wb1224 - Thermodynamics 2

Lecture 11 – Energy Conversion Systems

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16-12-2010

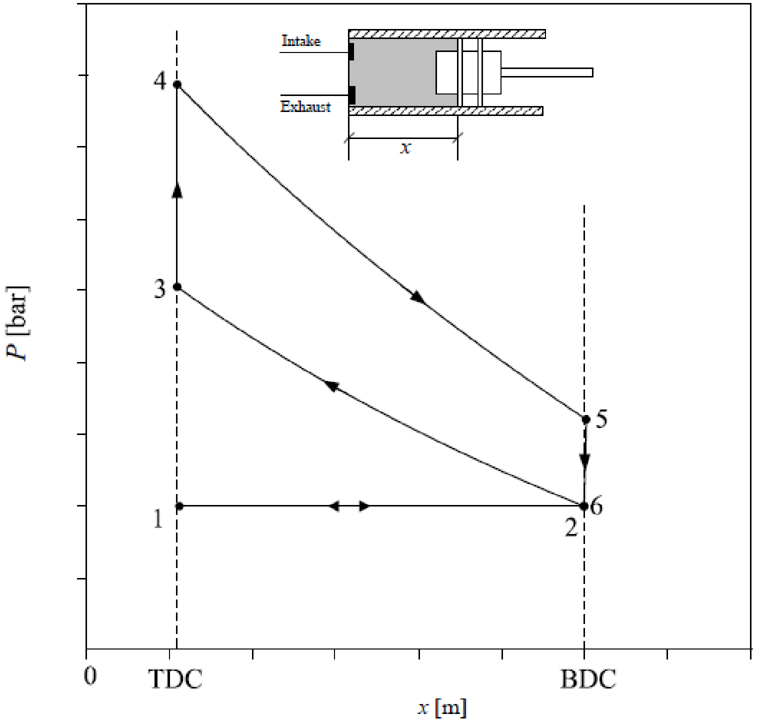
Content

Lecture 3 - overview

- Other gas cycles: Overview of the Otto and Diesel cycle (recip engines)
- Comparison Otto, Diesel, Brayton
- Outlook on fuel cells
- Improvement on efficiency: combined cycles and cogeneration
- Exergy: an intro

Ideal Otto cycle (1)

- Open cycle, air as ideal gas (no combustion)
- Model for spark-ignition recip engines
- Valves: top dead center (TDC) and bottom dead center (BDC)
- Ideal: instantaneous ignition at TDC
- Ideal: compression and expansion as isentropic
- Work done on and by the piston only during expansion and compression
- Isochoric combustion and discharge

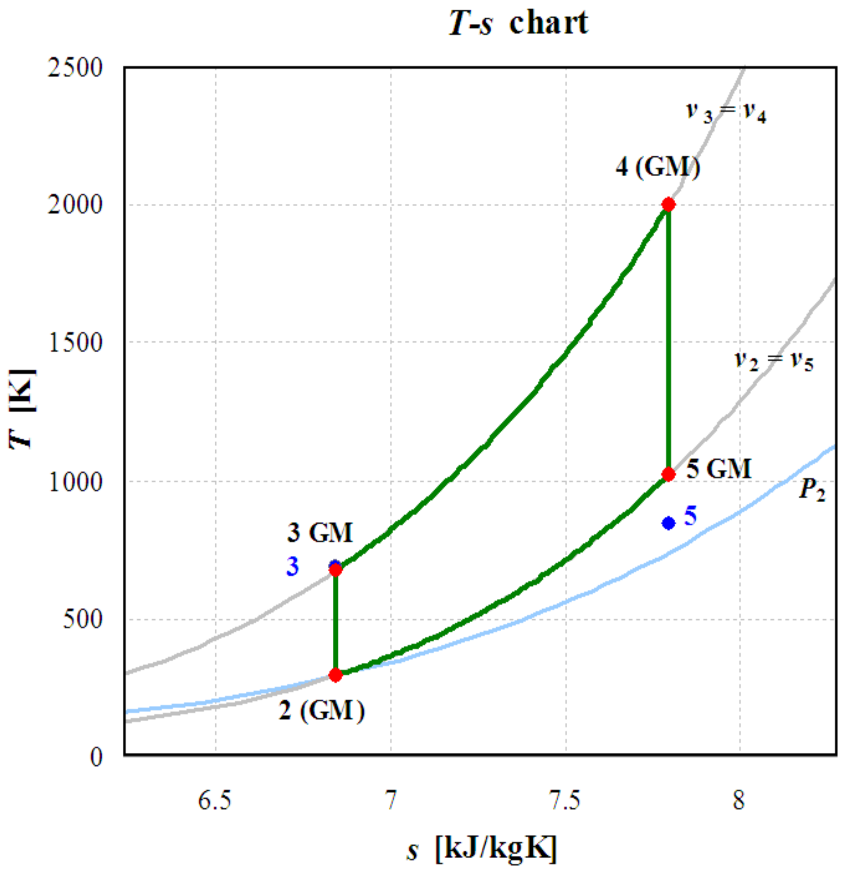


Ideal Otto cycle (2)

DATA:

- P_{in} = 1.013 bar
- T_{in} = 293.15 K
- T_{max} = 2000 K
- ρ = 8.5
- v = 1600 cm^3

$$\boxed{c_v = c_v(T)}$$



Ideal Otto cycle (3)

