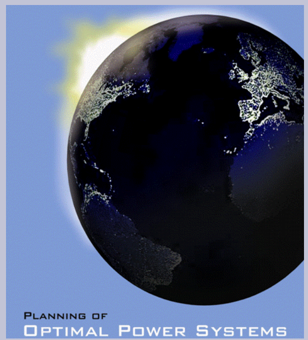


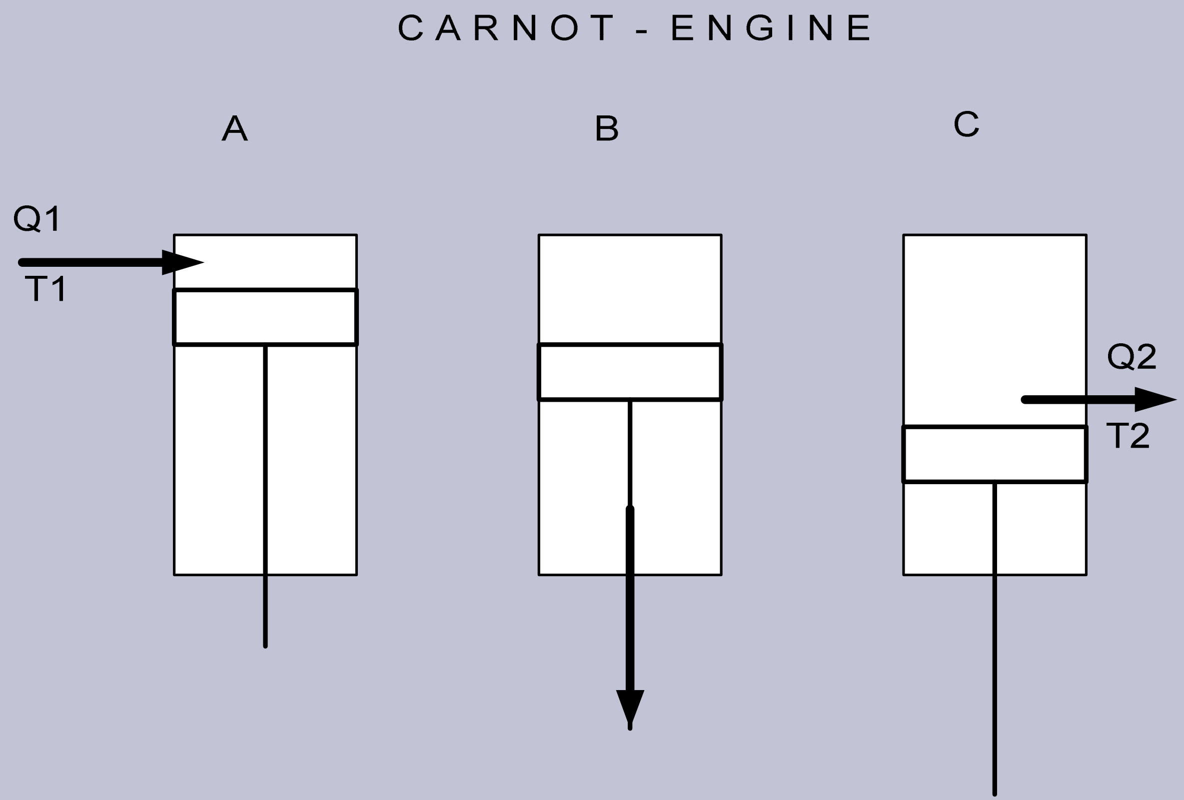
FUNDAMENTALS OF POWER PLANTS

Asko Vuorinen

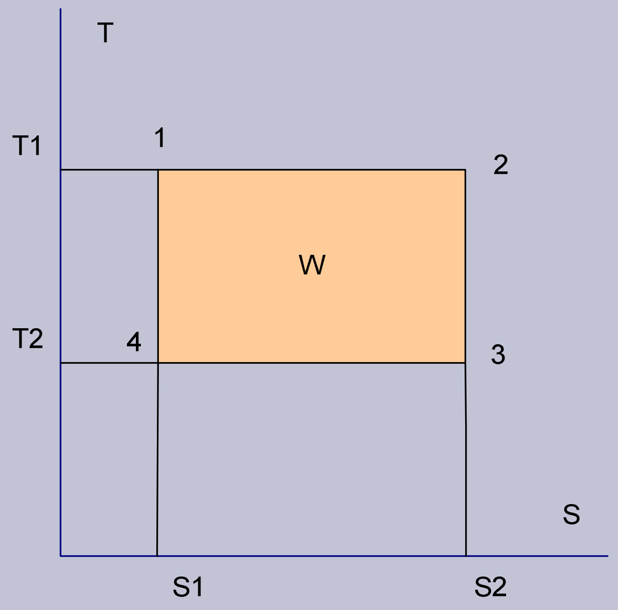
Engine cycles

- Carnot Cycle
- Otto Cycle
- Diesel Cycle
- Brayton Cycle
- Rankine Cycle
- Combined Cycles

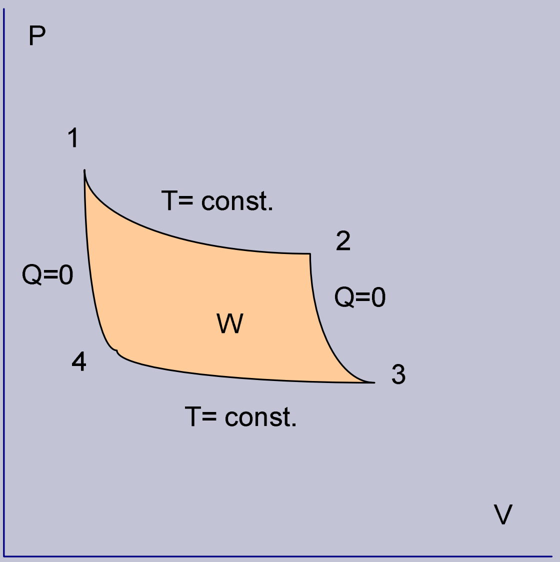
Carnot Engine



Carnot Cycle



T-S Diagram



P-V Diagram

Carnot Cycle , continued

- Ideal gas cycle, discovered by French engineer Sadi Carnot in 1824
- Heat is added at constant temperature T_1
- Heat is discharged at constant temperature T_2

