Two-step optimization approach for increase of engine-ORC efficiency

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Outline

- state of the art in engine-ORC technology and motivation
- methods: thermodynamic and performance optimization
- 1. step: thermodynamic calculation:
  - assumptions
  - results
  - definition of reference design
- 2. step: performance evaluation:
  - variation of system design parameters
  - results
  - comparison of results
- conclusion and outlook

State of the art and motivation

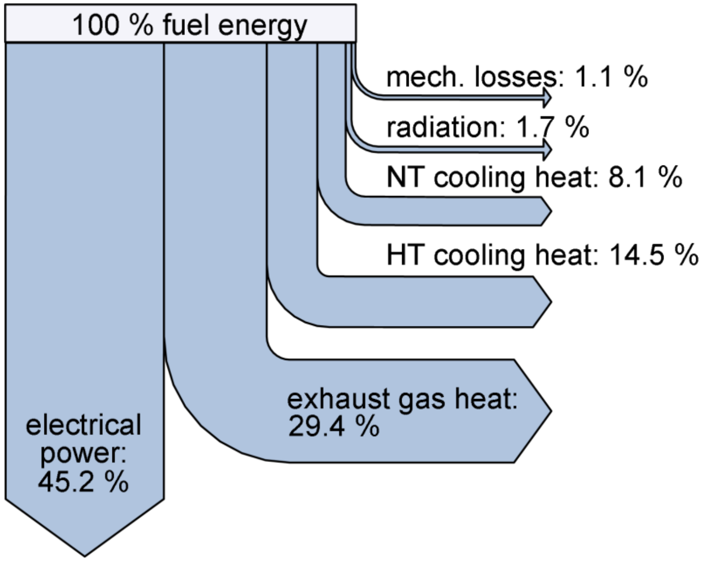
Internal combustion engines:

- independent power producers with high electrical efficiency (up to 47 %)
- fuel flexibility (natural gas, biogeneous fuels, Diesel and heavy fuel oil)
- fast respond to load changes, good part load behaviour

→ up to 45 % of fuel input as waste heat:

temperature levels:

- exhaust gas: 300 °C to 400 °C
- engine cooling water: ~ 90 °C



Heat flux diagram of state of the art internal combustion engine

State of the art and motivation

Waste heat recovery systems:

- water/steam cycle: heat source temperature 350 ° C to 600 ° C
- Organic-Rankine-Cycle: heat source temperature 90 ° C to 400° C

→ ORC technology especially for state-of-the-art engines with low exhaust gas temperatures

Engine-ORC technology:

- use of exhaust gas or cooling water as heat source
- no integration of both
- use of recuperator
- standardised engine and ORC technology → no combined system optimization
- fluids: pentane, R245fa, MDM

Methods for engine-ORC evaluation

1. step: Thermodynamic optimization:

- evaluation of different system configurations
- evaluation of different fluids

} with software Ebsilon Professional

- variation of fluid evaporation pressure

→ definition of thermodynamic optimum: $\left(P_{ORC,net} = P_{turbine} - P_{pump}\right)_{\max}$

→ thermodynamic optimum = reference configuration

2. step: Fast performance evaluation:

- rough calculation of heat exchanger areas: $A_{tot} = A_{exhaustgas} + A_{evaporator} + A_{rec} + A_{cond}$
- variation of design parameters:
  - evaporation pressure
  - recuperator performance (pinch point)
  - engine cooling water temperature