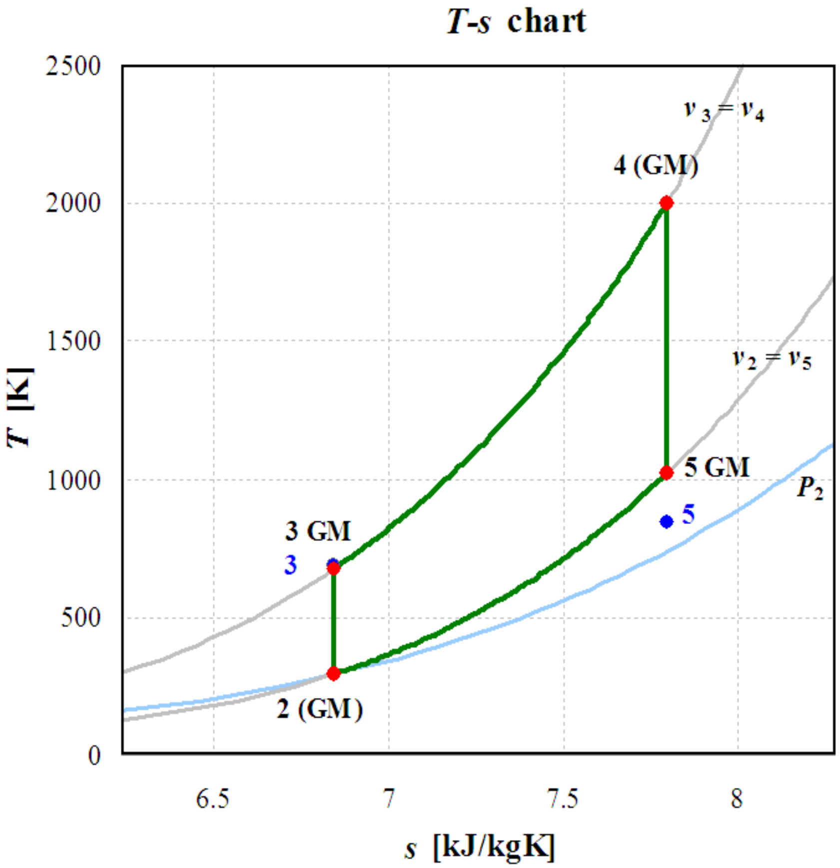
- Assumption: no combustion
  (no change of working fluid)
- Working fluid: polytropic ideal gas
- Similarly with ideal Brayton cycle:

$$Pv = RT, \quad \bar{c}_v = \text{const.}$$

$$w_{\text{comp/exp}} = \Delta u \longleftarrow \boxed{\text{(isochoric)}}$$

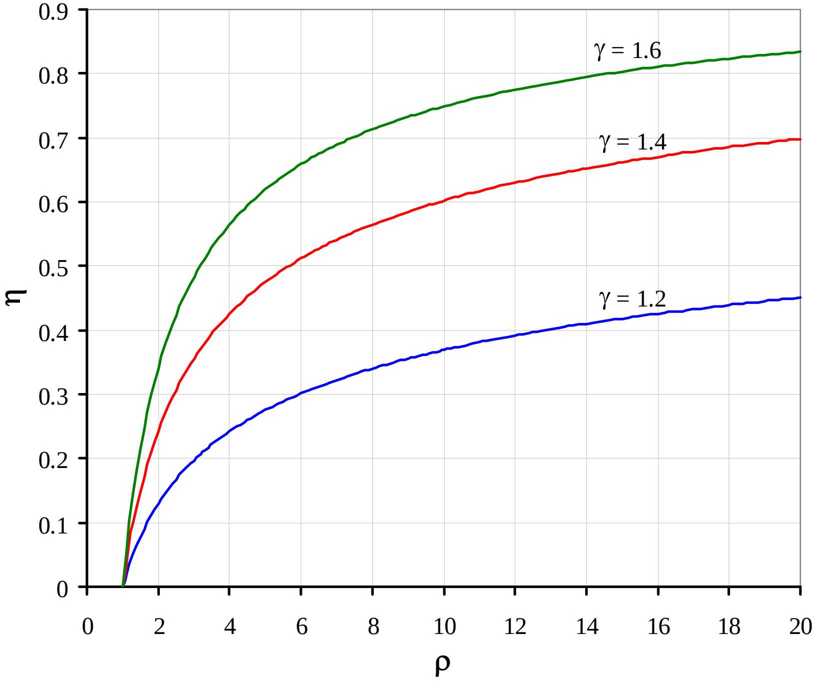
$$\rho \equiv \frac{v_2}{v_3} = \frac{v_5}{v_4} \qquad \frac{T_3}{T_2} = \left(\frac{v_3}{v_2}\right)^{\gamma-1}$$

$$\eta = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{\bar{c}_v\left(T_5 - T_2\right)}{\bar{c}_v\left(T_4 - T_3\right)} = 1 - \rho^{1-\gamma}$$



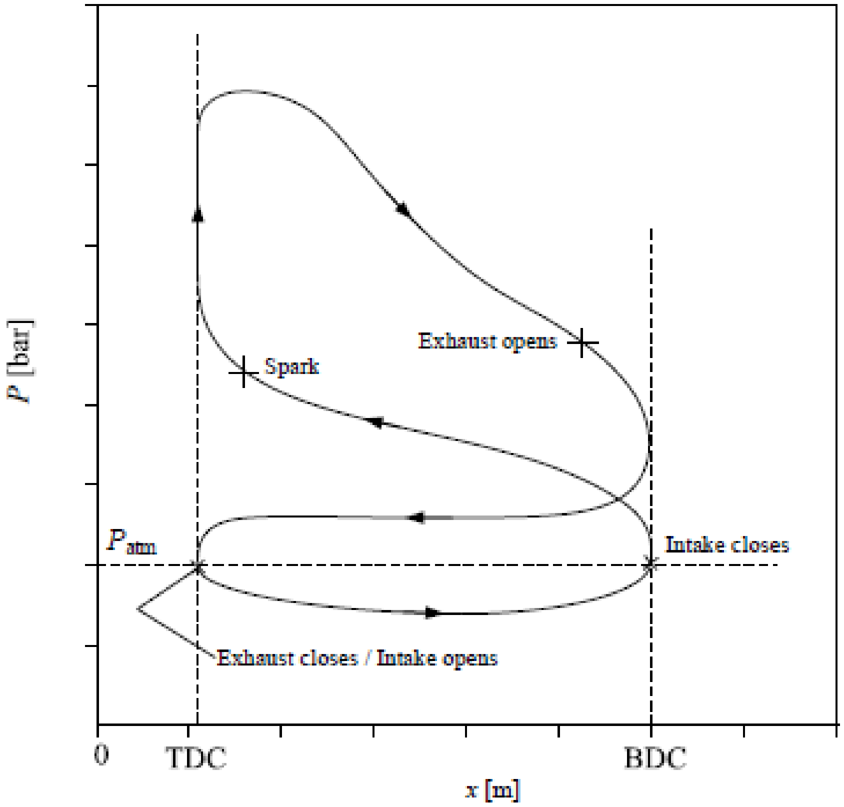
Efficiency of the ideal Otto cycle

- Difference with Brayton: fluid dynamic losses $\propto \frac{1}{2} w_{\text{Fluid}}^2$
- No maximum value for η as Brayton (real cycle), but η increases with ρ ➔ Ideal cycle efficiency is a good parameter for real-cycle evaluation
- Influence of γ: better if high air/to fuel ratio (more air)



