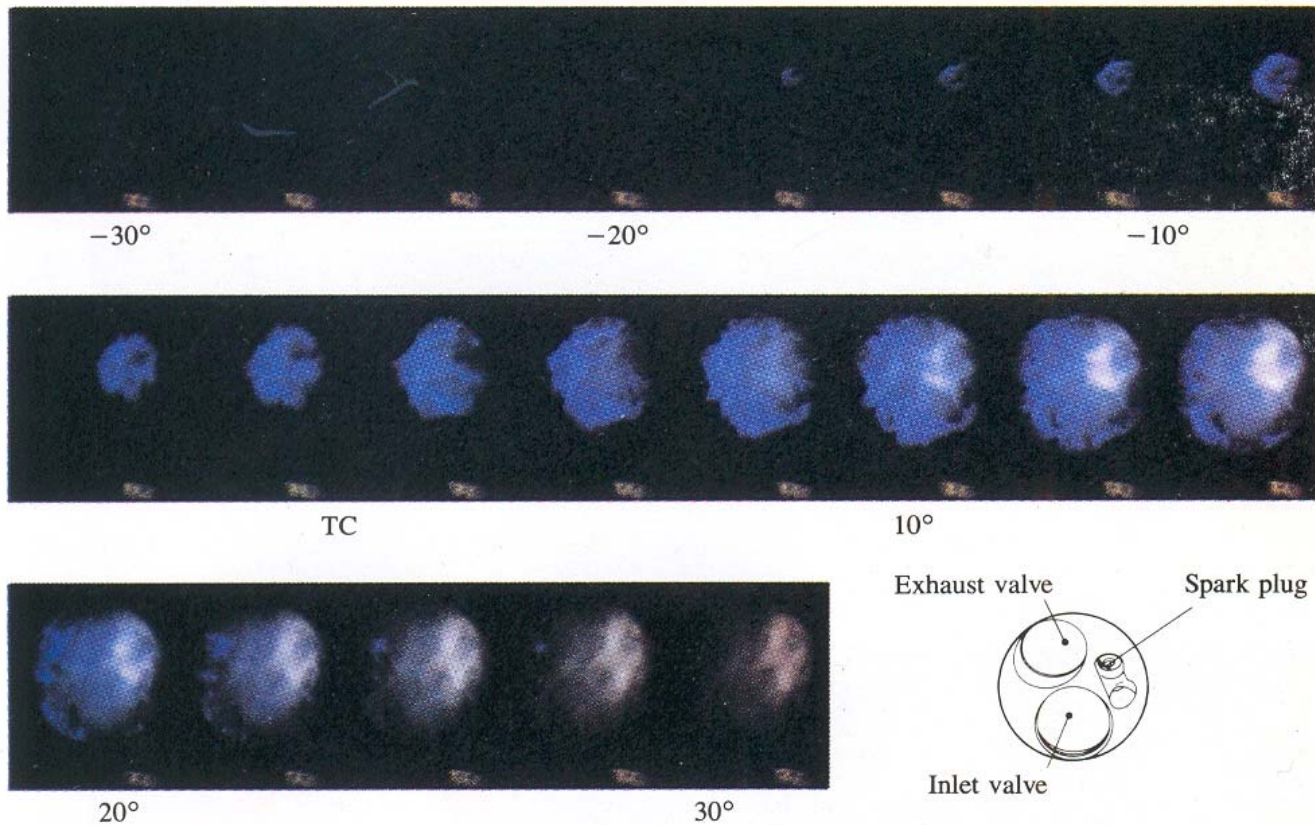


Sequence of events in four-stroke spark-ignition engine operating cycle. Cylinder pressure  $p$  (solid line, firing cycle; dashed line, motored cycle), cylinder volume  $V/V_{max}$ , and mass fraction burned  $x_b$ , are plotted against crank angle.

# Combustion visualization in an ICE

SI engine combustion (left) – advancing flame front through a homogeneous fuel/air mixture.

CI engine combustion (right) – self-ignition and spray-type combustion of the injected fuel droplets.

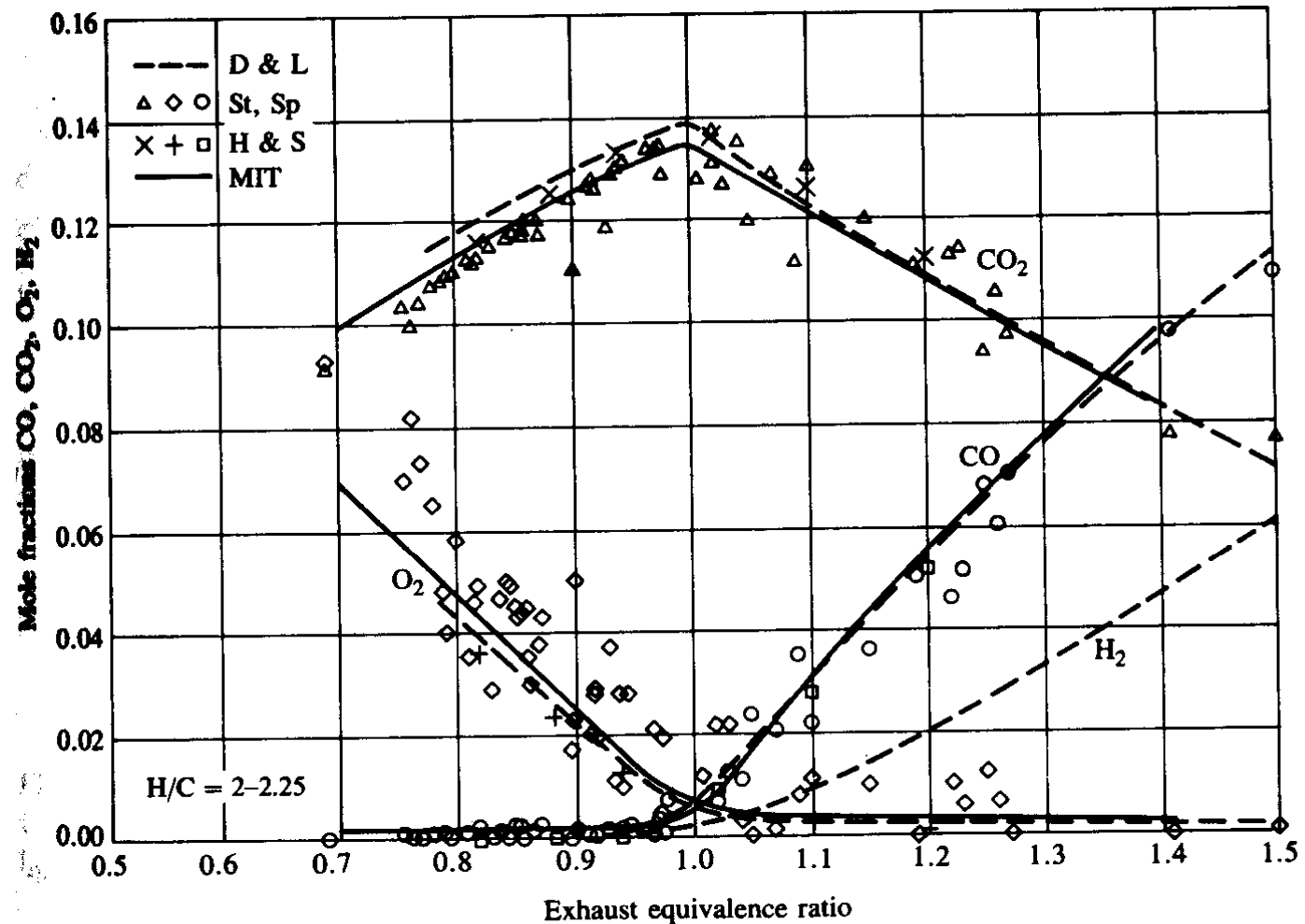


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# Combustion Efficiency



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Spark-ignition engine exhaust gas composition data in mole fractions as a function of fuel/air equivalence ratio. Fuels: gasoline and isooctane, H/C 2 to 2.25. (From D'Alleva and Lovell,<sup>24</sup> Stivender,<sup>25</sup> Harrington and Shishu,<sup>26</sup> Spindt,<sup>27</sup> and data from the author's laboratory at MIT.)



# Environmental performance of IC engines

SI engines tend to produce unburned HC, CO, and NO<sub>x</sub>.

CI engines tend to produce lots of NO<sub>x</sub> and soot, but very little unburned HC or CO.

*Possible solutions for improving the environmental profile:*

- Better control on fuel injection and ignition timing.
- Better construction for proper fuel-air mixing.
- Catalytic converters.
- Exhaust gas recirculation.
- Aftertreatment of exhaust gases with active De-NO<sub>x</sub> systems (chemicals sprayed in the exhaust gas for heavy truck engines).