Carnot Cycle , continued

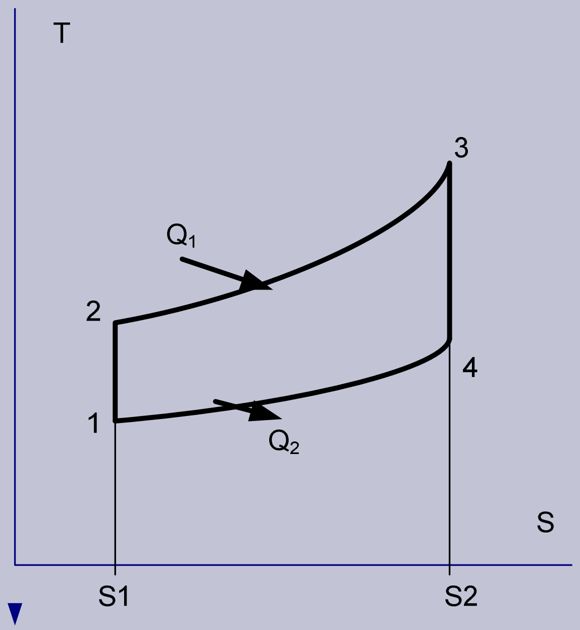
Efficiency

$$\eta = 1 - T_2/T_1$$

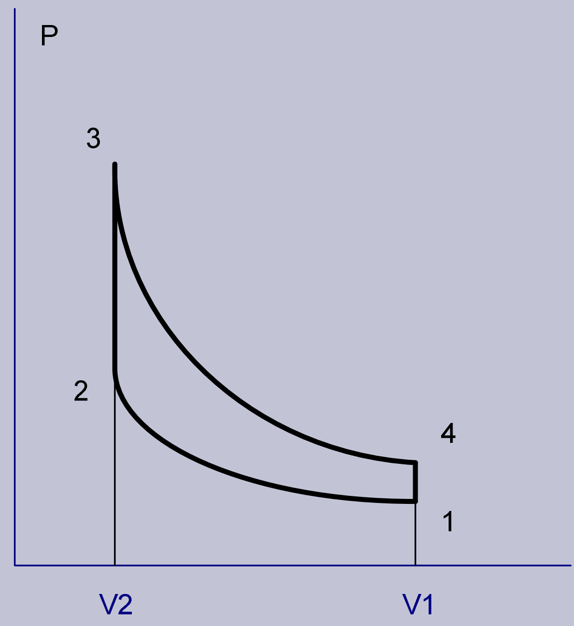
The work done is area W in diagram

Higher the T_1 and lower T_2 more work can be done by the Carnot engine

Otto Cycle



T-S Diagram



P-V Diagram

Otto Cycle, continued

- Nicolaus Otto discoverd spark ignition (SI) four stroke gas engine 1876
- Heat is added in constant volume V_1 at top dead center (TDC) by igniting gas air mixture by spark
- Heat is discharged at constant volume V_2 at botton dead center (BDC)

Otto Cycle, continued

Efficiency of Otto Engine

$\eta = 1 - 1/ r^{k-1}$

where

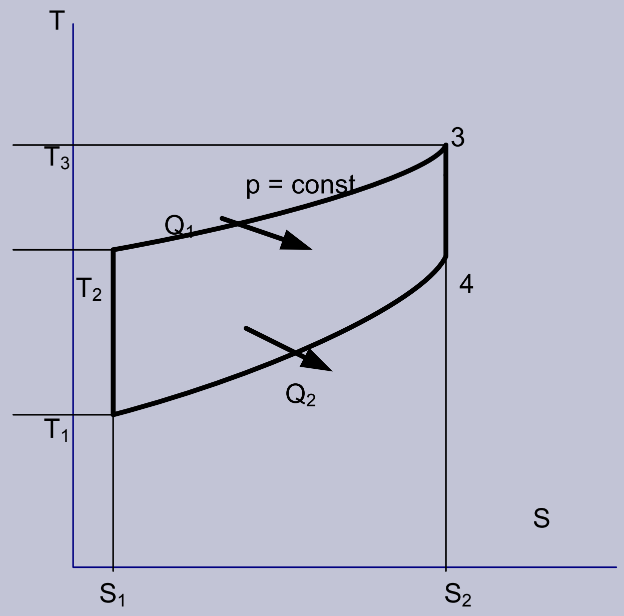
r = compression ratio= V_2/V_1

k= gas constant

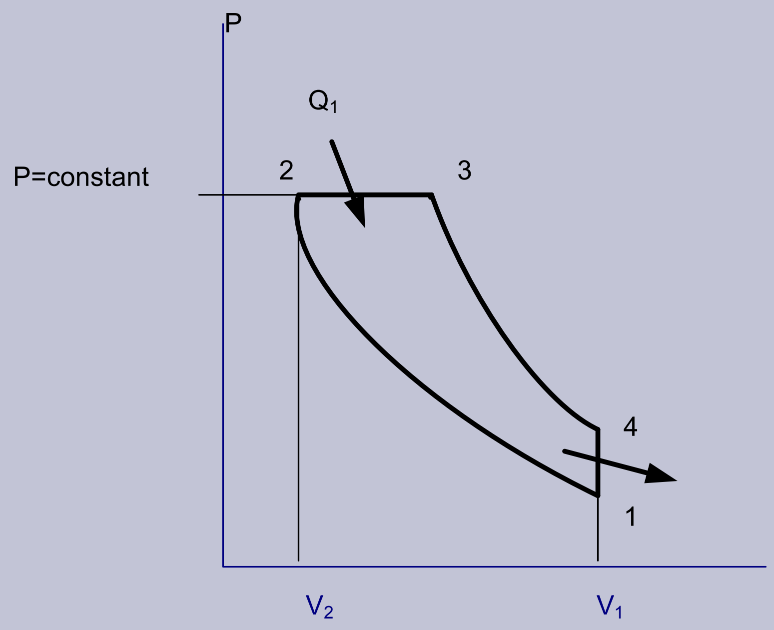
Otto Cycle, continued

- Spark ignition (SI) engines are most built engines in the world
- About 40 million engines/a for cars (200 000 MW)
- About 4000 engines/a for power plants (4000 MW/a)

Diesel Cycle



T-S Diagram



P-V Diagram

Diesel Cycle, continued

- Rudolf Diesel outlined Diesel engine in 1892 in his patent
- Heat is added at constant pressure and discharged at constant volume
- Ignition happens by self ignition by injecting fuel at top dead center
- Some call Diesel engines as compression ignion (CI) engines