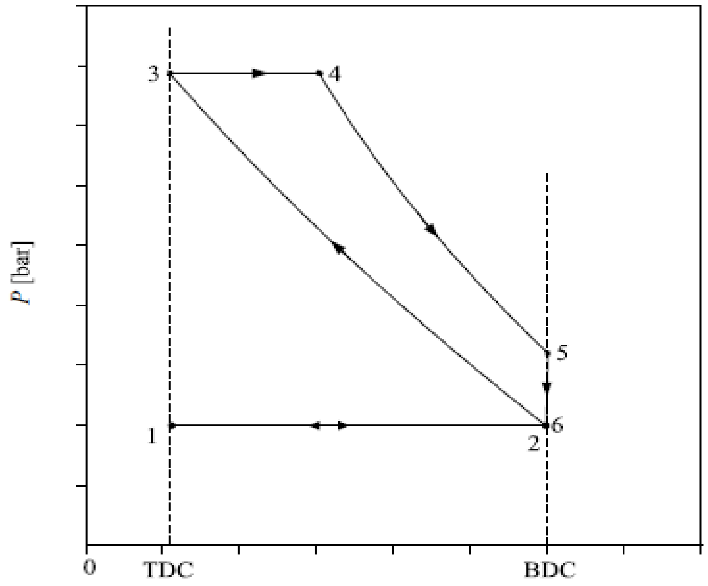
Real Otto cycle

- Combustion takes time: anticipation wtr opening of intake valve/ closing of exhaust valve
- Piston work to push the gases out
  -> gas work on cylinder during intake
- Compression and expansion non adiabatic (non isentropic)
- High ρ but problem of detonation

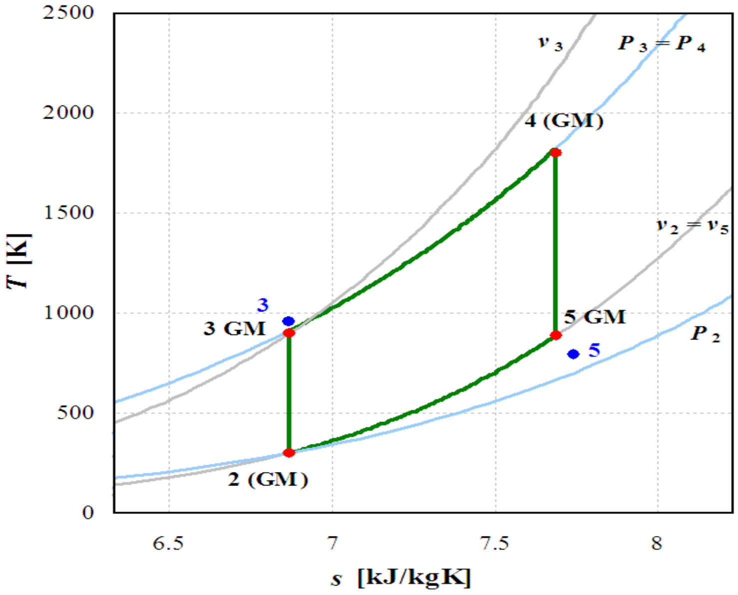


Ideal Diesel cycle

- To avoid detonation ➔ fuel injection after compression/spontaneous ignition
- Isobaric expansion
- Isentropic expansion/compression



T-s chart



Efficiency of the ideal Diesel cycle

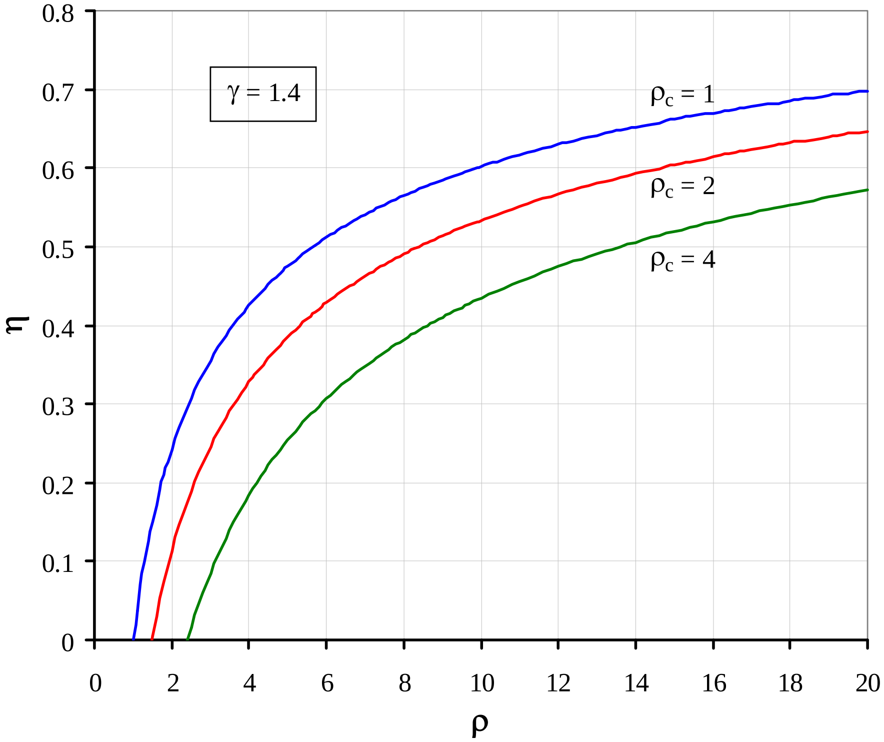
$$Pv = RT, \quad c_P = \text{const.}$$

$$\eta = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{1}{\rho^{\gamma-1}} \frac{\rho_{\text{c}}^{\gamma} - 1}{\gamma\left(\rho_{\text{c}} - 1\right)}$$