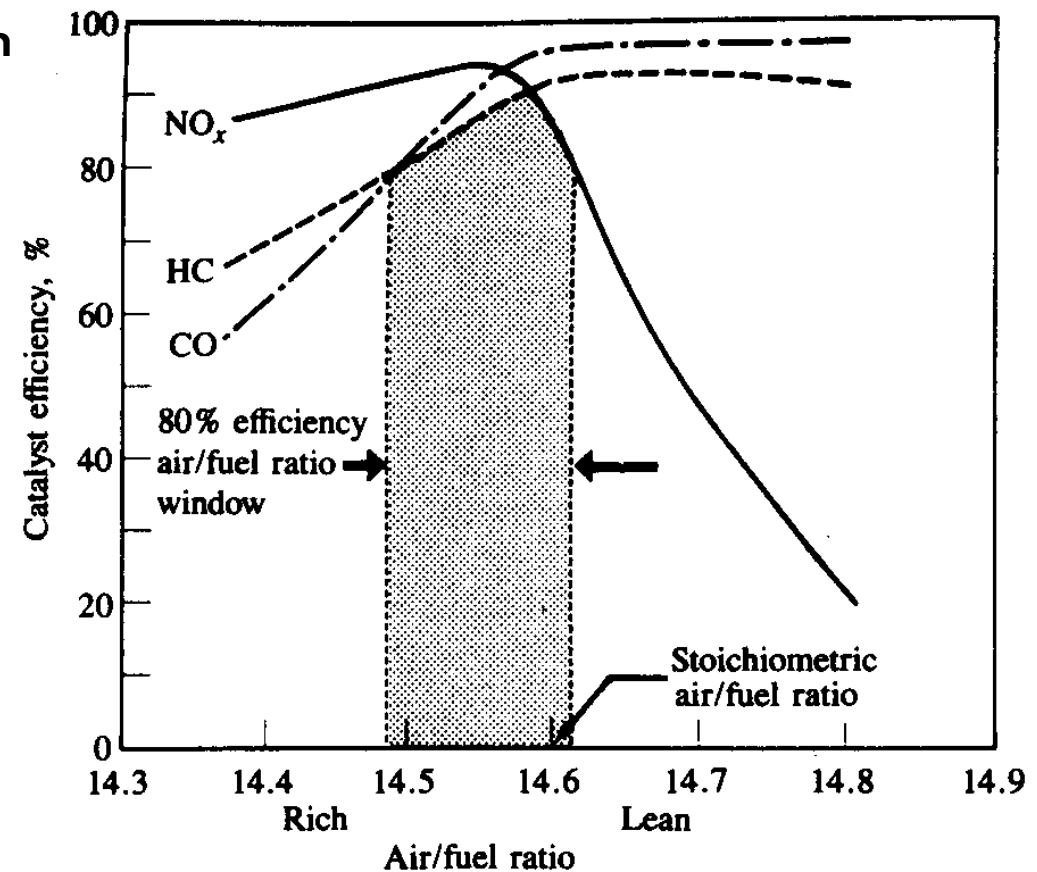
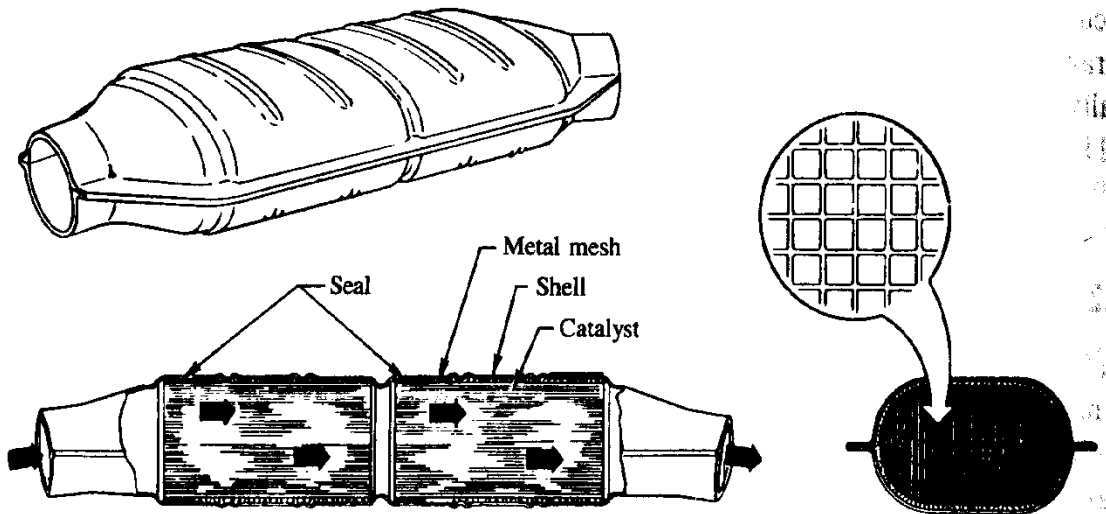
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# The 3-way catalytic converter

Catalytically oxidises CO and unburned HC, and reduces NO<sub>x</sub> to nitrogen and water. Needs stoichiometric conditions (no O<sub>2</sub> left in the gases) in order to function properly.





# Improving ICE efficiency

Common gasoline car engines have typically an efficiency of  $< 20\%$

Diesel car engines can reach 25-30 % efficiency

Truck diesel engines are around 30-35% efficient

Large stationary or marine gas or diesel engines reach  $> 40\%$ , some close to 50% efficiency - the most efficient single-cycle!



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*Ways to improve the efficiency of internal combustion engines:*

- Lean-burn gas engines
- Direct injection for car-size gasoline engines
- Homogeneous-charge compression ignition (HCCI) approach
- Stratified charge or dual-fuel combustion
- Atkinson cycle or other optimized concepts
- Turbocompound systems



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# Atkinson cycle

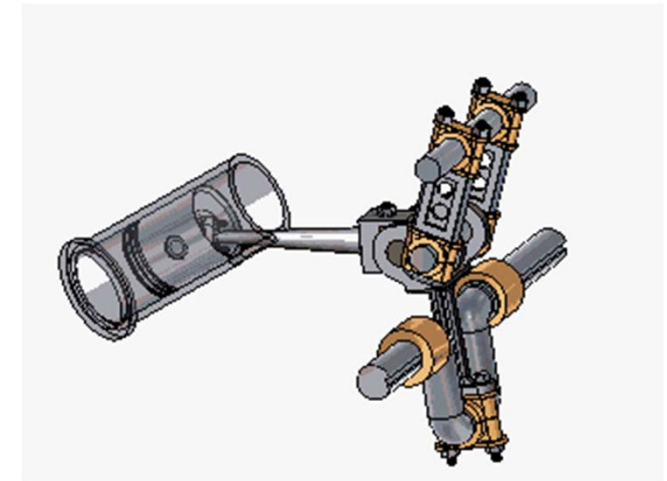
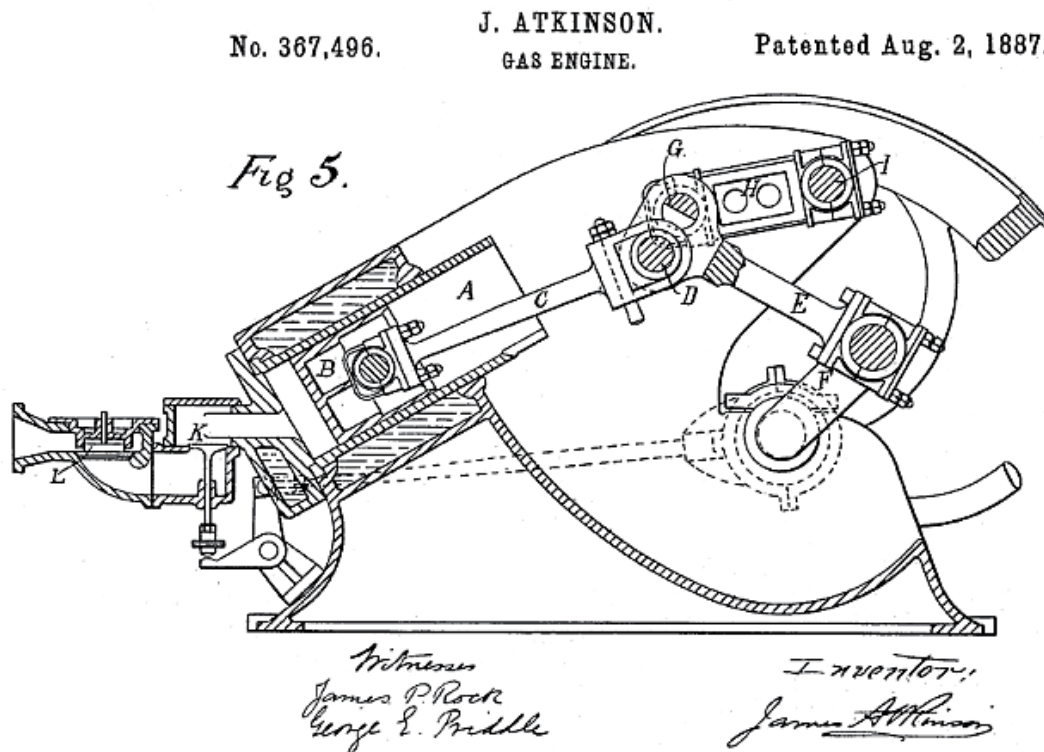
James Atkinson, in the end of the 19th century, proved that a piston engine would be more efficient if the expansion stroke is longer than the compression stroke.

**Difficult to construct mechanically, needs a complicated crankshaft.**

Modern car engines often imitate the Atkinson concept simply by utilizing variable valve timing – for example Toyota.



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Source:  
[www.aqpl43.dsl.pipex.com/MUSEUM/POWER/unusualCeng/atkinson/atkinson.htm](http://www.aqpl43.dsl.pipex.com/MUSEUM/POWER/unusualCeng/atkinson/atkinson.htm)

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# Lean-burn gas engine concept

SI engine efficiency rises with higher compression ratios and leaner combustion (less than stoichiometric fuel-air mixture).