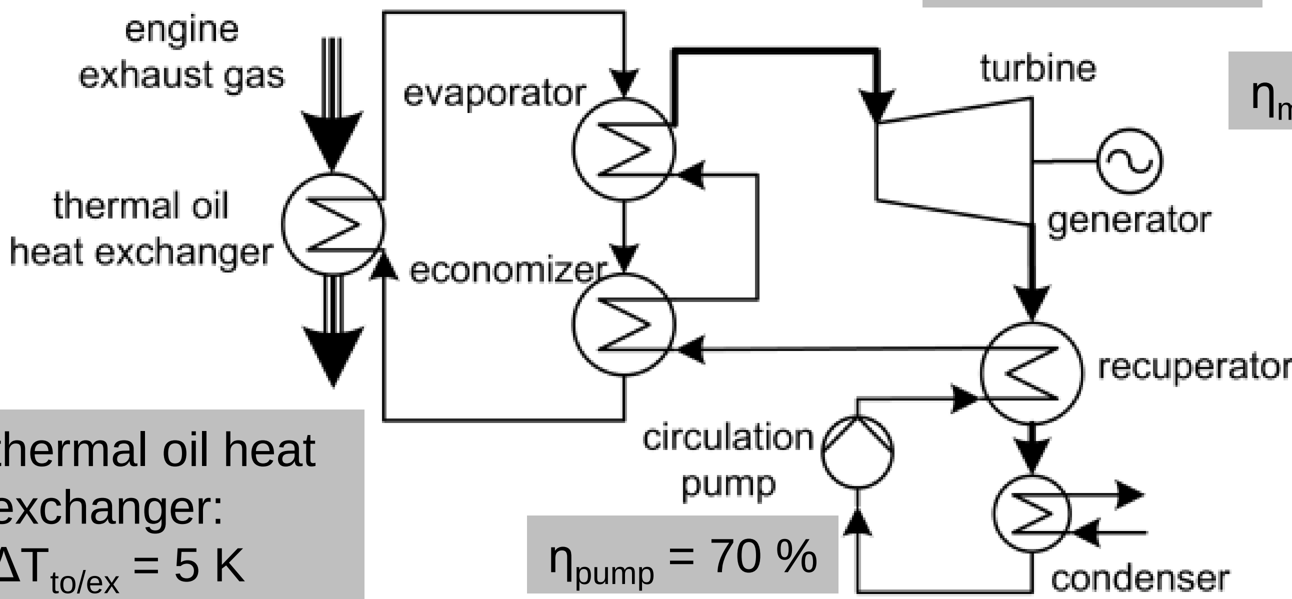
→ performance optimum: $\left(\frac{P_{ORC,net}}{A_{tot}}\left[\frac{kW}{m^2}\right]\right)_{\max}$

Thermodynamic calculation - assumptions

evaporator pinch point = 5 K

$\eta_{turbine}$ = 82 %

η_{mech}, η_{gen} = 98 %



recuperator:
pinch point = 5 K
pressure loss:

- MDM: 2 kPa
- pentane: 50 kPa
- R245fa: 100 kPa

thermal oil heat exchanger:
$\Delta T_{to/ex}$ = 5 K
$T_{min,ex}$ = 65 ° C

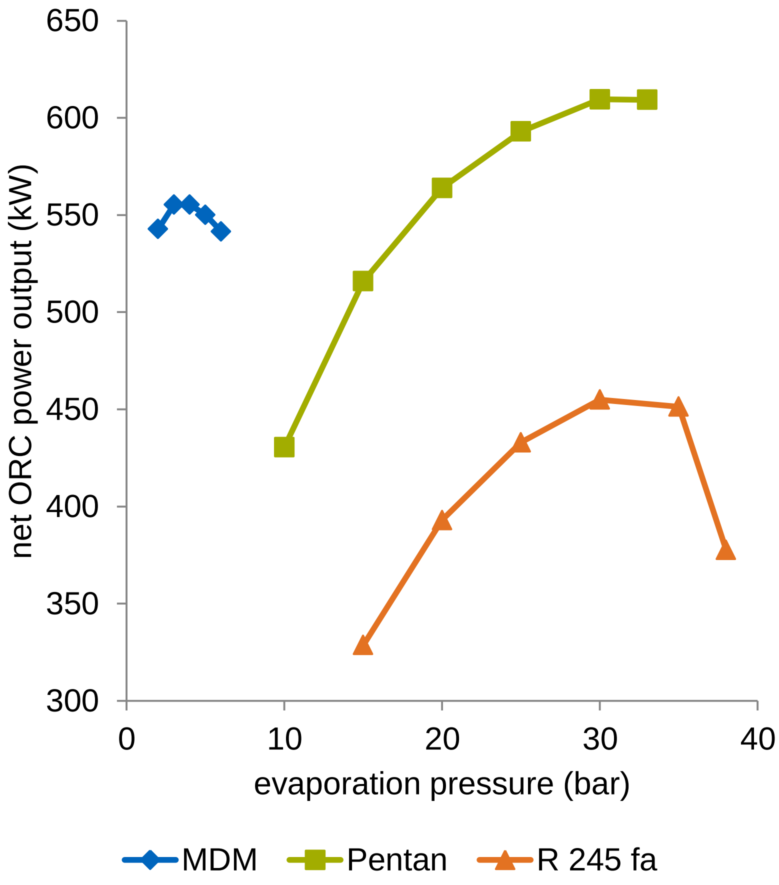
η_{pump} = 70 %

condenser:
T_{cond} = 55 ° C
ΔT_{cond} = 7 K

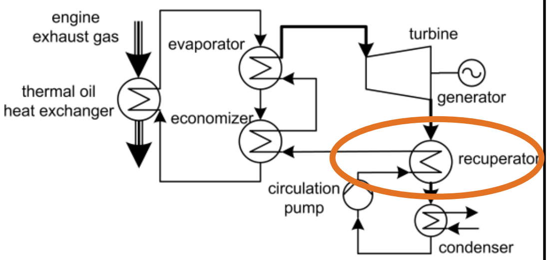
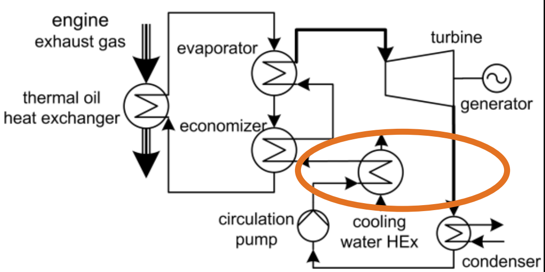
Thermodynamic calculation – results

maximum power output:

- MDM: 4 bar → 555 kW
- pentane: 30 bar → 610 kW
- R245fa: 30 bar → 455 kW



Definition of reference design

ORC systems	pentane	MDM
ORC with recuperator 	p_{fluid} = 30 bar T_{fluid} = 189 °C thermal oil: 225 / 95 °C $T_{exhaust}$ = 100 °C $P_{el,net}$ = 610 kW	p_{fluid} = 4 bar T_{fluid} = 214 °C thermal oil: 270 / 158 °C $T_{exhaust}$ = 163 °C $P_{el,net}$ = 555 kW
ORC with engine cooling water heat exchanger 	p_{fluid} = 30 bar T_{fluid} = 189 °C thermal oil: 225 / 92 °C $T_{exhaust}$ = 97 °C T_{cw} = 90 °C $P_{el,net}$ = 607 kW	

System design and variation parameters

- evaporation pressure: 10 bar to 33 bar (critical pressure for pentane: 33,7 bar)
- recuperator pinch point: 1 K to 20 K
- engine cooling water temperature: 85 °C to 120 °C (within technical feasibility of engine construction)

Evaluation of:

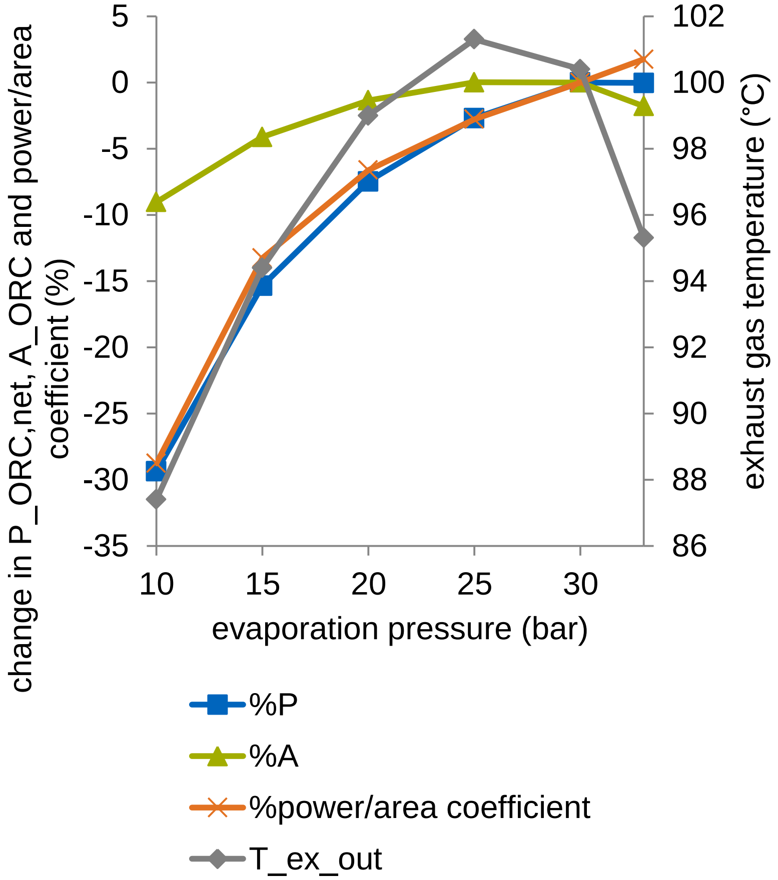
- net ORC power output
- heat exchanger areas
- exhaust gas temperature
- power/area coefficient

Variation of design parameters – evaporation pressure

Influence of evaporation pressure on ORC cycle performance:

- maximum net power output of ORC system at 30 bar
- minimum overall heat exchanger area at 10 bar
- great influence of decreasing power with decreasing pressure