Diesel Cycle, continued

Efficiency

$\eta = 1 - 1/r^{k-1} (r_c^k - 1)/(k(r_c - 1))$

where

r = comperssion ratio = V_2/V_1

rc = cut off ratio = V_3/V_2

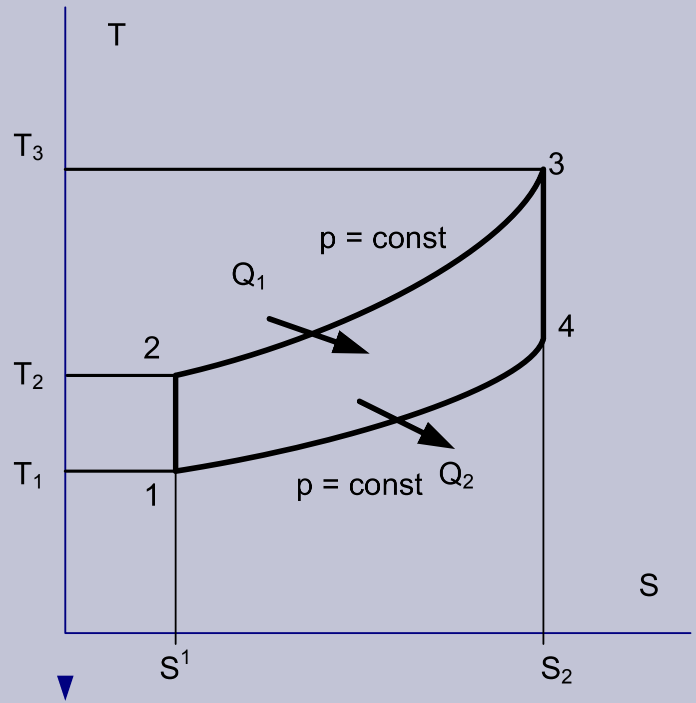
note

If r is the same, Diesel cycle has lower efficiency than Otto cycle

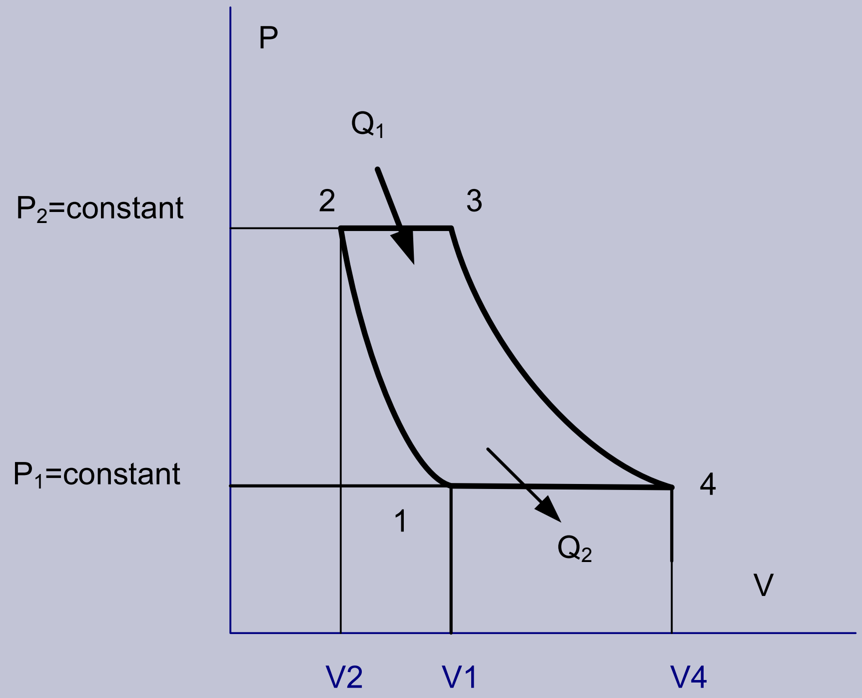
Diesel Cycle, continued

- Diesel engines are most built energy conversion machines after SI-engines
- Car industry builds about 20 million/a diesel cars and trucks (200000 MW/a)
- > 90 % market share in large ships
- Power plant orders are 30 000 MW/a

Brayton Cycle

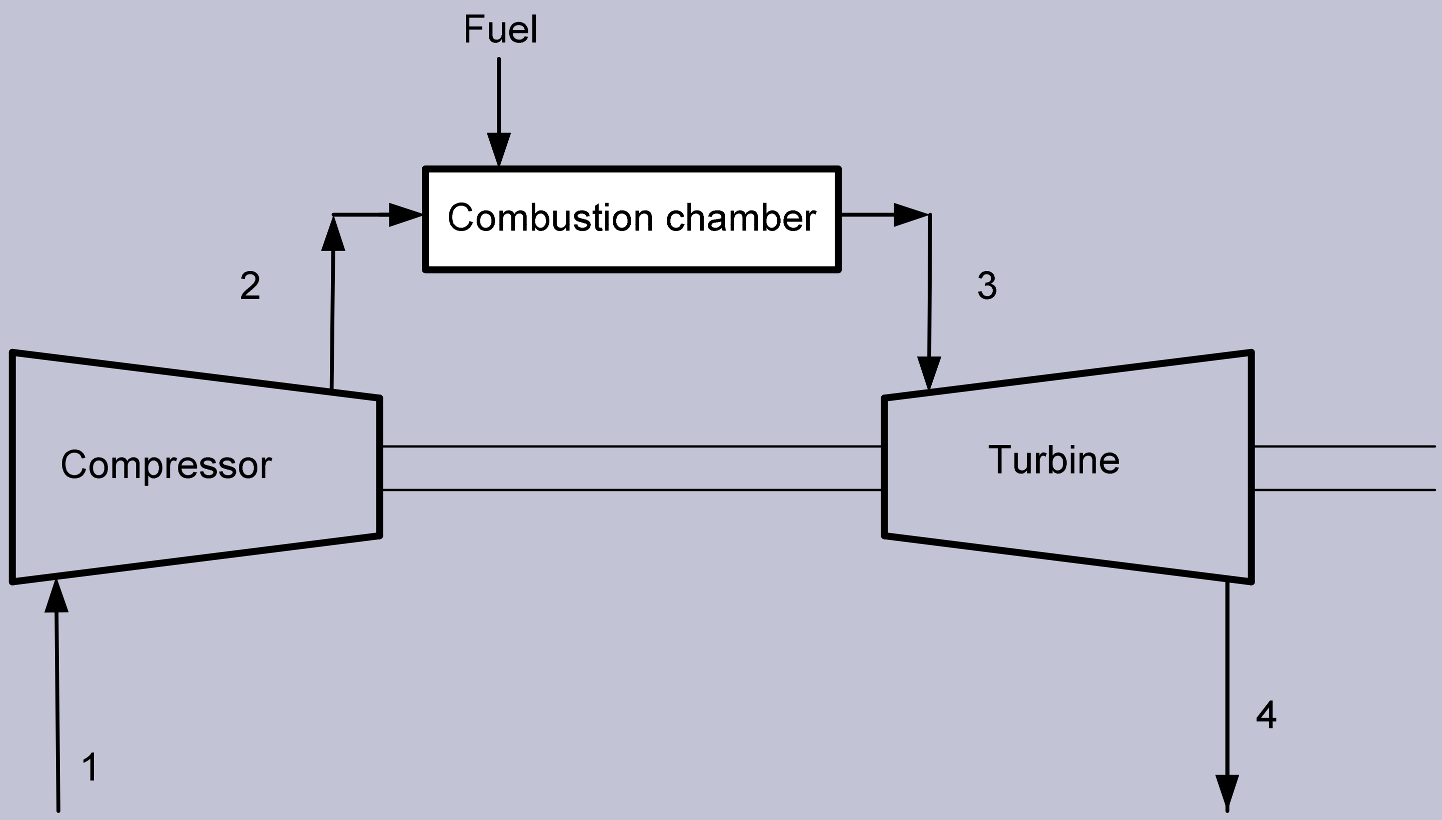


T-S Diagram



P-V Diagram

Brayton Cycle



Brayton Cycle

- Developed by Georg Brayton (1832 - 1890)
- Heat is added and discharged at constant pressure
- Applied in Gas Turbines (GT) (Combustion Turbines in US)