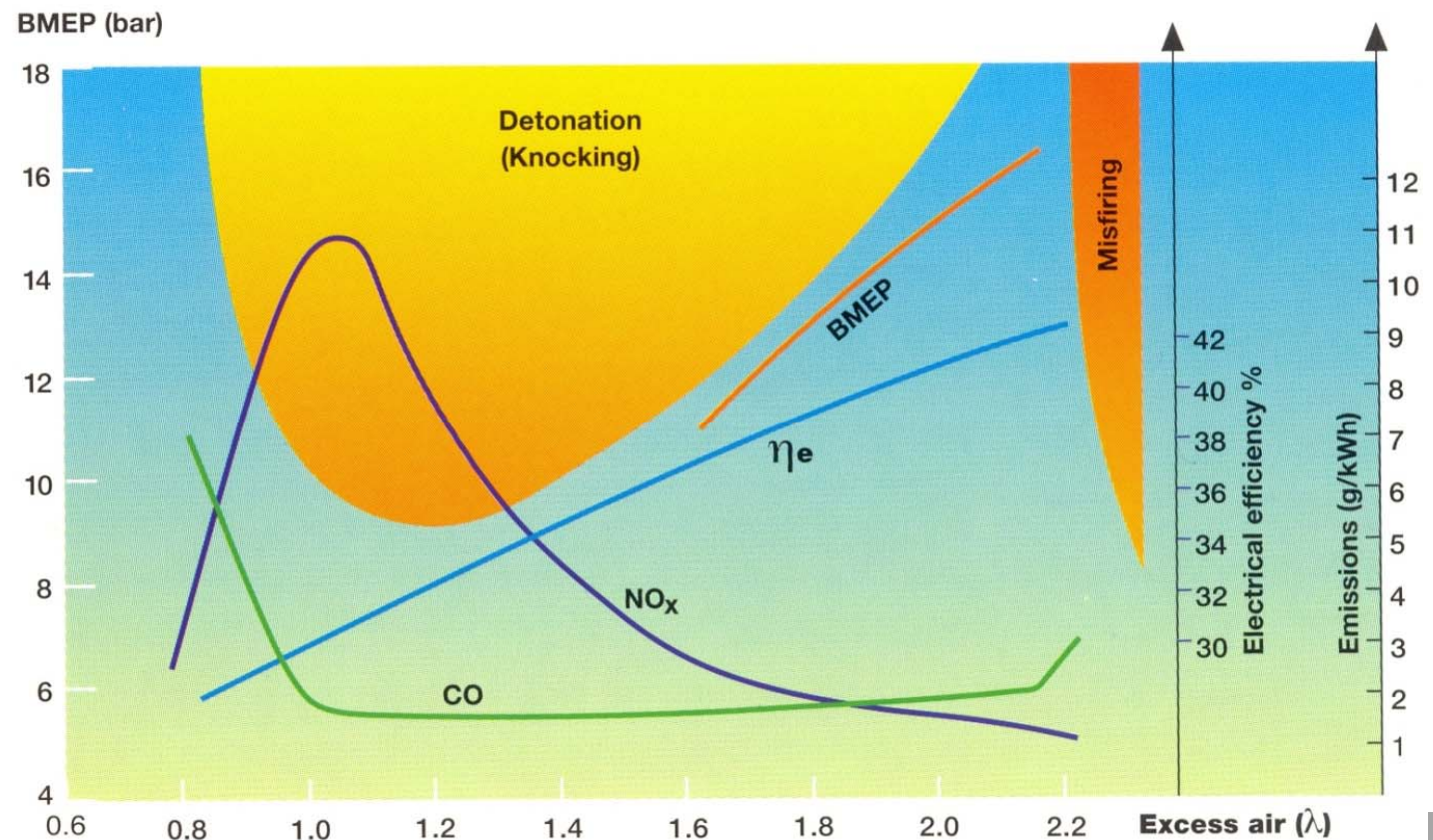
Difficult to control and to keep the combustion process steady between the detonation or misfiring regions at varying loads.

Applied initially in large stationary engines, now state-of-art also for cars.



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Source: Wärtsilä Corp.



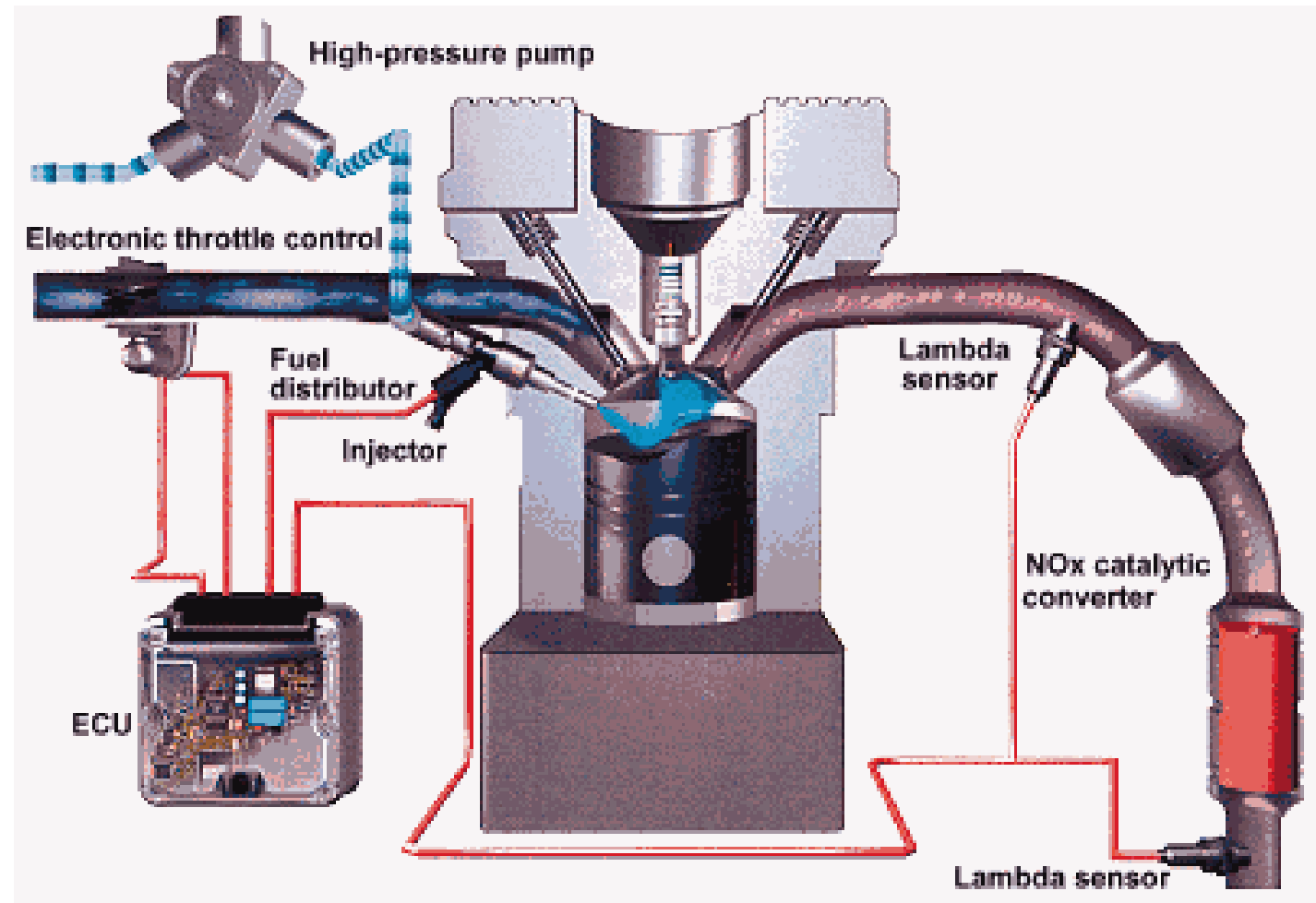
# Direct Injection for SI engines

Leads to higher efficiency and better control on combustion.  
Was problematic until recently.



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Source: [www.sae.org](http://www.sae.org)



# HCCI engines

The homogeneous-charge compression ignition engine is still in a test phase and attempts to blend the positive features of both SI and CI engines.

It is basically a gas engine with a very high compression ratio, where a lean fuel-air mixture self-ignites without a spark.

Main advantages are higher efficiency than typical gas engines and lower emissions than diesels (low NO<sub>x</sub>, no soot).

The disadvantage is the impossibility to properly control the combustion timing, and unstable operation at part-loads.



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Source: [www.naftc.wvu.edu](http://www.naftc.wvu.edu)

<b>Diesel</b> (compression ignition)	<b>Gasoline</b> (spark ignition)	<b>HCCI</b> (Homogeneous Charge Compression Ignition)
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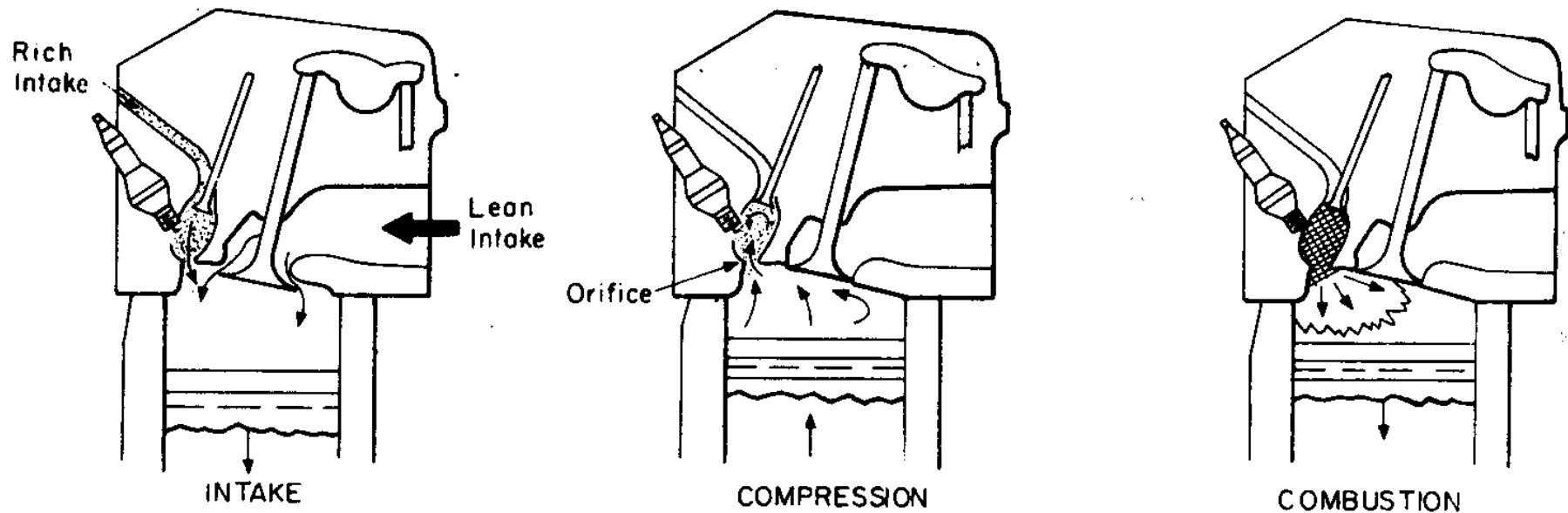


# The stratified charge or dual-fuel approach

A small pre-chamber with rich fuel mixture can be ignited first, then expanding into the main cylinder igniting a lean fuel-air mixture. Used also in gas-diesel dual-fuel engines for igniting the main charge (lean gas-air mixture) by a small pilot flame of diesel fuel. Achieving higher efficiency by lean operation without misfiring.