$$\rho \equiv \frac{v_2}{v_3}$$

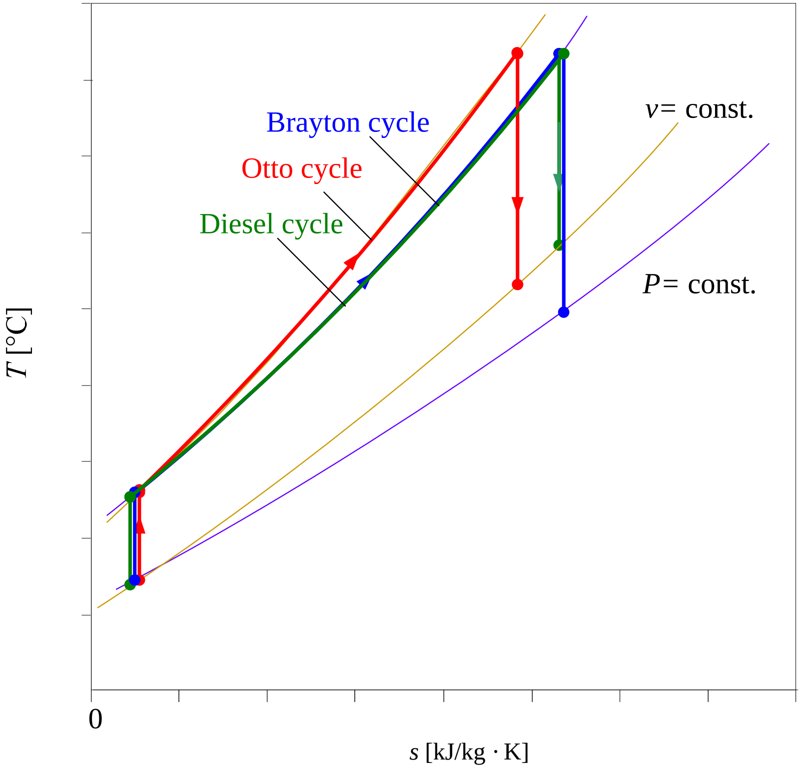
$$\rho_{\text{c}} \equiv \frac{v_4}{v_3}$$

Note: $\eta_{\text{DIESEL}}\left(\rho_{\text{c}} = 1\right) = \eta_{\text{OTTO}}$



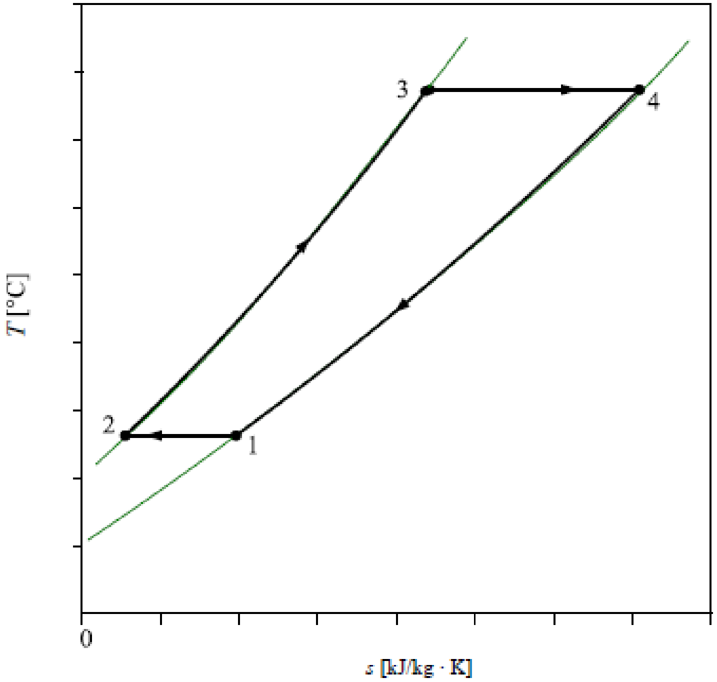
Comparison Brayton, Otto, Diesel

- If q_{INPUT} is the same: Diesel gives less net work output
- Therefore η_{DIESEL} is lower **for the same** β (ρ) and $T_{\min}$ and $T_{\max}$
- But β_{DIESEL} can be much higher than β_{OTTO} and β_{BRAYTON}

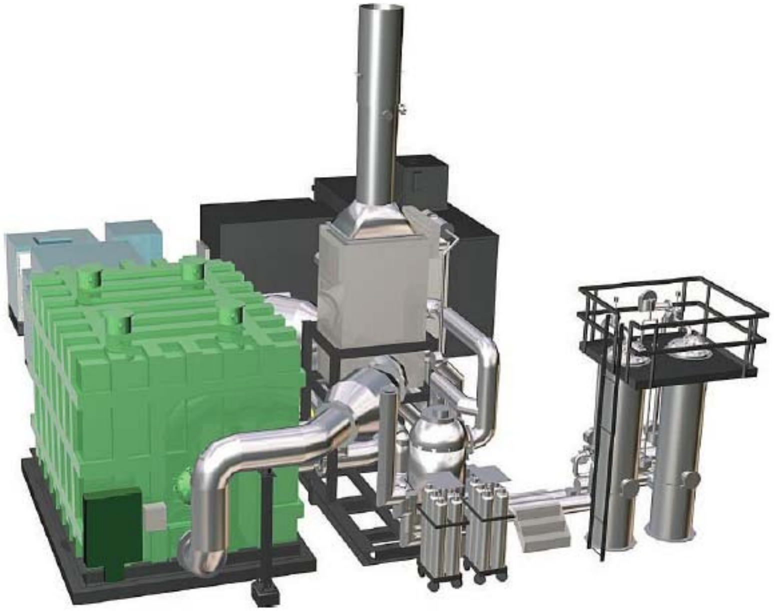


Stirling engine

- Closed cycle
- Isochoric heating and cooling
- Isothermal compression and expansion
- Complex
- Also reversed (cooling-heat pump)