Brayton Cycle, continued

Efficiency

$$\eta = 1 - 1/\, r_p^{\,(k-1)/k}$$

where

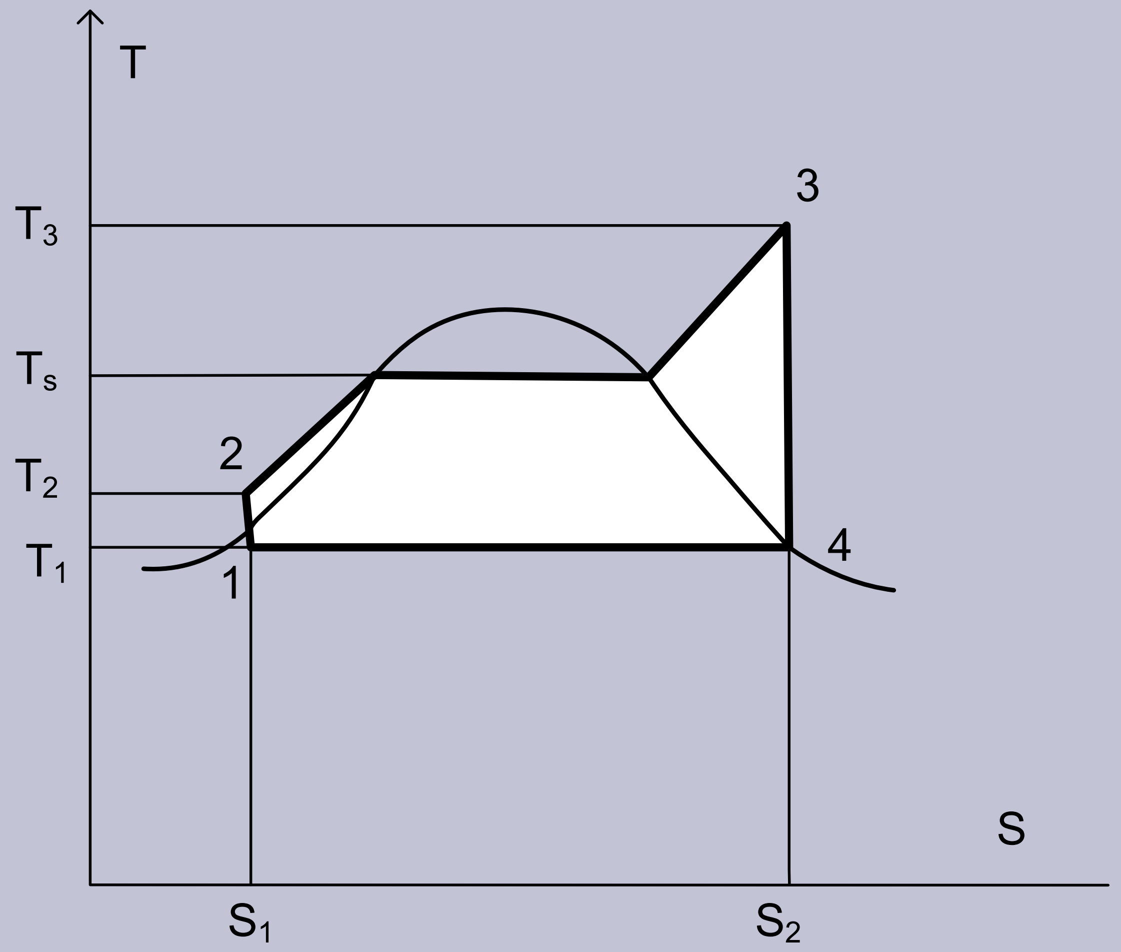
r_p = compressor pressure ratio = p_2/p_1

k = gas constant

Brayton cycle, continued

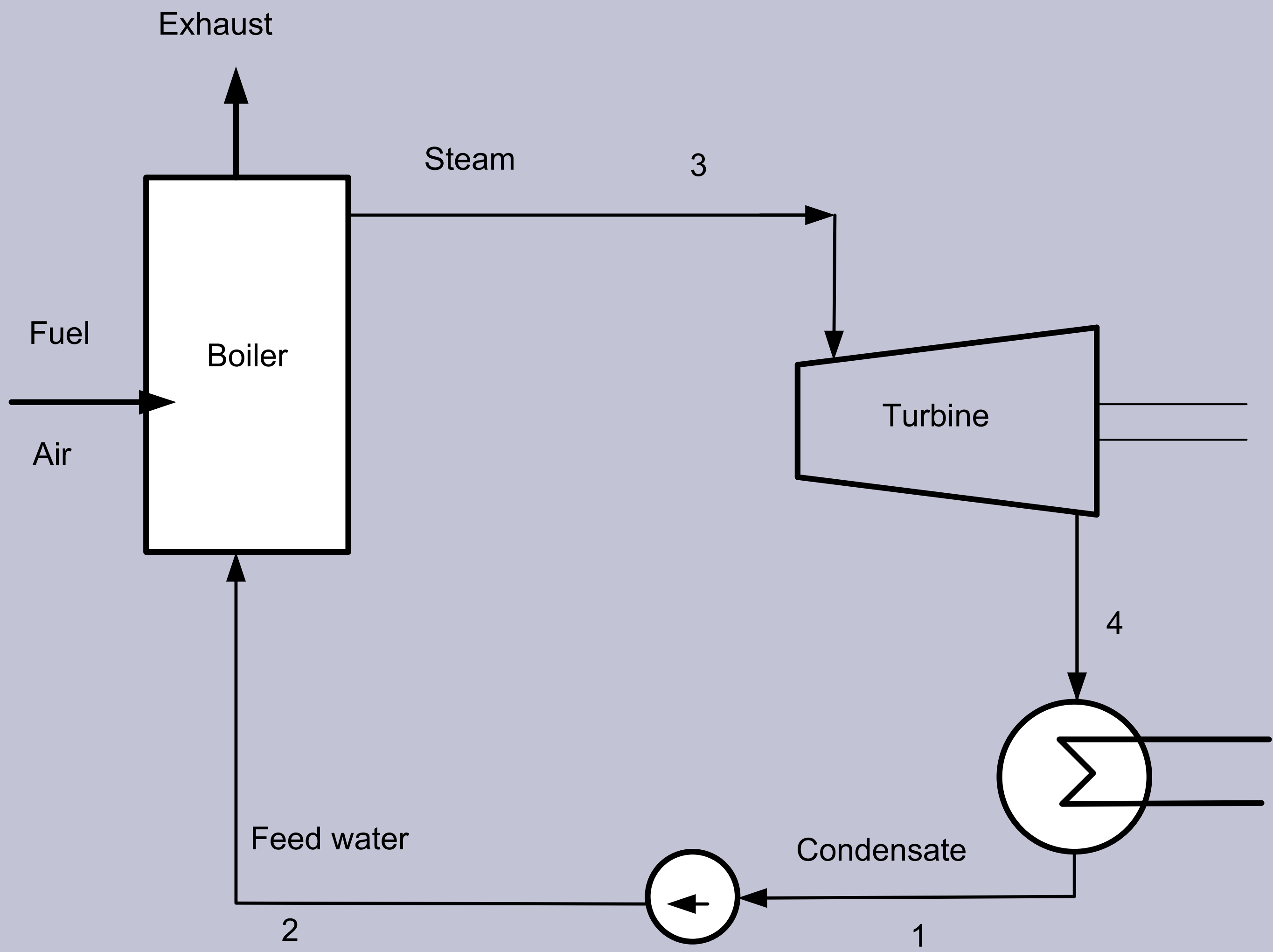
- Gas turbines are number third power conversion machines after SI- and CI-engines
- > 90 % market share in large airplanes
- Power plant orders are 40 000 MW/a