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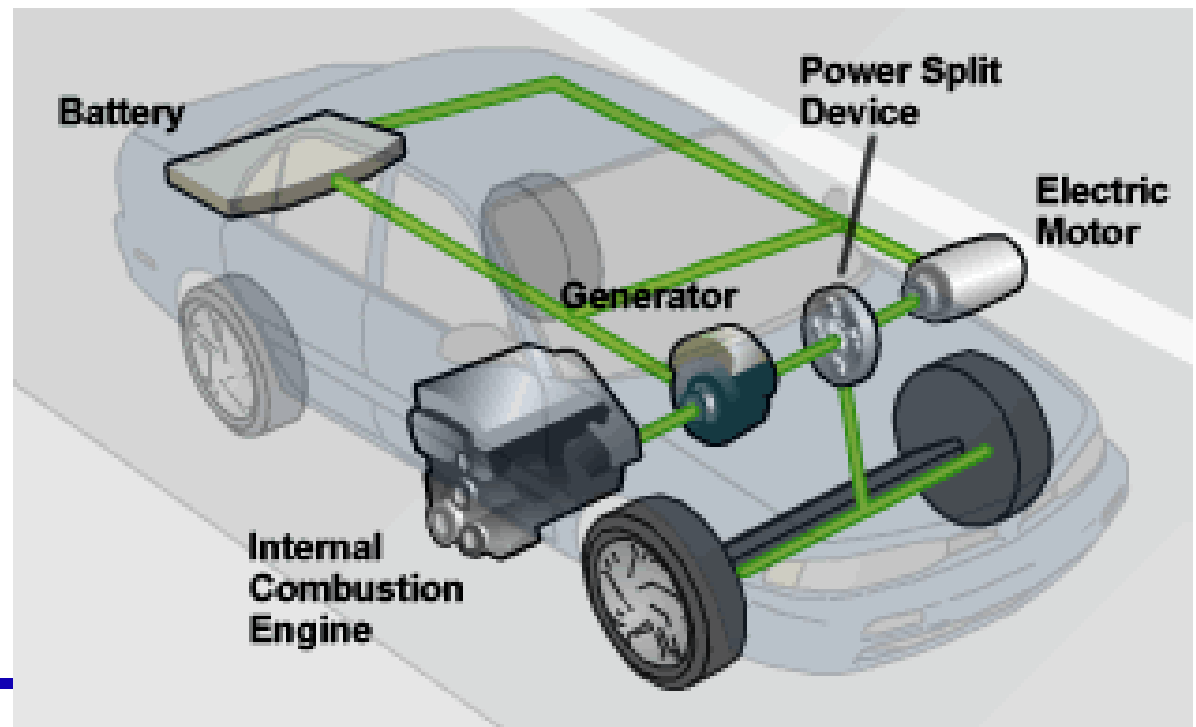
# The Hybrid Vehicle concept

Vehicle engines usually run outside of their optimum parameters, often in deep part-load or idling. One possible way to improve efficiency without changing the engine is to put an energy buffer in the vehicle (e.g. electrical batteries), and let the engine run continuously at its optimum load. The result: hybrid cars!



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Source: [www.fueleconomy.gov](http://www.fueleconomy.gov)



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# Example of ultra-efficient car-size ICE

A small company in Germany - ELSBETT AG – had developed a 50 kW diesel engine to be run on straight vegetable oil (SVO, a biofuel) with efficiency reaching 42%, unrivaled at that size.

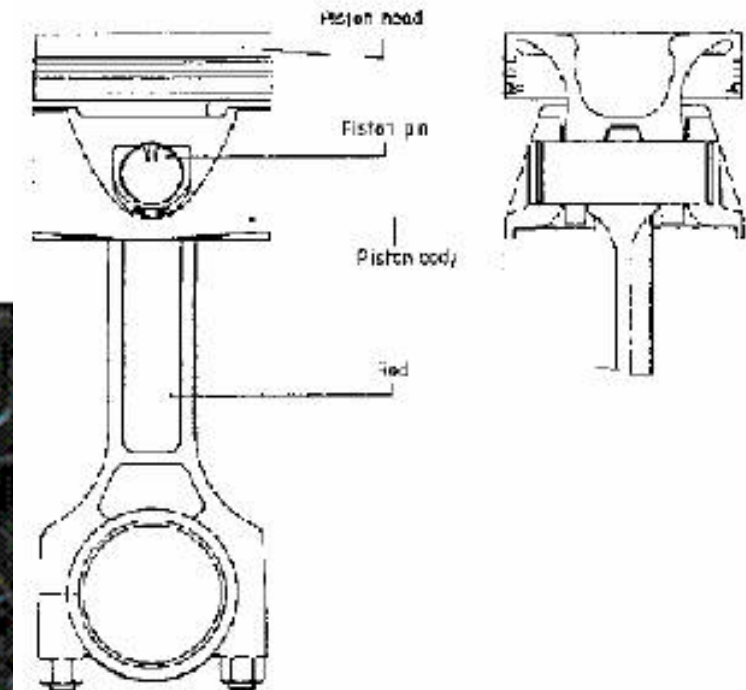
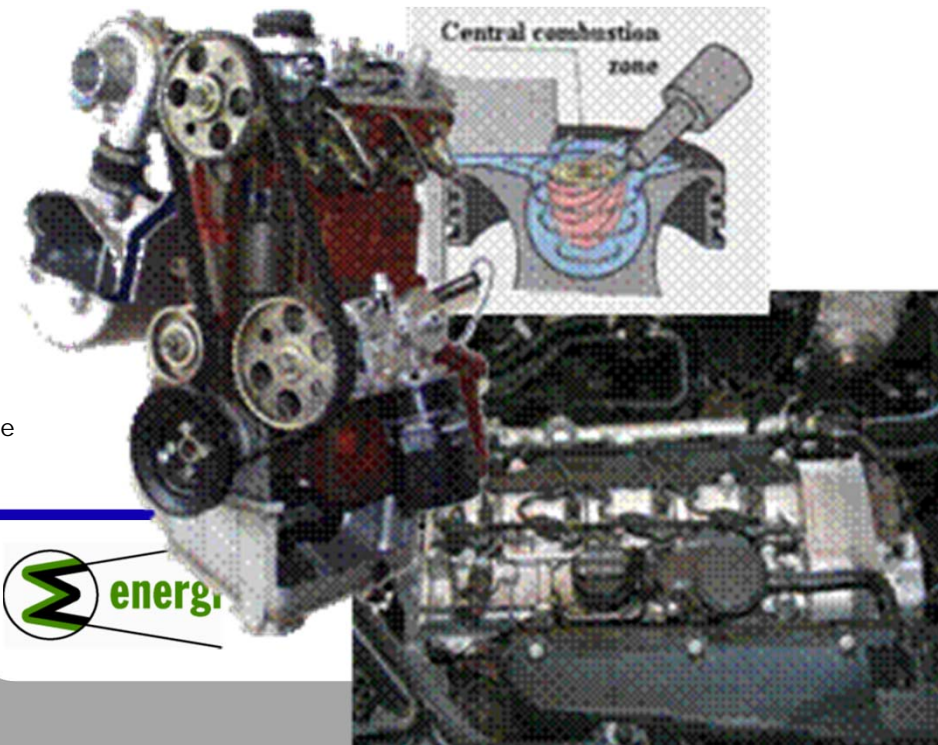
The Elsbett engine used a special swirl fuel injection technique, double-head heat-resistant piston, and very low heat rejection requirements so that cooling via the lubrication oil was enough, without jacket water.

**Equipping all modern cars with such engines in hybrid configuration would decrease the fuel consumption worldwide by half!**



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Source: [www.elsbett.de](http://www.elsbett.de)



# Forced Charging: Supercharger and Turbocharger

Forced charging (**forced aspiration**) delivers more air (= more oxygen) into the cylinder at higher pressure ( $>1$  atm), allowing to produce more work by combusting more fuel in a given cylinder size, if compared to natural aspiration.