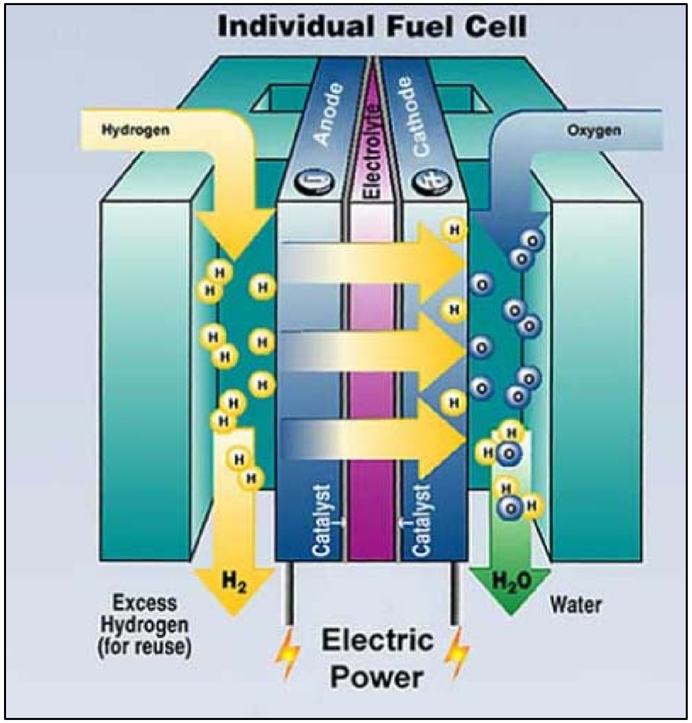
Fuel Cells



- Direct conversion of fuel into electricity with no thermodynamic cycle: efficiency very high
- Controlled reaction between fuel and oxidizer to produce electricity
- Continuous feed of fuel and oxidizer

Fuel cell: principle of operation

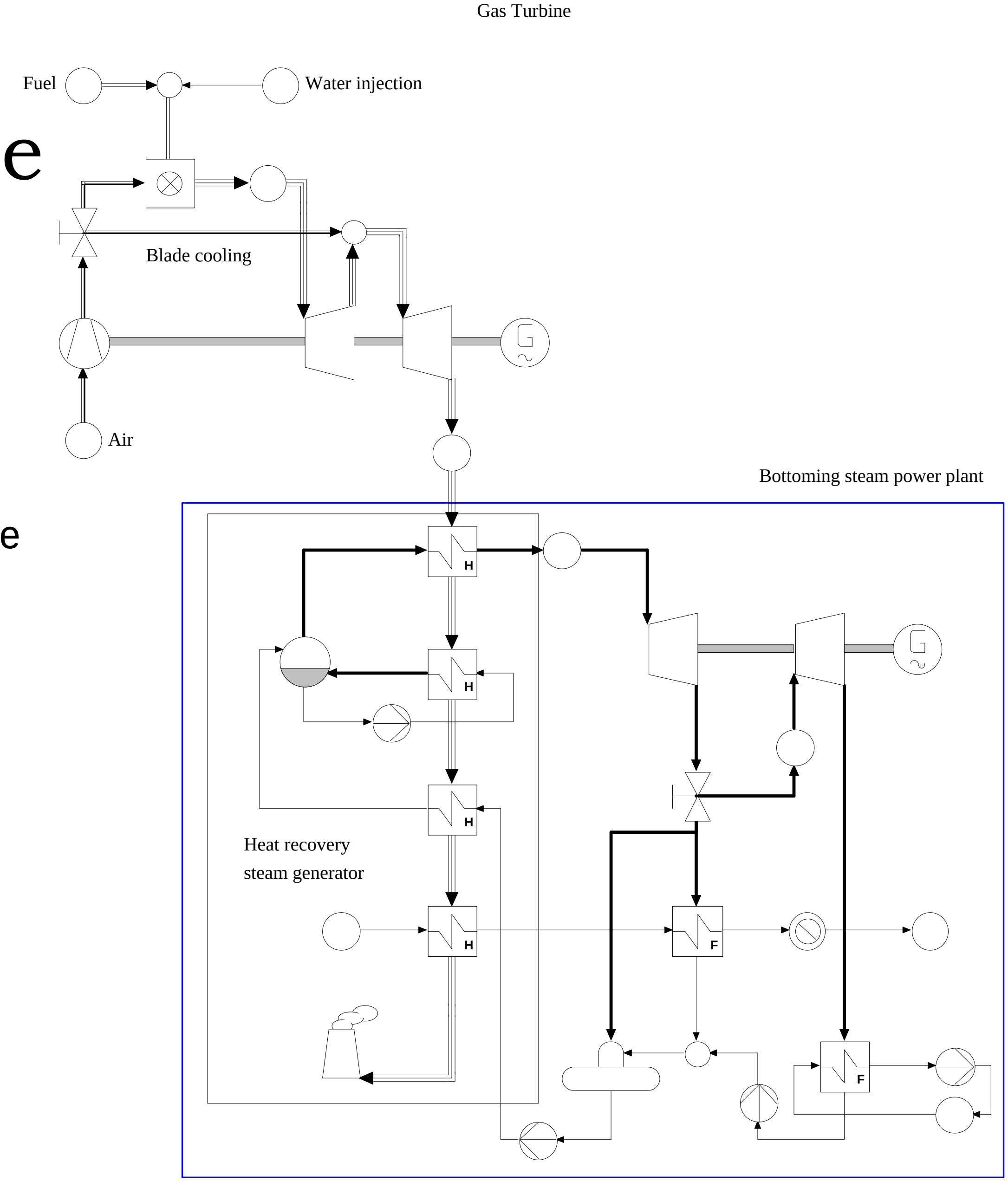
- Porous electrodes between O_2 and H_2
- Electrolyte (solid or liquid) limits reaction rate
- H_2 diffuses through anode, is absorbed on surface of cathode and reacts with OH^- in the electrolyte and forms H_2O, yielding free electrons
- O_2 diffuses through the cathode, is absorbed by the surface, and reacts with H_2O forming OH^-
- H_2O is formed at the anode and decomposed at the cathode,
- Electrons are produced at the cathode and provide electrical current for loads