Rankine Cycle



T-S Diagram

Rankine Cycle, continued



Rankine Cycle, continued

- Scottish engineer William Rankine (1820-1872) developed a theory of steam cycles
- Heat is added in a water boiler, where the water becomes steam
- Steam is fed to a steam turbine, which generates mechanical energy
- After turbine the steam becomes water again in a condenser

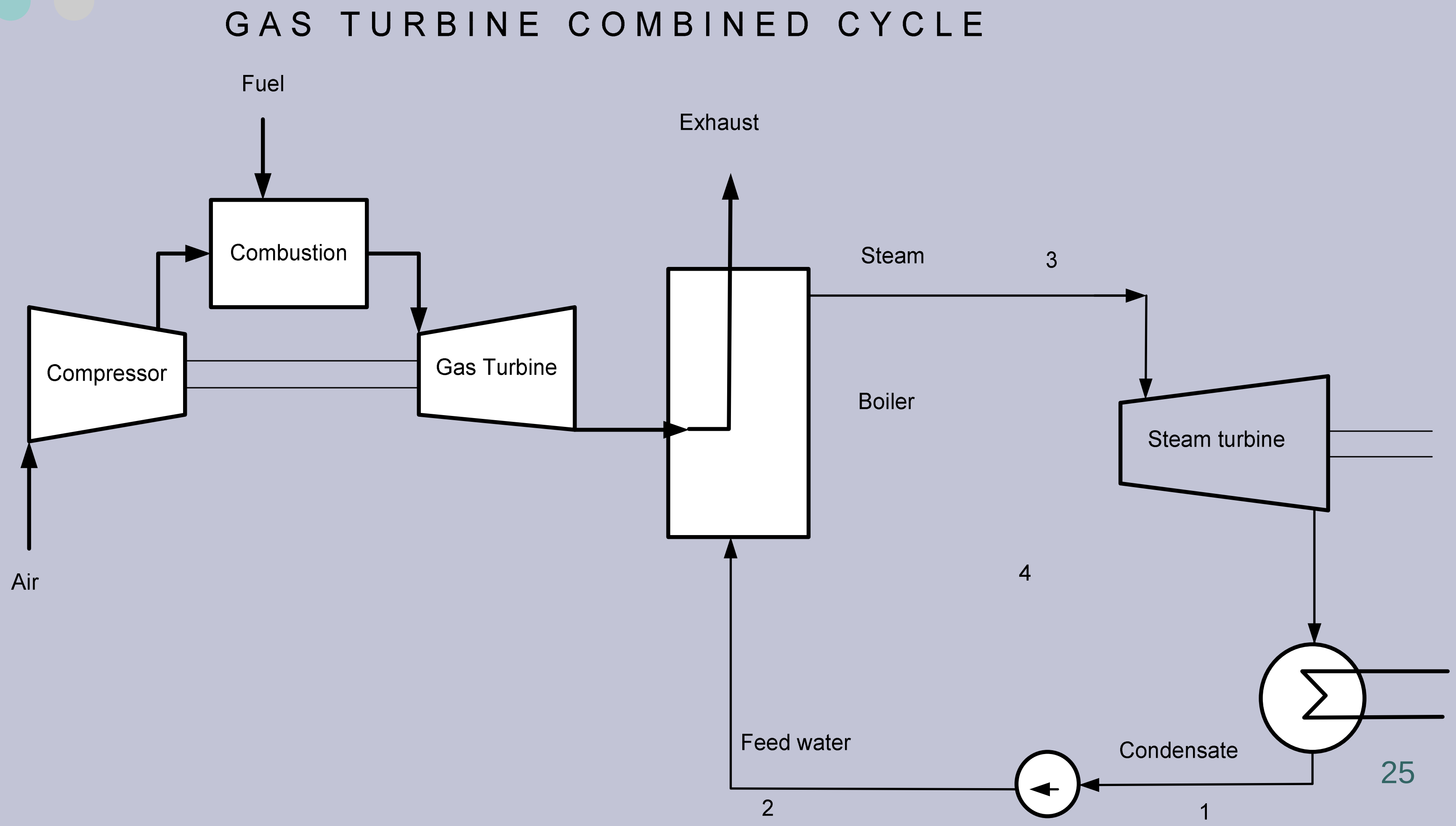
Rankine cycle, continued

- The efficiency varies from 20 % in small subcritical steam turbines to 45 % in large double reaheat supercritical steam turbines
- The rankine cycle is ideal for solid fuel (coal, wood) power plants

Rankine cycle, continued

- Steam turbines are most sold machines for power plants as measured in output (100 000 MW/a)
- They are used in coal fired, nuclear and combined cycle power plants
- Coal and nuclear plants generate about 50 % of world electricity