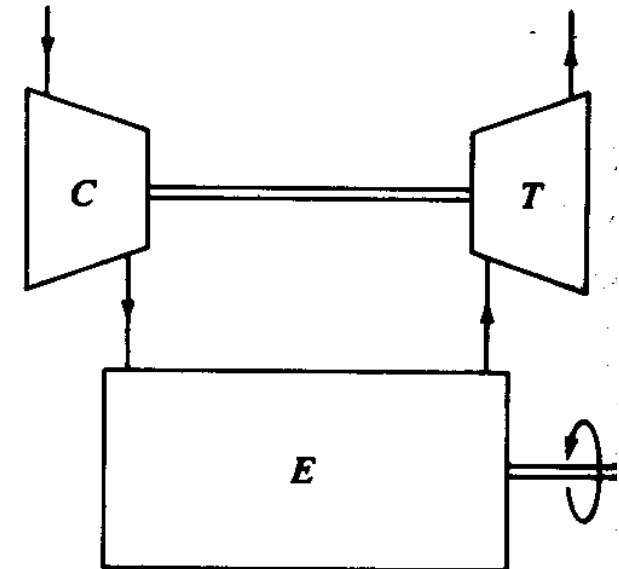
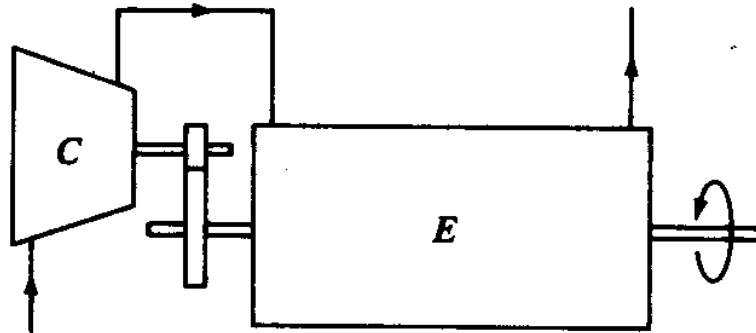
**Supercharger** = air compressor driven by the engine shaft.

**Turbocharger** = free-rotating turbocompressor driven by exhaust gases.

Both can be used, but only the latter can bring along efficiency improvements!



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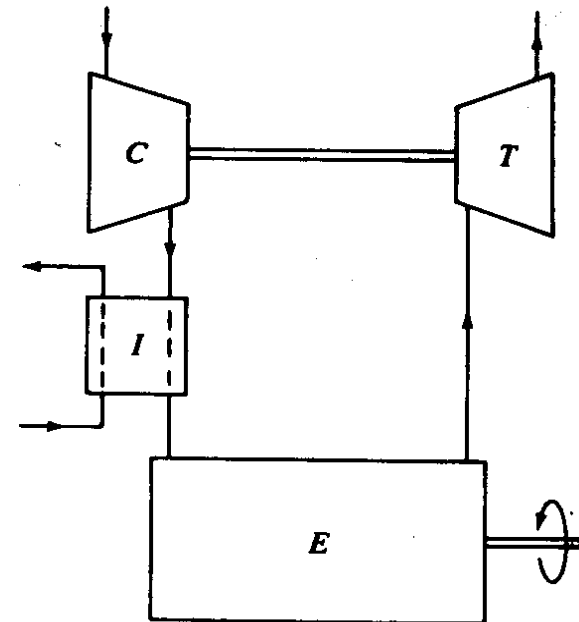
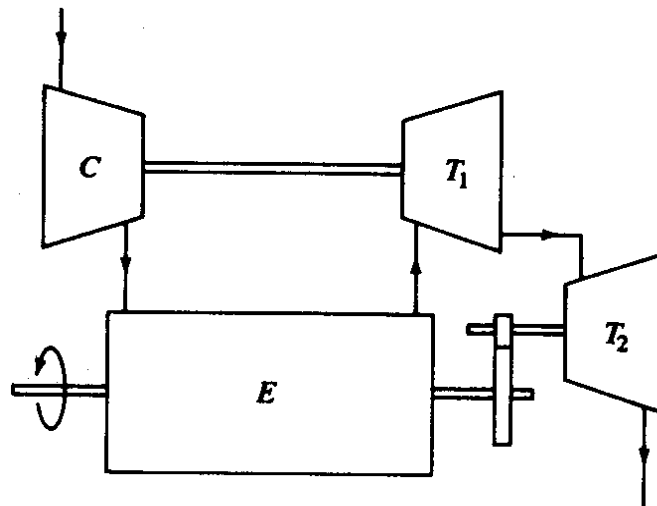
# Turbocompounding and Intercooling

There is more energy to take out of the turbocharger than that used for compressing the intake air. A second expander coupled to the engine shaft can aid in work output, resulting in a sort of a combined cycle.

Intercooling is very important for achieving a good result with forced charging. All modern high-performance engines are turbocharged and intercooled!

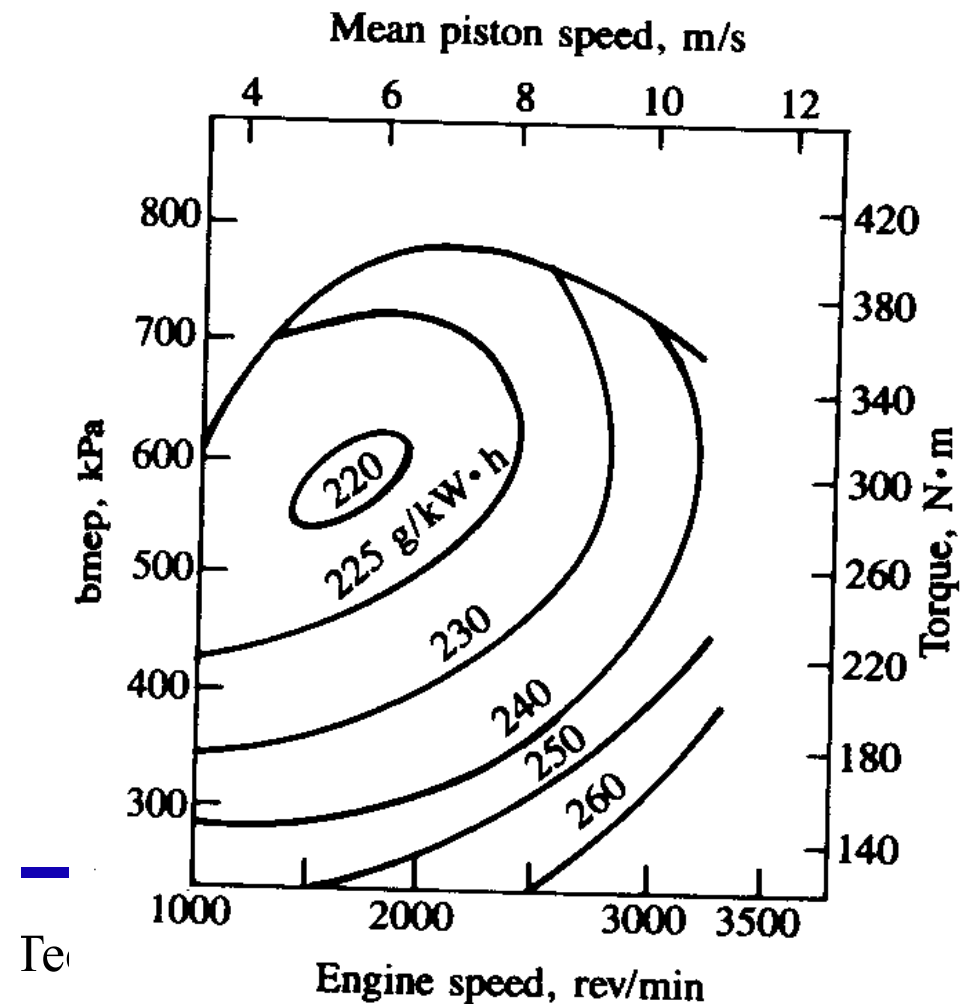
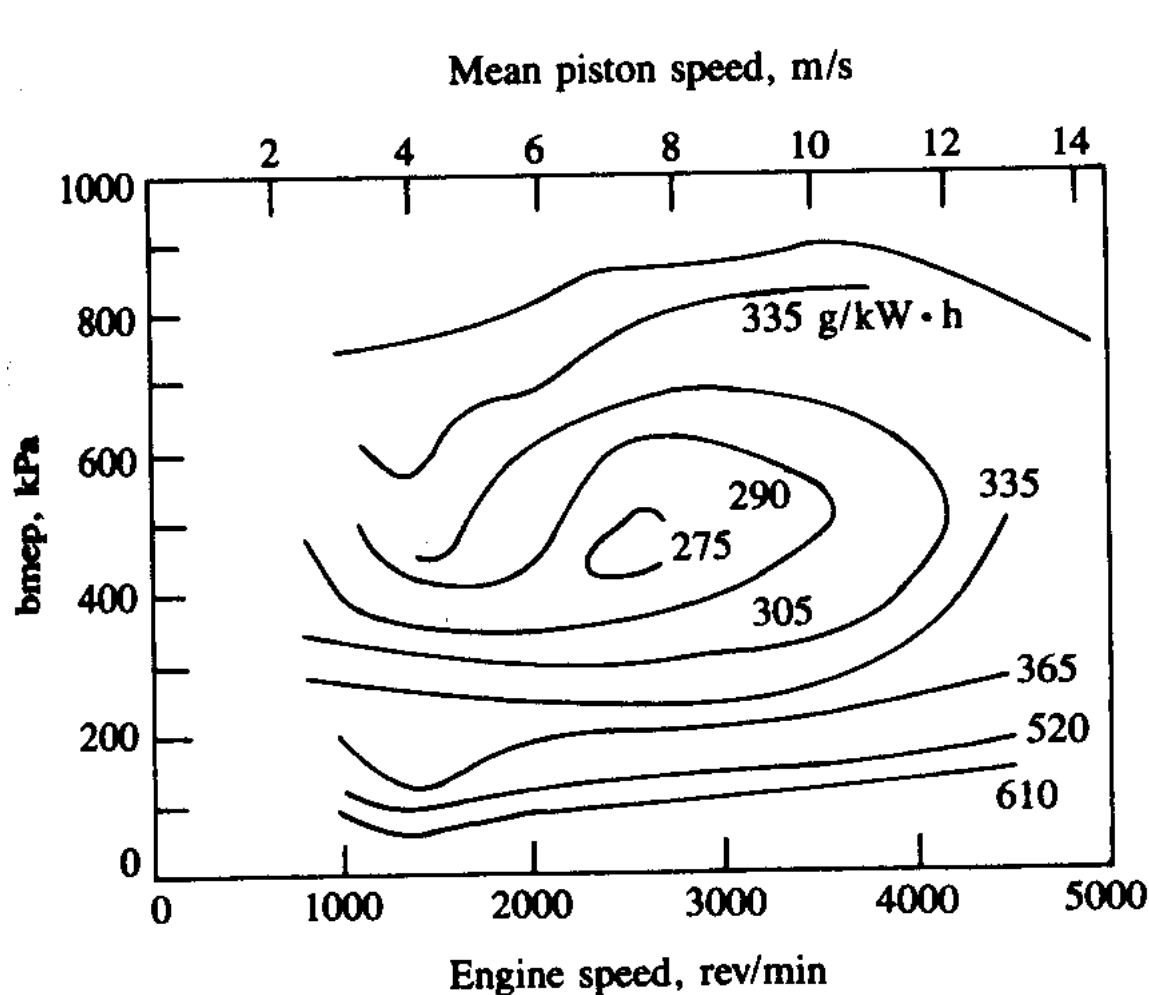