Fuel cells characteristics

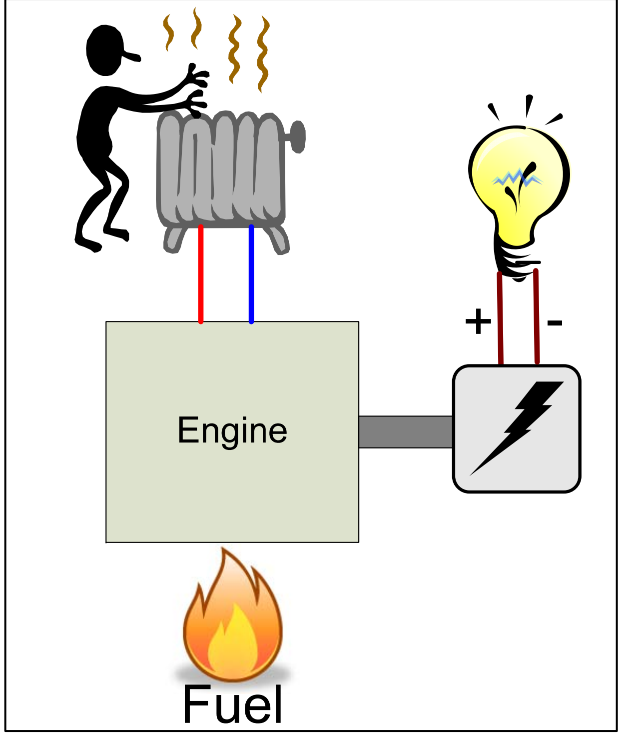
- Combinations of fuel/oxydizer/electrolyte operated at difference temperatures: PEM, SOFC, MCFC,...
- The fuel cell is not a “thermal engine”: the electrochemical process is isothermal
➔ Carnot efficiency is irrelevant
- Electrochemical reactions are more efficient than combustion + thermal engine
- Maximum theoretical efficiency of fuel cell is 100% (real is up to 60%)
- Stationary and propulsion applications but problem: initial investment cost

Combined cycle power plant

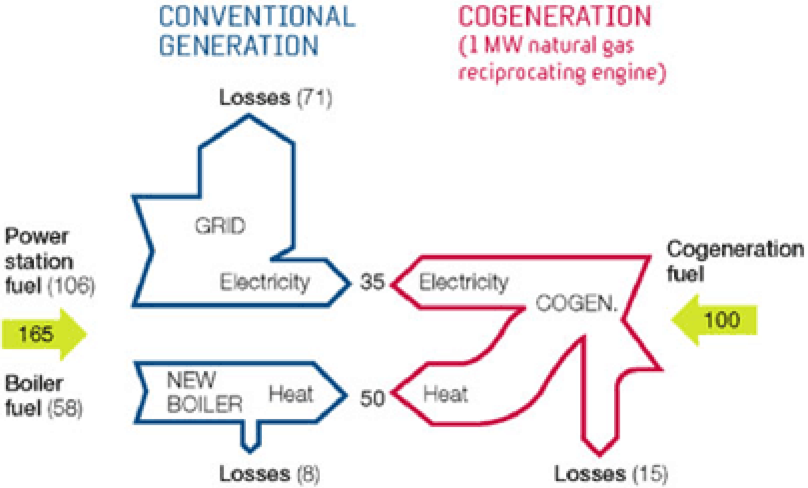


- Thermal power discarder by a gas turbine powers a steam cycle turbine (HRSG)
- Electrical Efficiency > 60 % (NG)
- Thermodynamic optimization: lower efficiency of gas turbine
- Solar combined-cycle technology?

Co- and trigeneration



- Residential and process heating: temperature level
- Better use of primary energy: convert into electrical and thermal (or cooling) power at the same time
- Cogeneration of heat and power (CHP)



Example: comparison of CHP with conventional supply

INPUT DATA

Efficiencies	η
ORC turbogenerator, electrical	0.18 (18%)
ORC CHP system (el+heat)	0.96 (96%)
Average EU power plants, electrical	0.35 (35%)
Average grid losses	0.06 (6%)
Non-condensing boiler, thermal	0.87 (87%)

Power	$\dot{W}$ **[kW]**
ORC turbogenerator, electrical	120

Cogen and conventional: same electrical and thermal power output

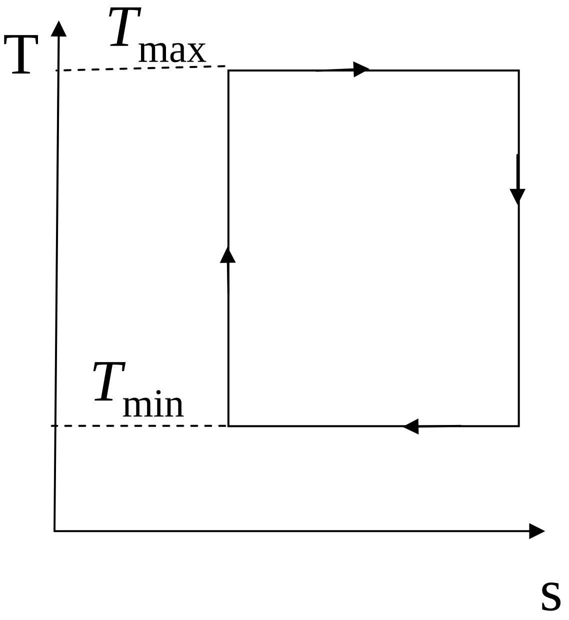
CHP:
comparison with conventional supply

Power	$\dot{W}, \dot{Q}$ **[kW]**
Electrical power output	120
ORC turbogenerator, total input power	**667**
ORC turbogenerator, cogen thermal (90°C)	525
Input power, conventional power plant	365
Boiler, thermal power (90°C)	525
Input power, conventional boiler	603
Total input power (Power Plant + boiler)	**968**

Efficiency gain of CHP system = 31.1 %

Exergy Analysis: basic observations

- Work if the system is not in equilibrium with the surrounding
- Maximum work between $T_{\max}$ and $T_{\min}$: Carnot cycle
- What is the maximum amount of work that can be extracted from a system (optimization)?