Gas turbine combined cycle

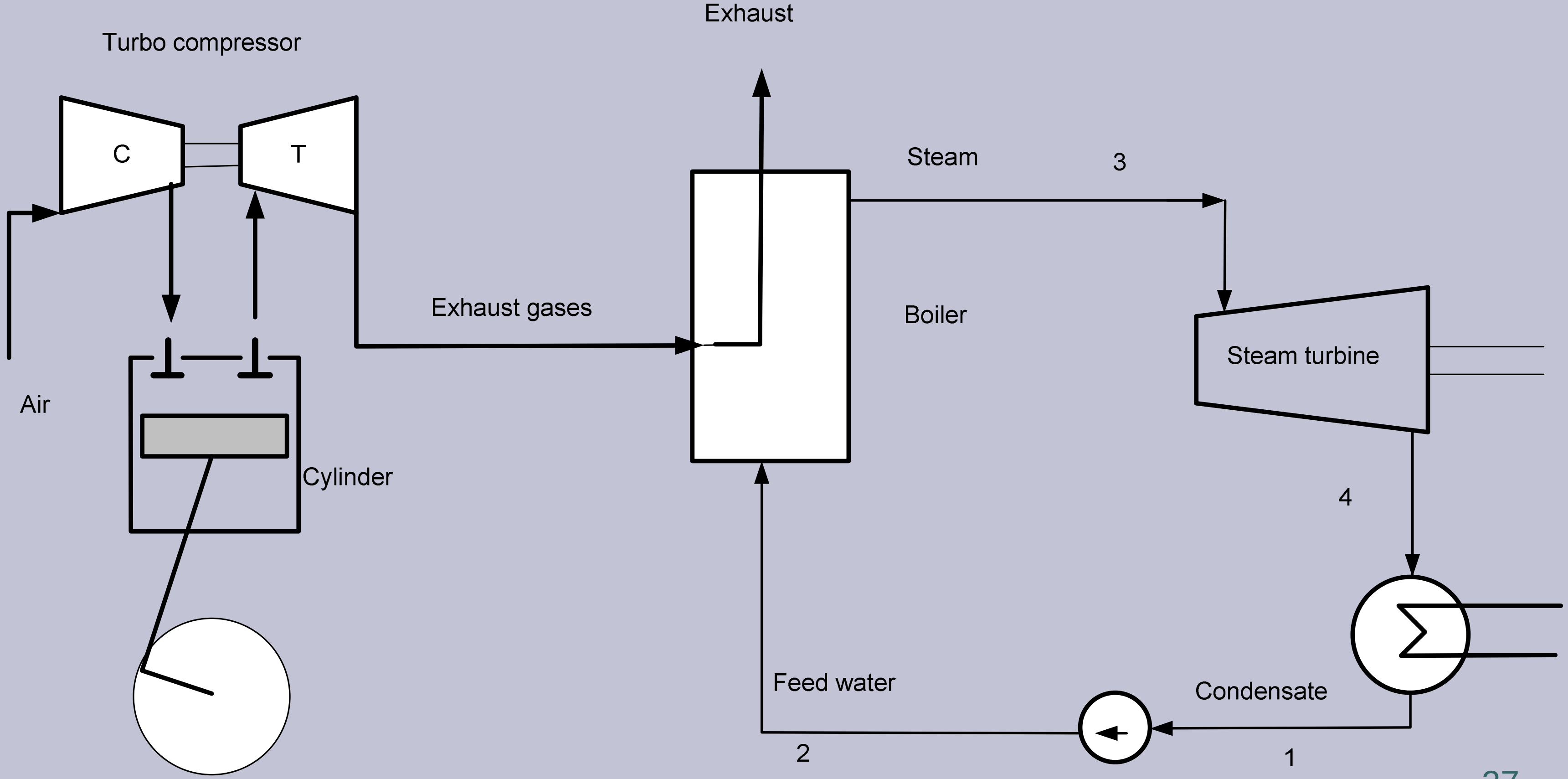


Gas Turbine Combined Cycle

- Combines a gas turbine (Brayton cycle) and steam turbine (Rankine Cycle)
- About 66 % of power is generated in gas turbine and 34 % in steam turbine
- Efficiency of GTCC plant is typically 1.5 times the efficiency of the single cycle gas turbine plant

IC Engine Combined Cycle

IC- ENGINE COMBINED CYCLE



Planning of Optimal Power Systems

IC Engine Combined Cycle

- Combines a Internal combustion Engine (Diesel or Otto cycle) and steam turbine (Rankine Cycle)
- About 90 % of power is generated in gas turbine and 10 % in steam turbine
- Efficiency of GTCC plant is typically 1.1 times the efficiency of the single cycle IC engine plant