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# Optimum operation

Charts showing optimum operation parameters for lowest specific fuel consumption in grams per kWh, for a gasoline engine (left), and a diesel engine (right):



# Advantages and Drawbacks of ICE

Very suitable for small- or medium-scale power generation.

Their main **advantages** are:

- High efficiency (higher than single-cycle gas turbines at same size);
- Good part-load performance (better than turbines);
- Somewhat lower cost & faster production/delivery than gas turbines;
- Suitable for unit-wise installation – adding separate units for higher total power output, allowing also for efficient part-load strategy.



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**Disadvantages** of ICE, generally:

- Low-temperature waste heat streams, not good for combined cycles;
- Too large volumes and dimensions at high power outputs – engines not feasible for power ratings higher than 40-50 MW per unit;
- Low rpm or induced vibrations detrimental for certain applications;
- May often have high maintenance costs.



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# Modern automotive engines

- SI engines – ECU-controlled direct injection with catalytic converter, exhaust gas recirculation, turbocharging with intercooling, electronic ignition...
- CI Engines – ECU-controlled direct injection of common-rail or injector-pump (pumpe-düse) type, multipoint injectors, multiple injections per stroke, exhaust gas recirculation, double turbochargers with intercooler, particle filter (soot filter)...



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# Electronic control of modern engines

Modern electronics (cheap and reliable) allow for better control on engine operational characteristics, optimising engine performance.

The following major parameters are constantly monitored by sensors, sending signals to the ECU, deciding the amount of injected fuel and the ignition/injection timing:

- Intake air mass flow;
- Intake air temperature and pressure;
- Cooling water temperature;
- Lambda-value ( $O_2$  remaining in exhaust gases);
- Load on the engine at the given moment (gas pedal position);
- Fuel type (for multifuel engines).



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# Large Stationary or Marine Engines

Stationary ICE are used for power generation in isolated grids or as flexible load-following peak-shavers.

Typically as gas or diesel (or dual-fuel) engines of up to 24 cylinders, V-shape.

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Here an example of a new flexible power plant using several 20V34SG gensets from Wärtsilä.

Source: [www.wartsila.com](http://www.wartsila.com)



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# ICE power plants

**Many small electrical grids around the world (often on islands) completely rely on stationary IC engines for both base-load and peak-load power.**

Most of the small-scale local CHP plants burning natural gas or biogas would typically use an ICE instead of a gas turbine.

IC engines are also the backbone of most island grids and especially on marine vessels, both for ship propulsion and for on-board electricity generation.

**Also, many flexible peak-load or back-up power plants in utility grids are based on IC engines instead of gas turbines.**

***Largest ICE power plant in the world: Total capacity of 573 MW!***

The Al Manakher IPP3 plant near Amman, Jordan.

Featuring 38 engines delivered by Wärtsilä, 22 of them operating at base-load with 60% capacity factor, the remaining 16 engines serving variable peak loads with about 40% capacity factor.

All engines are able to operate on triple-fuel (tri-fuel) mode – using either natural gas, LFO or HFO as fuel.





## ICE power plants (2)

Also, many industrial sites rely on ICE for local power and machine drives, including the oil and nat.gas drilling & exploration sector.



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Here an example of a new 24 MW<sub>el</sub> power plant using 4 units of the Caterpillar G16CM34 generator sets.

Source: [www.cat.com](http://www.cat.com)



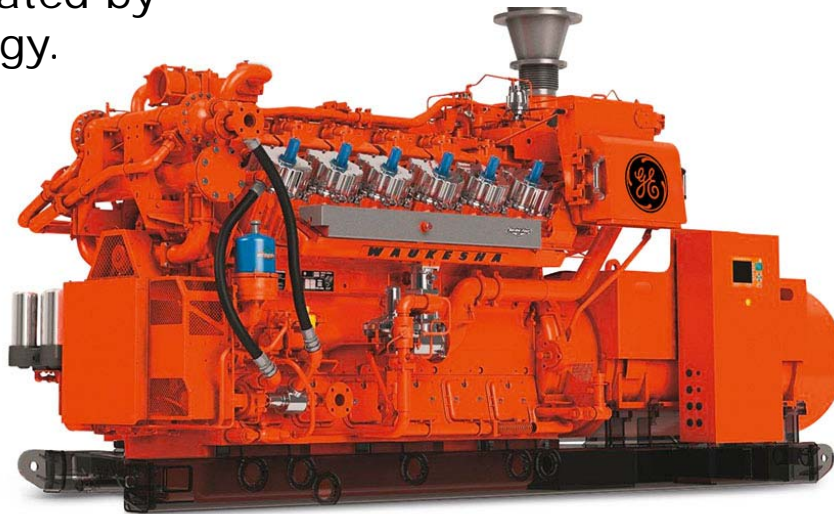
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## ICE power plants (3)

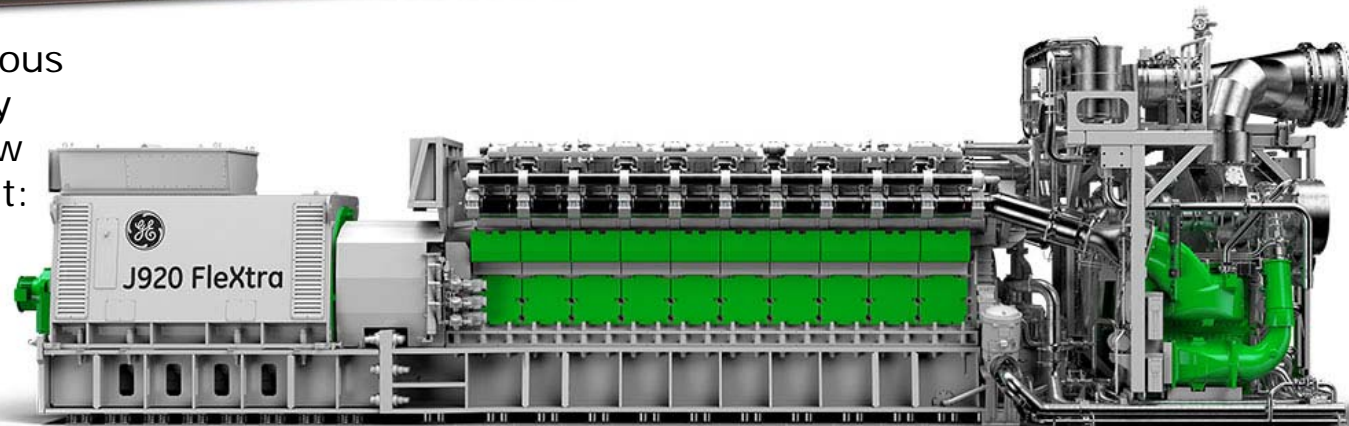
Most importantly, ICE have become a preferred choice in dynamic applications such as back-up and balancing power for grids dominated by renewable energy.



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Here are examples of some famous (now GE-owned) gensets by Waukesha and the very new Jenbacher J920. Above-right: a 51 MW<sub>el</sub> gas-fired plant using 6 units of the J920.



Source: [www.powergen.gepower.com](http://www.powergen.gepower.com)



# Two-stroke Marine Diesels

The most efficient engine today is the 2-stroke diesel for marine propulsion, with power output of up to 80 MW per unit!



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Source: [www.emma-maersk.com](http://www.emma-maersk.com)



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# Waste heat from an ICE

**The ICE is a very efficient single-cycle engine, rejecting waste heat at low temperature levels in three or four separate streams.**

Below is a list of main heat sink streams and their typical energy content (% of fuel energy) & temperature levels:

- Exhaust gas ~ 20–35% @ 300–450°C
- Jacket water (or air cooling of engine block) ~ 10–30% @ 90°C
- Lubrication oil cooler (sometimes missing) ~ 6–10% @ 70–80°C
- Charge air cooler / intercooler ~ 8% @ 50–150°C

Small engines lose more heat with jacket cooling than with exhaust gas, while it is the opposite for large engines.

**Internal combustion engines are not suitable for combined cycles due to very low temperature waste heat in several streams.**

They are, however, very suitable for CHP applications!