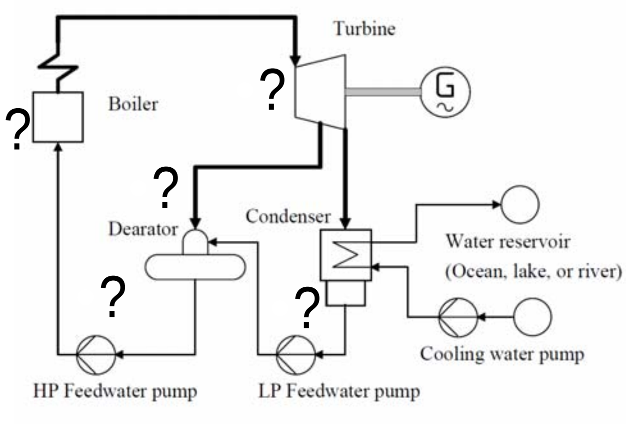


Tmd engineer's questions

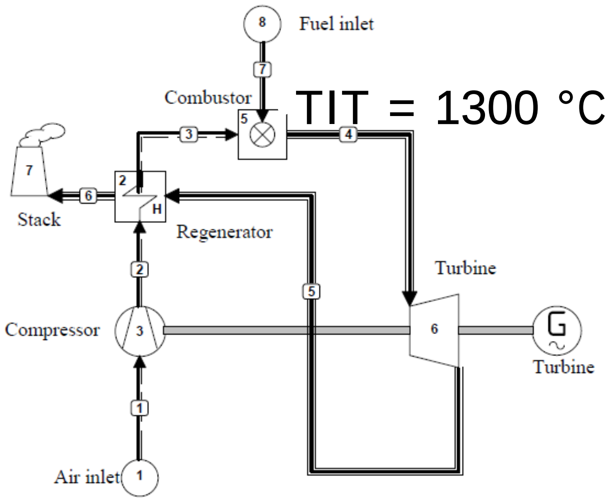
- Given a system made of components (sub-systems), which are most responsible for thermodynamic dissipation?

- Given two different energy systems operating between different temperature level, which one is operating better given its potential?

Geothermal TIT = 150 °C



$\eta = 0.11$



TIT = 1300 °C

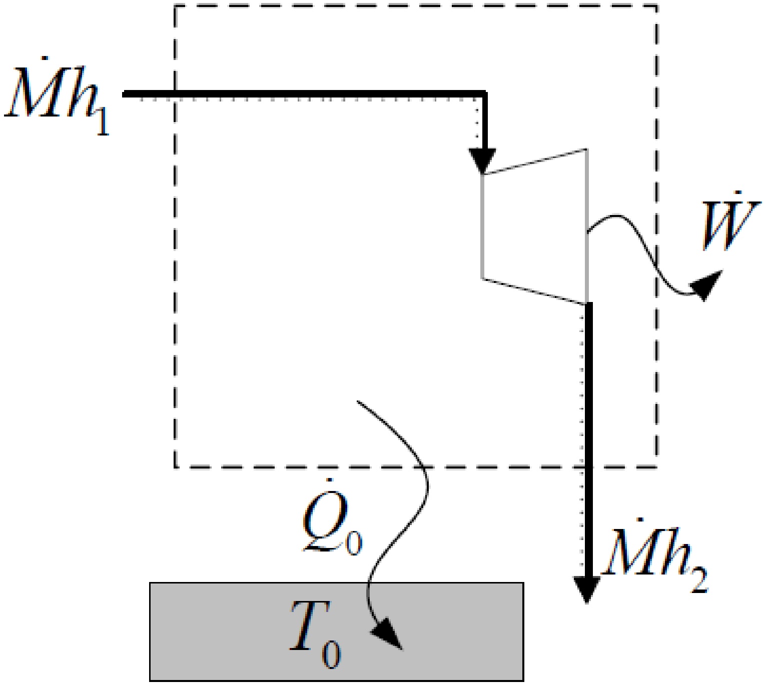
$\eta = 0.35$

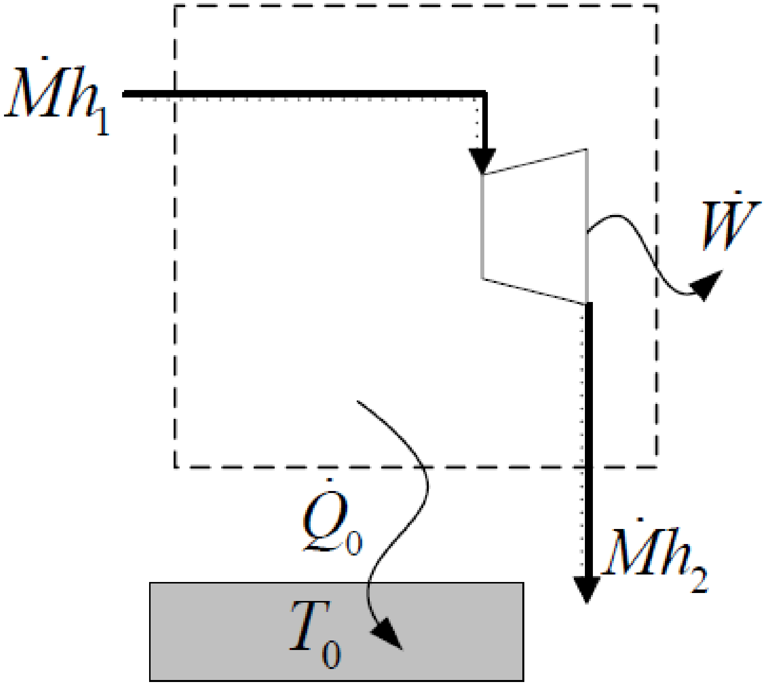
Available Energy

- **Example:** steady flow device

- What is the maximum power it can generate? (given some amount of energy, how much ENERGY is available to be converted into useful work?)