Electrical efficiency

Efficiency $\eta = (P - P_{aux})/Q \times K_t \times K_l$

where

P = electrical output

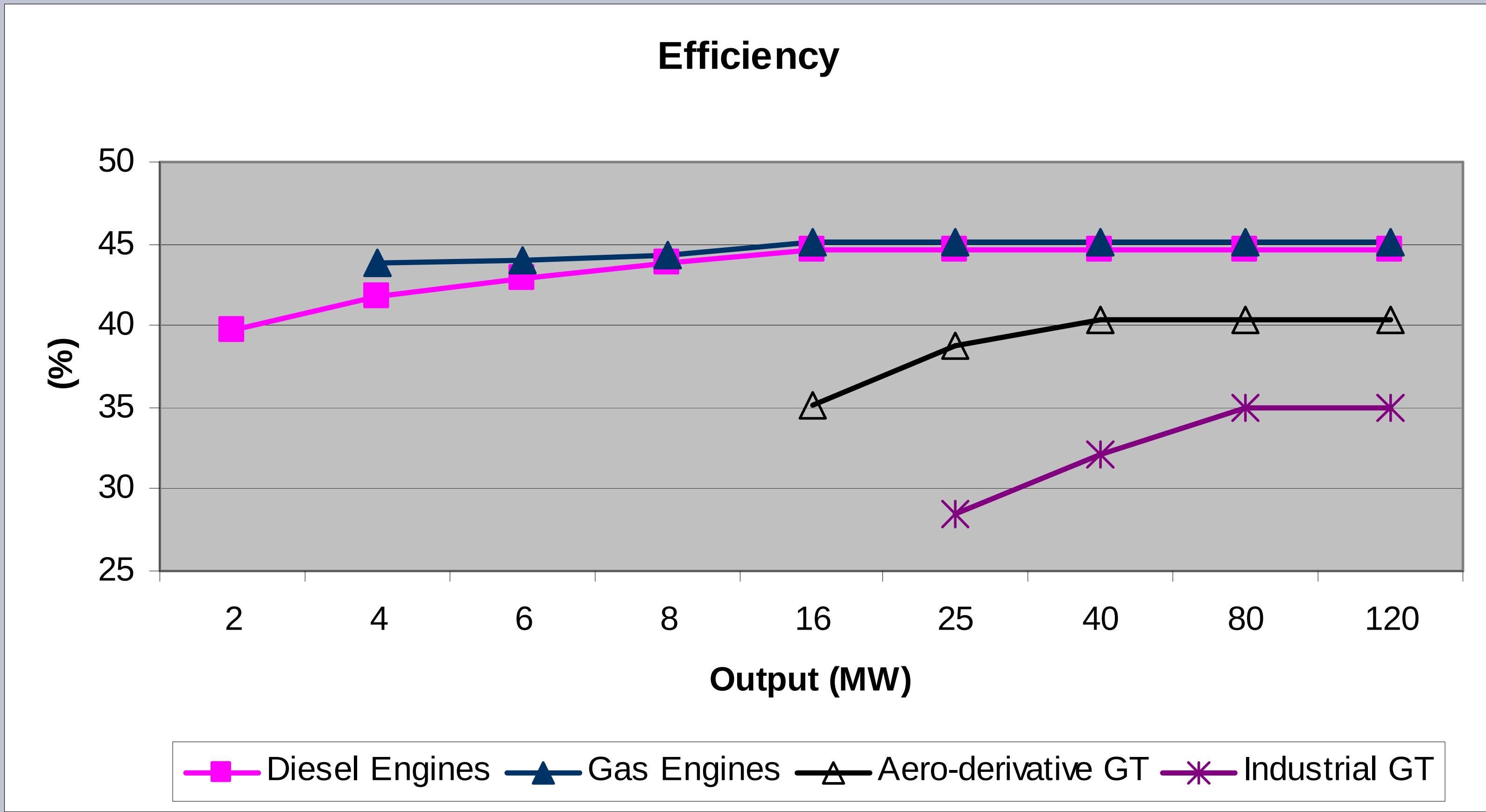
P_{aux} = auxiliary power consumption

Q = heat output

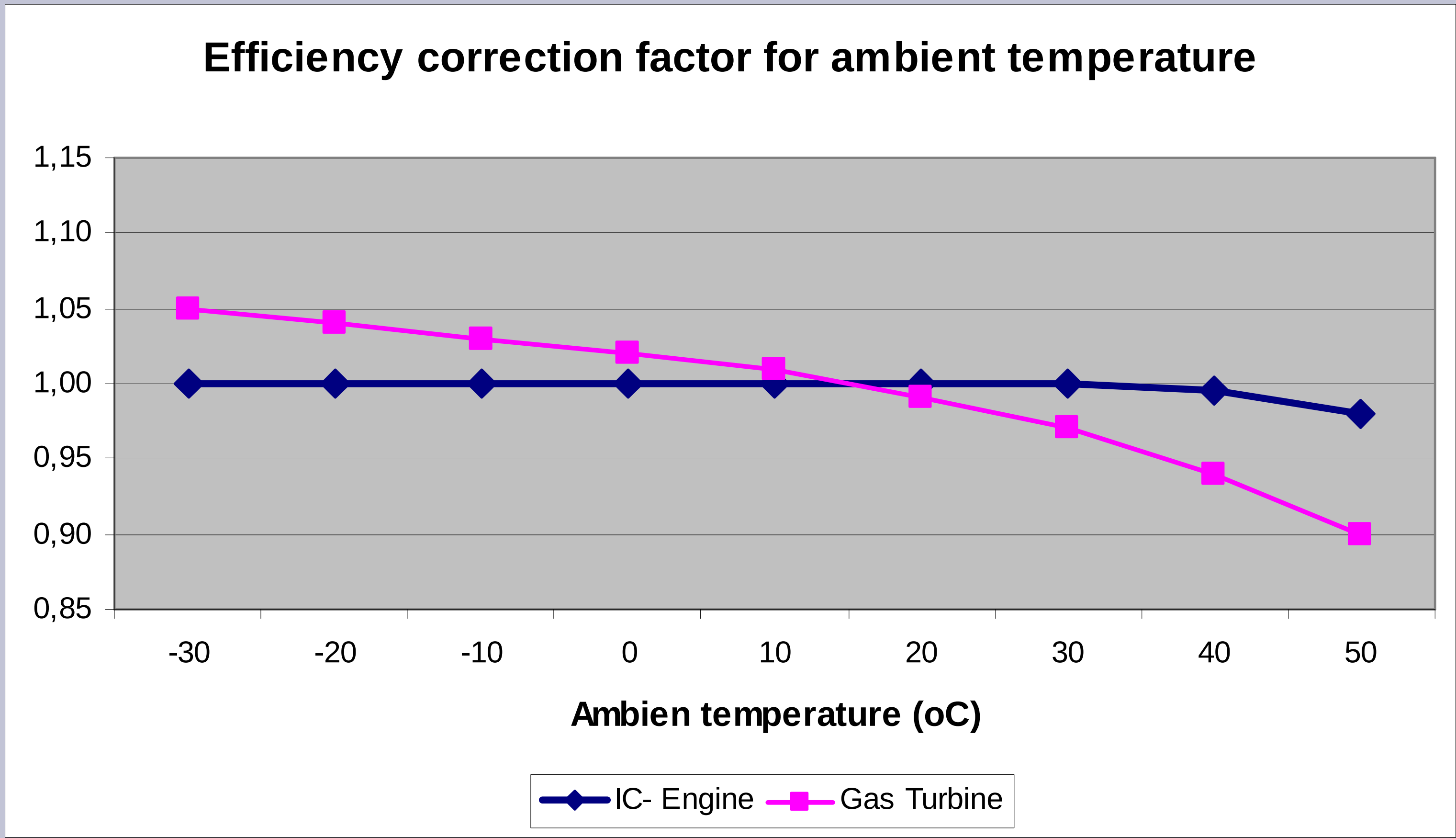
K_t = temperature correction factor

K_l = part load correction factor

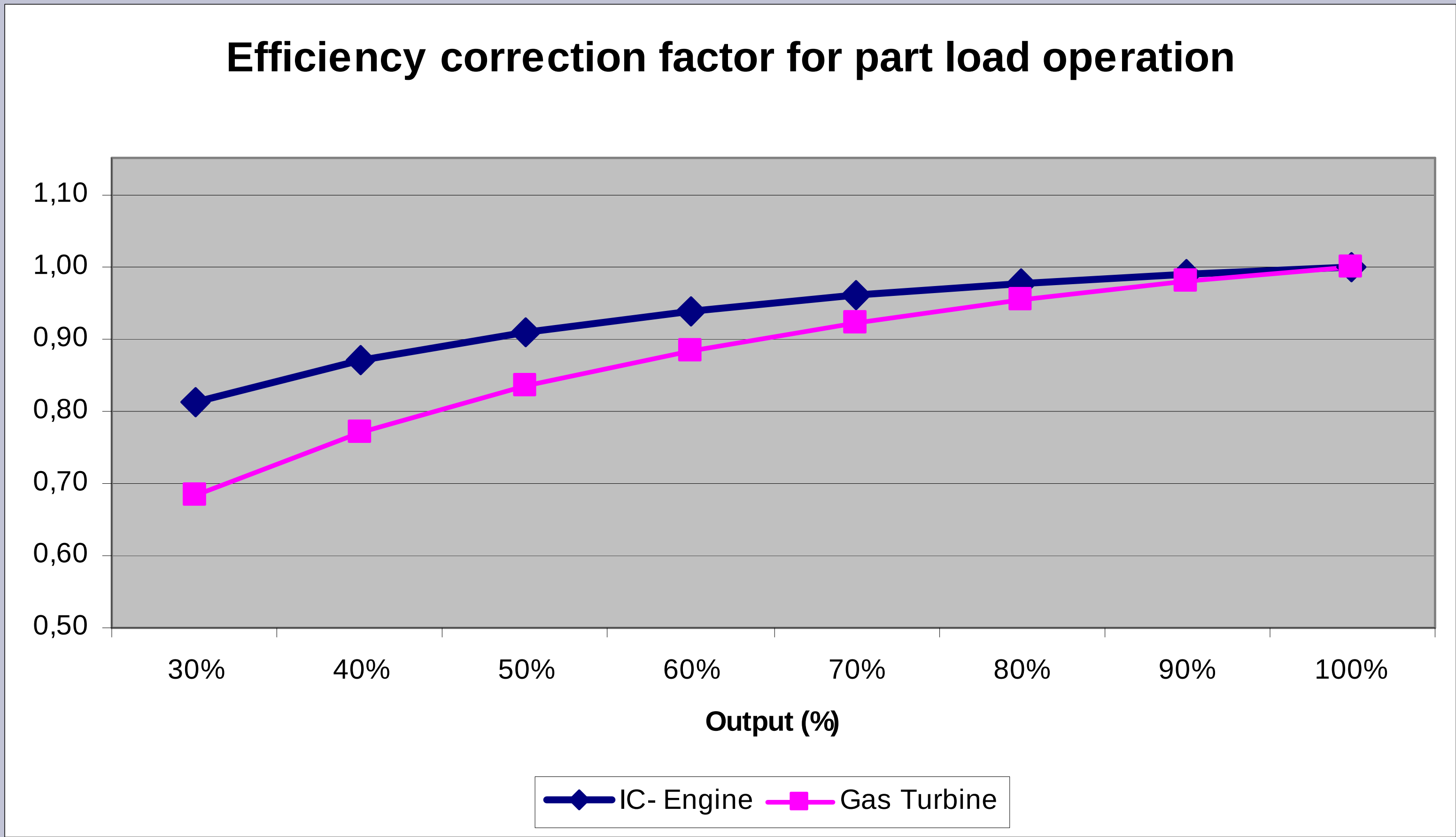
Electrical efficiency



Efficiency correction factor for ambient temperature



Efficiency correction factor for part load operation



Classification of power plants by place of combustion

- Internal combustion engines
  - Diesel engines
  - Gas engines
  - Dual-fuel engines
- External combustion engines
  - Steam engines
  - Stirling engines
  - Gas turbines
  - Steam turbines

Classification of internal combustion engines

- By speed or rotation
  - Low speed < 300 r/min (ship engines)
  - Medium speed 300 - 1000 r/min (power plants)
  - High speed > 1000 r/min (Standby power plants and cars)
- By number of strokes
  - 2 - stroke (large ships)
  - 4 - stroke (power plants and cars)

Classification of internal combustion engines, continued

- By type of combustion
  - Lean burn (lambda > 1.2 -2.2)
  - Stoichiometric (lambda = 1)
- By combustion chamber
  - Open chamber
  - Pre-chamber

Classification of internal combustion engines, continued

By fuel

- Heavy fuel oil (HFO)
- Light fuel oil (LFO)
- Liquid bio fuel (LBF)
- Natural gas (NG)
- Dual-fuel (NG/LFO)
- Tri-fuel (NG/LFO/HFO)
- Multi-fuel (NG/LFO/HFO/LBF)

Classification of gas turbines

- By type
  - Industrial (single shaft)
  - Aeroderivative (two shaft)
  - Microturbines (50 – 200 kW)
- By fuel
  - Light fuel oil (LFO)
  - Natural gas (NG)
  - Dual-fuel (NG/LFO)

Classification of steam turbine power plants

- By steam parameters
  - Subcritical (400 - 540 ^{o}C, 10 -150 bar)
  - Supercritical (600 ^{o}C, 240 bar)
- By fuel
  - Coal, lignite, biomass
  - Heavy fuel oil (HFO)
  - Dual-fuel (gas/HFO)

Classification of nuclear power plants