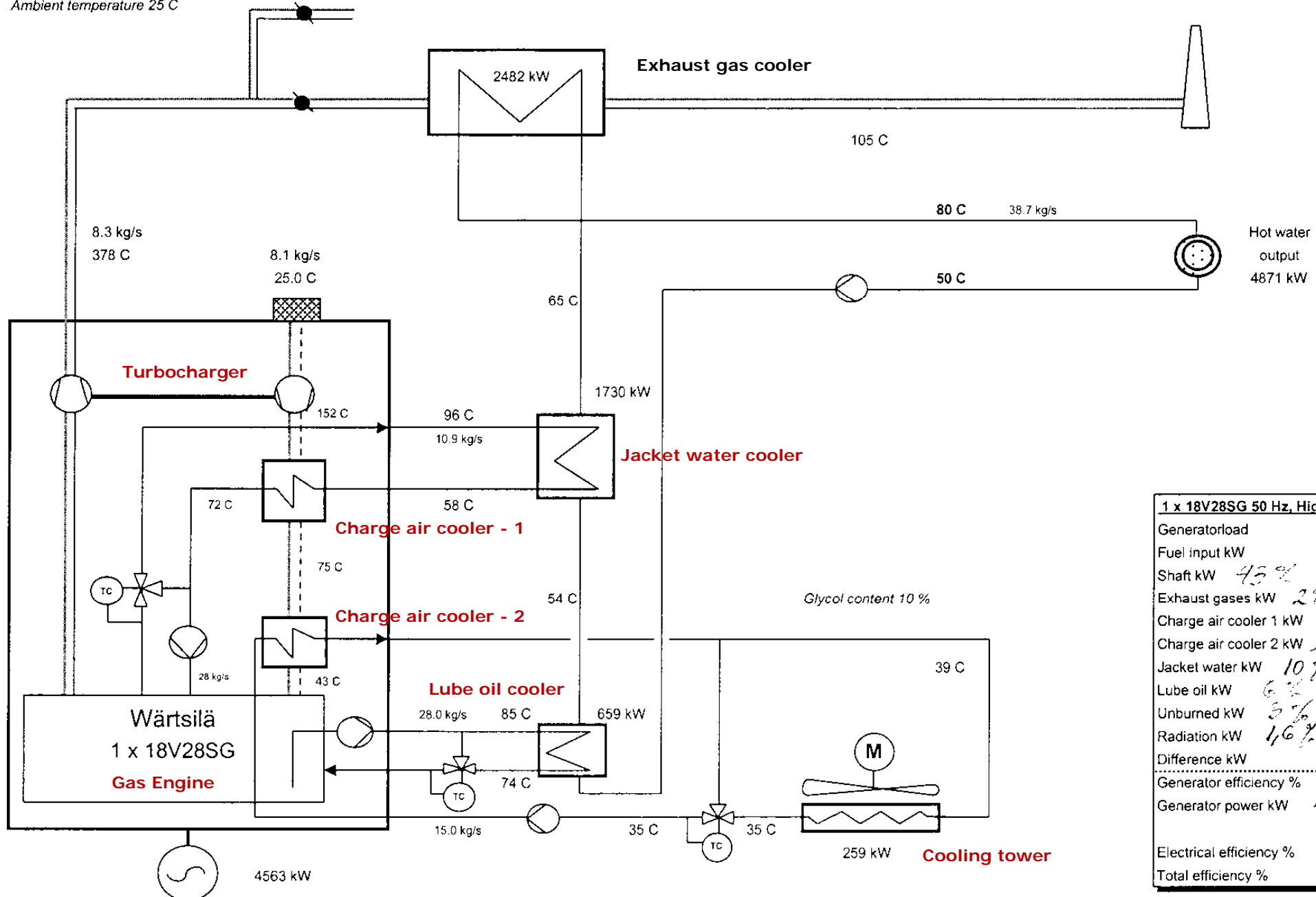
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# CHP applications of IC engines (1)

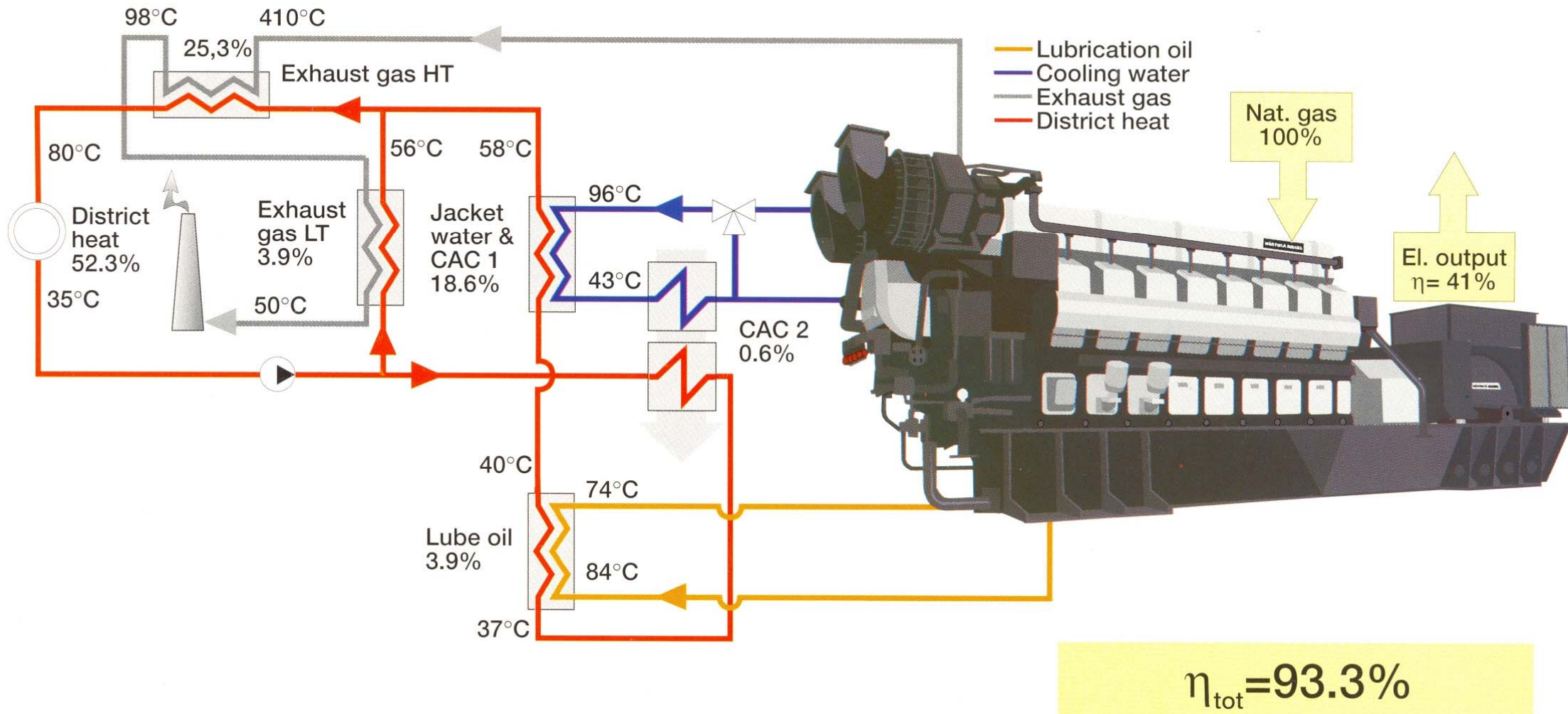
Ambient temperature 25 C



1 x 18V28SG 50 Hz, High efficiency		
Generatorload		100 %
Fuel input kW		10998
Shaft kW	45 %	4729
Exhaust gases kW	29.5 %	3129
Charge air cooler 1 kW	5.7 %	633
Charge air cooler 2 kW	2.4 %	259
Jacket water kW	10 %	1097
Lube oil kW	6 %	659
Unburned kW	3 %	321
Radiation kW	1.6 %	171
Difference kW		0
Generator efficiency %		96.5
Generator power kW	44.5 %	4563
Electrical efficiency %		41.5
Total efficiency %		85.8