- Apply I and II law of thermodynamics



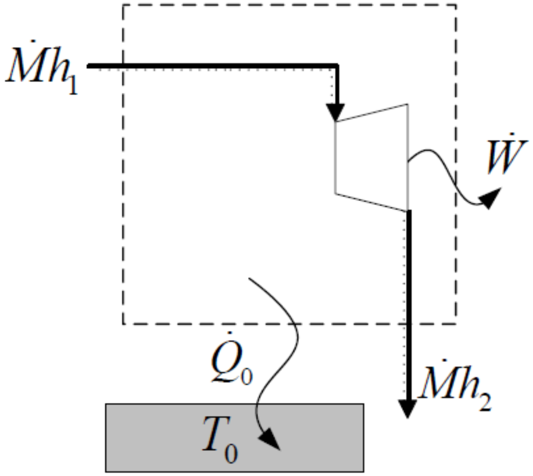

$\dot{M}h_1$
$\dot{W}$
$\dot{Q}_0$
$\dot{M}h_2$
T_0

A new thermodynamic function

$$\dot{W} = \dot{M}\left[\left(h_1 - T_0 s_1\right) - \left(h_2 - T_0 s_2\right)\right] - T_0 \cdot \dot{\mathscr{P}}_s$$

$$e \equiv h - T_0 s$$

$$\mathcal{E} = eM$$



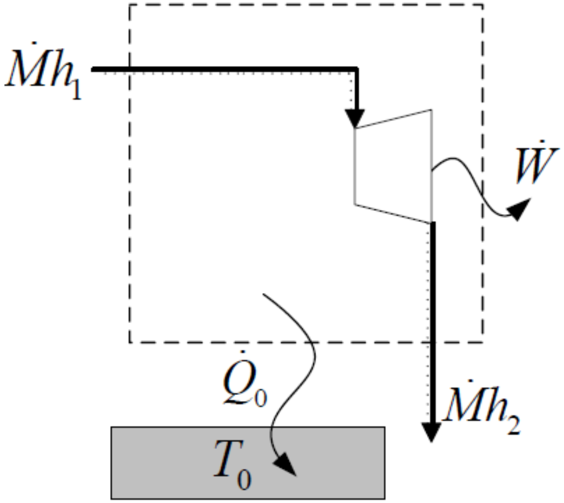
$\mathscr{P}_s$: thermodynamic loss (irreversibility)

In analogy with the example: calculation of $\mathscr{P}_s$ for every component-> primary causes of inefficiency

$\mathscr{P}_s$ ‘s has environmental and economic consequences

Result of the analysis

$$\boxed{\begin{aligned} &\dot{W} = \dot{M}\left[\left(h_1 - T_0 s_1\right) - \left(h_2 - T_0 s_2\right)\right] - T_0 \cdot \dot{\mathscr{P}}_s \\ &e \equiv h - T_0 s \\ &\mathcal{E} = eM \end{aligned}}$$



$\mathscr{P}_s$: cannot be avoided

Max $\dot{W}$ if state 2 is at T_0 and P_0

If T_2 is greater than T_0 : cogeneration!

If P_2 is greater than P_0, add a turbine stage

(P_2 must be slightly greater than P_0)

SPARE SLIDES

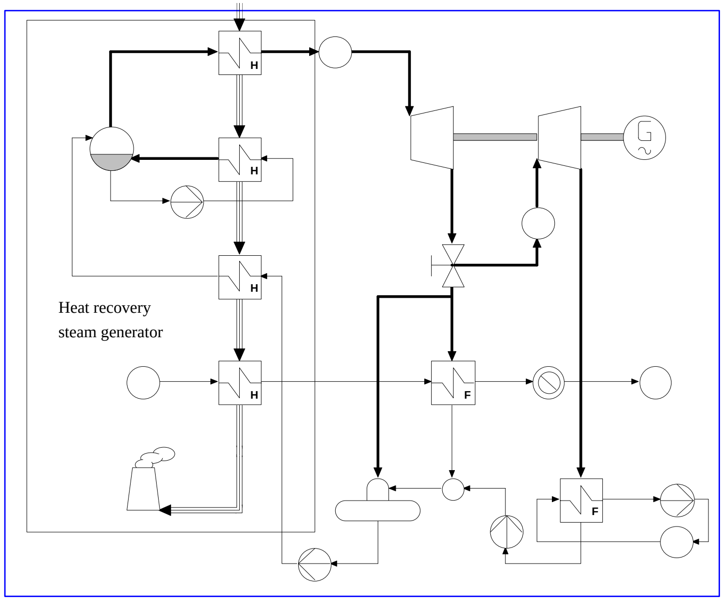
Thermodynamics and design (1)

- Pollution and global climate change
- Sustainable: it does not deplete permanently earth resources, (and it does not harm etc.)
- Sustainable energy systems exist: how to beat fossil-fuel based?
- First: reduce waste!
- What is the cost of energy?

Thermodynamics and design (2)

Design criteria:

- Sustainability (life cycle analysis, waste, recycle measures, etc.)
- Cost (Initial, operational, etc)
- Weight
- Volume
- Aesthetics
- ...



Analysis and optimization is based on system simulations:
Static and Dynamics

The future?

- Distributed energy conversion
- Solar, wind, geothermal, biomass, tidal, OTEC, etc.
- Energy storage and batteries
- Public transportation, electric cars (batteries for baseload storage?)
- ...