- By type of nuclear reaction
  - Fission (splitting U_{235} atoms)
  - Fusion (fusion of deuterium and tritium)
- By energy of neutrons in chain reaction
  - Fast reactors (fast neutrons)
  - Thermal reactors (”slow neutrons”)

Classification of thermal reactors

- By moderator (slow down of neutrons)
  - Water
  - Graphite
- By cooling media
  - Water
  - Helium

Classification of water cooled reactors

- Pressurised water
  - Toshiba (Westinghouse), Mitsubishi (Japan), Areva (France), Rosatom (Russia)
- Boiling water
  - General Electric (USA)
- Heavy water
  - AECL (Canada)

Operating parameters

- Start-up time (minute)
- Maximum step change (%/5-30 s)
- Ramp rate (change in minute)
- Emissions

Start-up time

Diesel engines	1 - 5 min
Gas engines	5 - 10 min
Aeroderivative GT	5 - 10 min
Industrial GT	10 - 20 min
GT Combined Cycle	30 – 60 min
Steam turbine plants	60 – 600 min

Maximum change in 30 s

Diesel engines	60 - 100%
Gas engines	20 - 30 %
Aeroderivative GT	20 - 30 %
Industrial GT	20 - 30 %
GT Combined Cycle	10 - 20 %
Steam turbine plants	5 - 10 %
Nuclear plant	5 - 10 %

Maximum ramp rate

- Diesel engines 40 %/min
- Gas engines 20 %/min
- Aeroderivative GT 20 %/min
- Industrial GT 20 %/min
- GT Combined Cycle 5 -10 %/min
- Steam turbine plants 1- 5 %/min
- Nuclear plants 1- 5 %/min

CO_2 emissions

- Gas fired plants — g/kWh
  - CHP 90 % efficiency — 224
  - GTCC 55 % efficiency — 367
  - Gas Engine 45 % efficiency — 449
  - Gas Turbine 33 % efficiency — 612
- Coal fired plants
  - Supercritical 45 % efficiency — 757
  - Subcritical 38 % efficiency — 896

Summary

- Power plants have different efficiencies, emissions and operational characteristics
- You should know the alternatives before start to plan of optimal power systems

For details see reference text book
”Planning of Optimal Power Systems”

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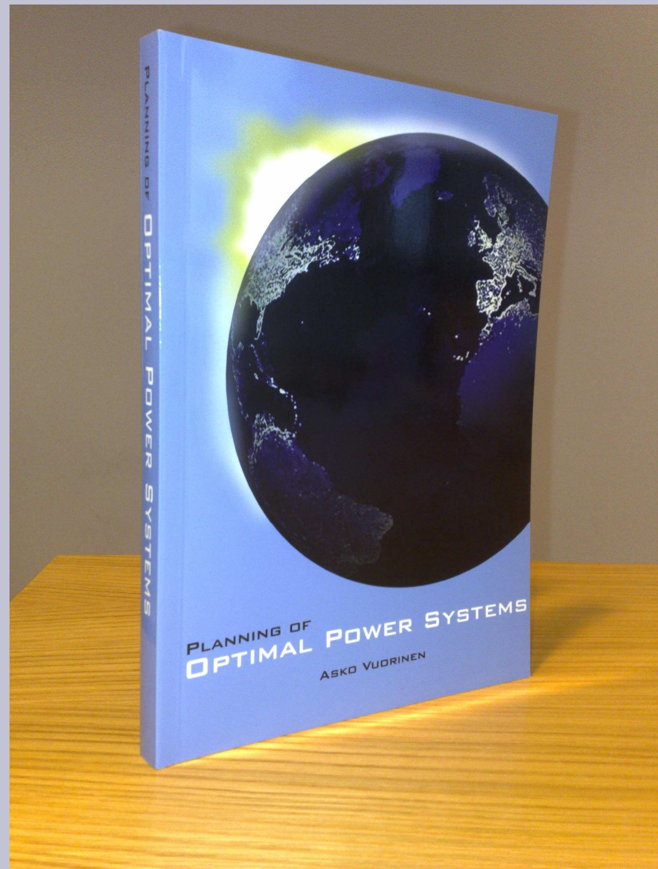

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