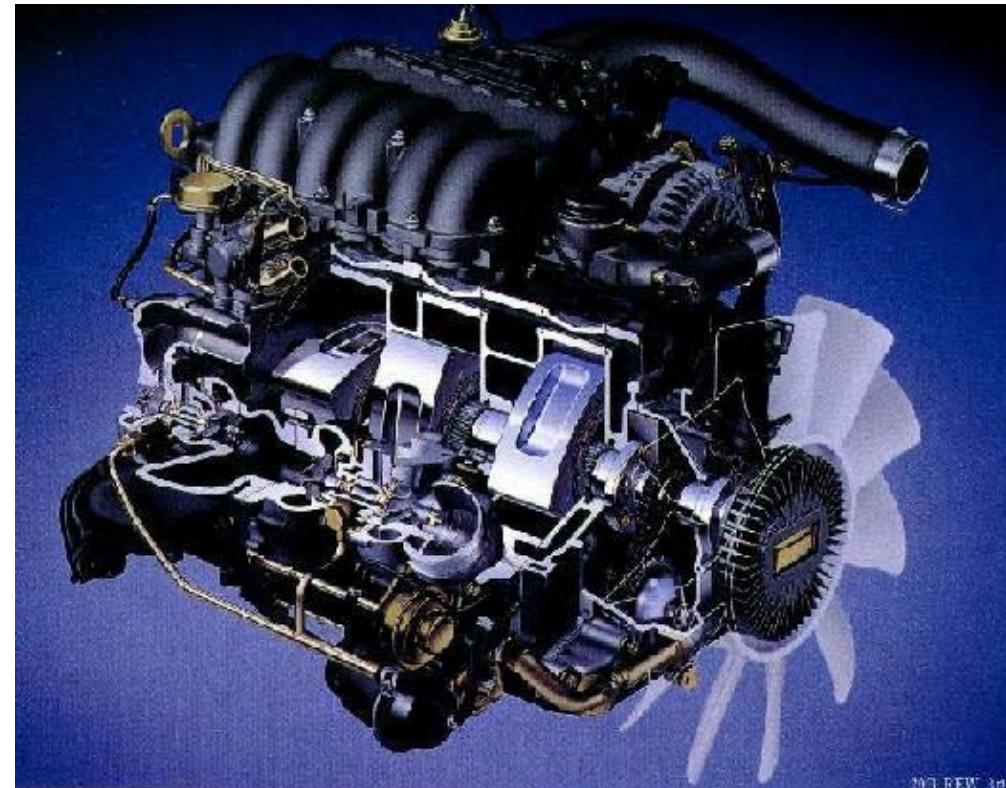
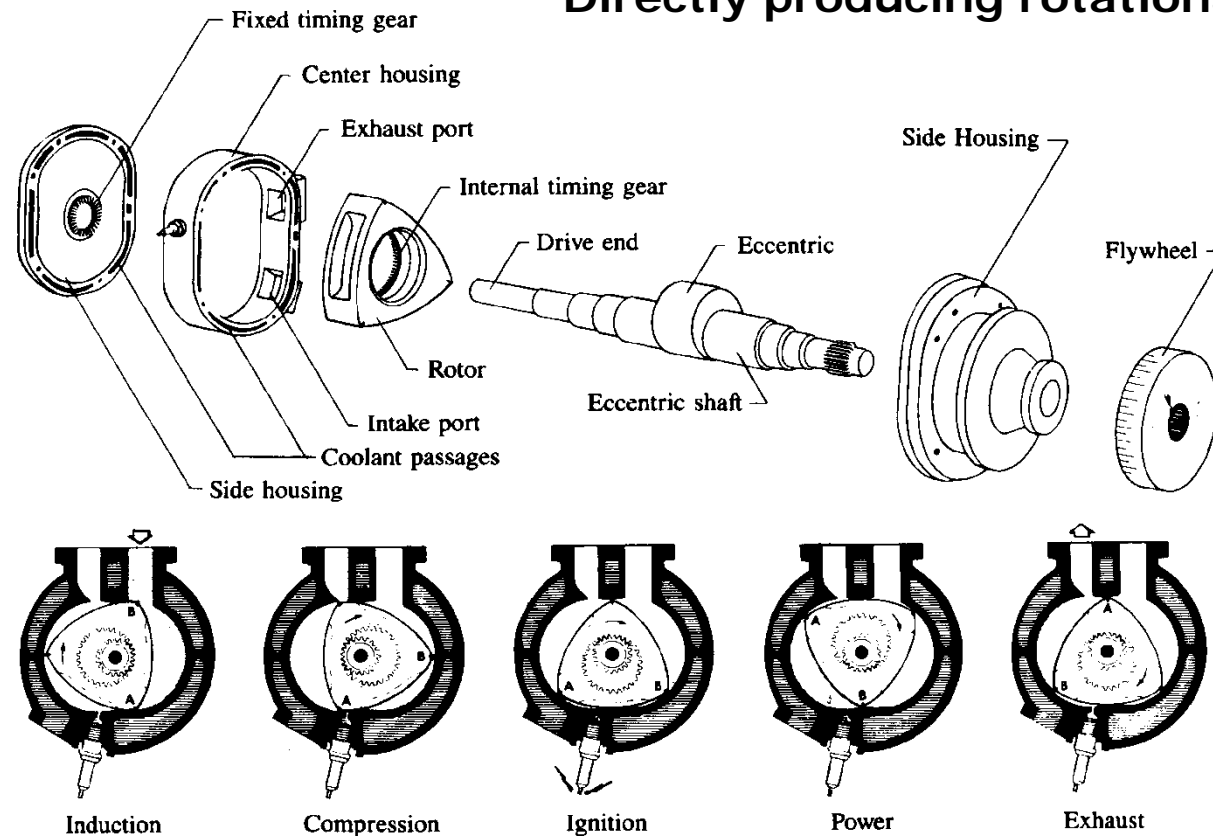


## CHP applications of IC engines (2)



# The Wankel Engine

Directly producing rotational piston motion, not reciprocating



(a) Major components of the Wankel rotary engine; (b) induction, compression, power, and exhaust processes of the four-stroke cycle for the chamber defined by rotor surface AB. (From Mobil Technical Bulletin, Rotary Engines, © Mobil Oil Corporation, 1971.)

Source: <http://fastjeff57.tripod.com/wankel2.jpg>

# Wankel Engine: pros and cons



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**The idea of constructing a rotary-piston IC engine is very old.**  
However, it is mechanically difficult to build.

**Felix Wankel was the first to come up with a possible solution.**

The Wankel engine is very fast and responsive, and achieves high rpm, but suffers from two main disadvantages:

- **Large friction surfaces between piston and cylinder walls;**
- **Large area of cylinder contact with cooling water.**

**This makes it far less efficient than conventional IC engines!**



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# The Stirling Engine

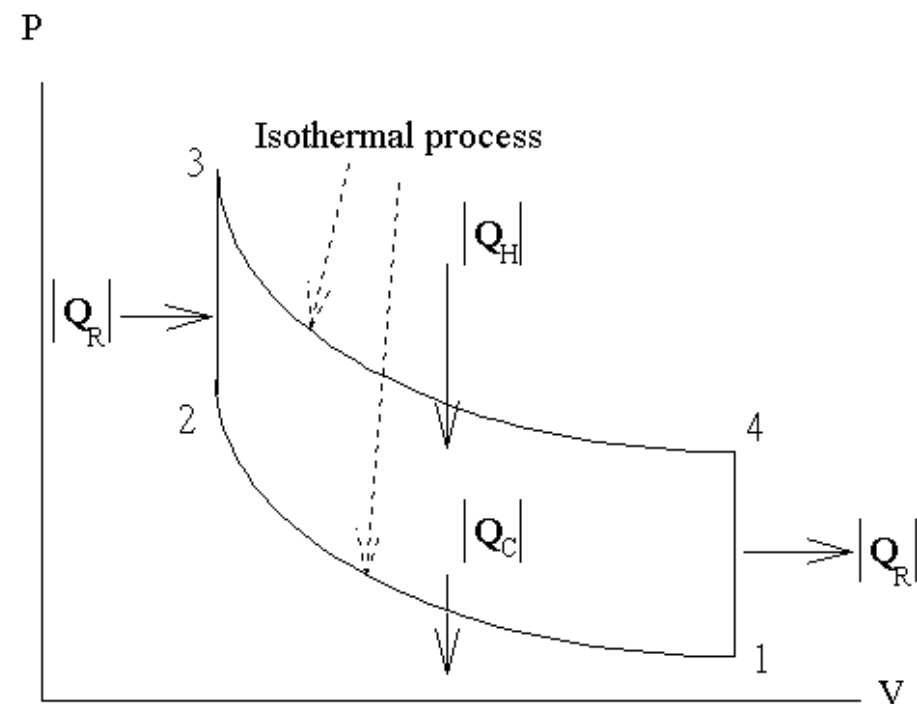
*Almost as old as the steam engine!*

**Intrinsically an externally-fired closed-cycle piston engine with air (or helium) as a working fluid.**

**Based on a thermodynamic cycle of two isohoric and two isothermal processes, theoretically good but practically difficult.**

**Heat is constantly added to the cycle to achieve isothermal expansion, then sunk during an isohoric pressure drop (3-4-1).**

**Heat is constantly rejected during the isothermal compression and then added for an isohoric pressure gain (1-2-3).**



Source: <http://phy.ntnu.edu.tw>



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# Stirling Engine Configuration

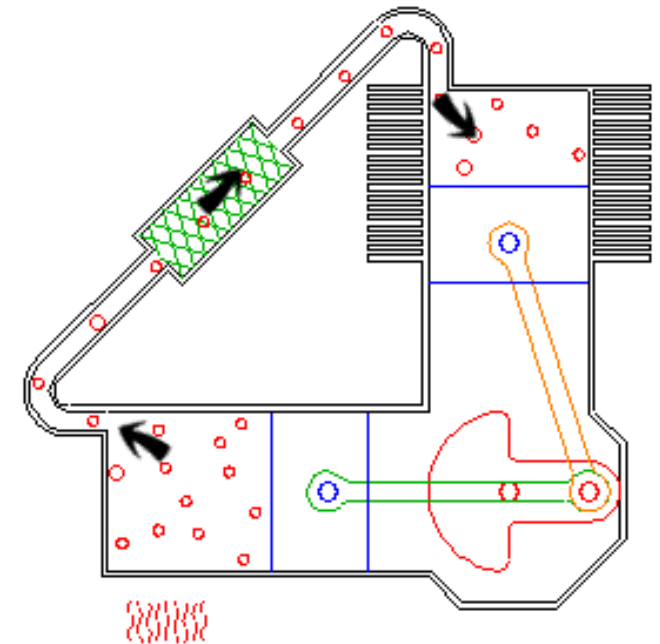
The working fluid is shuffled between the expansion and the compression cylinders, which have different sizes and stroke lengths. A regenerator in the middle improves the efficiency.

Hydrogen or helium gas (instead of air) is used as working fluid, for better heat exchange and compact size.

A practical Stirling engine works more like on adiabatic non-isothermal principles, losing its theoretical advantages.

It has a complex mechanical construction, and poor gas-to-gas heat exchange. It suffers also from material problems (limited temperatures) just like the steam cycles and gas turbines.

*A reversed Stirling cycle can nicely function as a refrigerator!*



Source: [www.animatedengines.com](http://www.animatedengines.com)



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# Stirling Engine Applications

If used in mechanical drives, the Stirling engine is difficult to seal across the shaft or the piston rod.

In power generation applications, the solution is to place the el. generator inside the engine casing, then fill in and pressurise the entire casing with the working fluid. In this way only the electric cables pass through the casing.

Stirling engines can achieve up to 30% efficiency in small scales, good enough for biomass-fired or solar-powered applications.

Solar dish concentrators with small Stirling engines are a promising technology – the picture here showing one at the Plataforma Solar de Almería, in Spain.



Source: [www.psa.es](http://www.psa.es)



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