→ best power/area coefficient at 33 bar

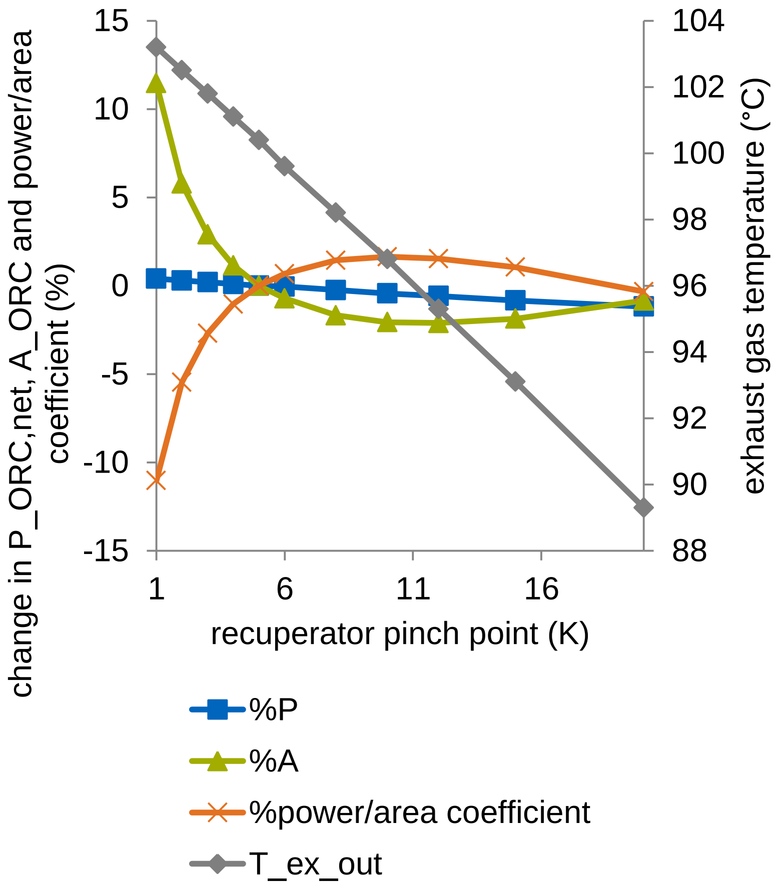


Variation of design parameters – recuperator pinch point

Influence of increasing pinch point on ORC cycle performance:

- almost no influence on power: +/- 2 %
- decreasing exhaust gas temperature: 103 ° C to 89 ° C
- optimal power/area coefficient at a pinch pint of 10 K

→ highest possible cooling of exhaust gas does not lead to the economically best performance



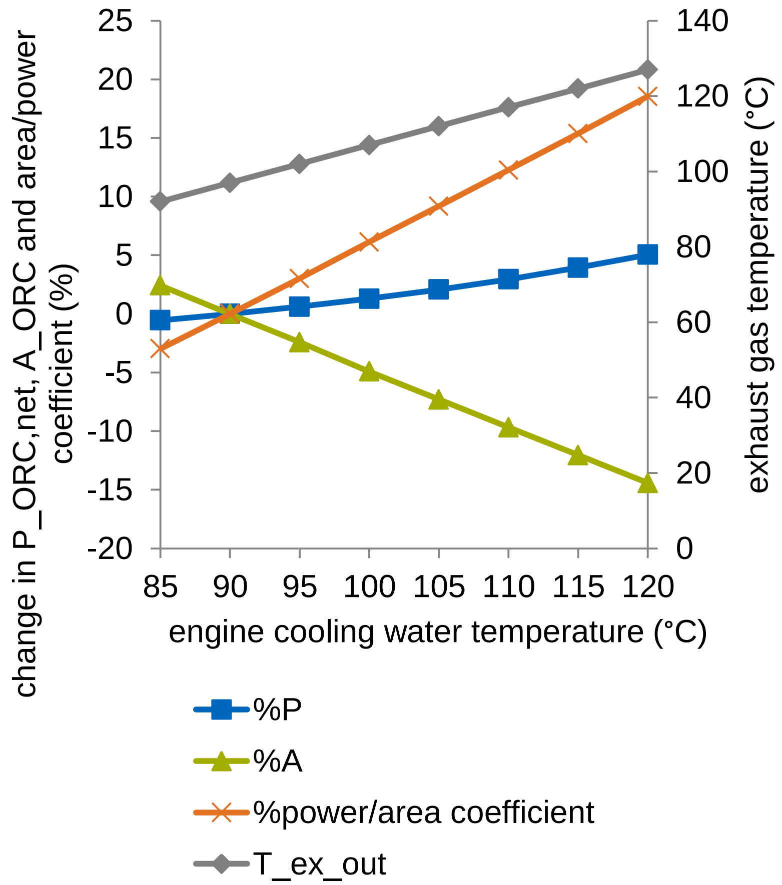
Variation of design parameters – cooling water heat exchanger

Influence of increasing cooling water temperature on ORC cycle performance:

- increasing power output (+ 5 %) → higher vapour mass flow
- decreasing over all heat exchanger area
- increasing power/area coefficient → up to – 20 %

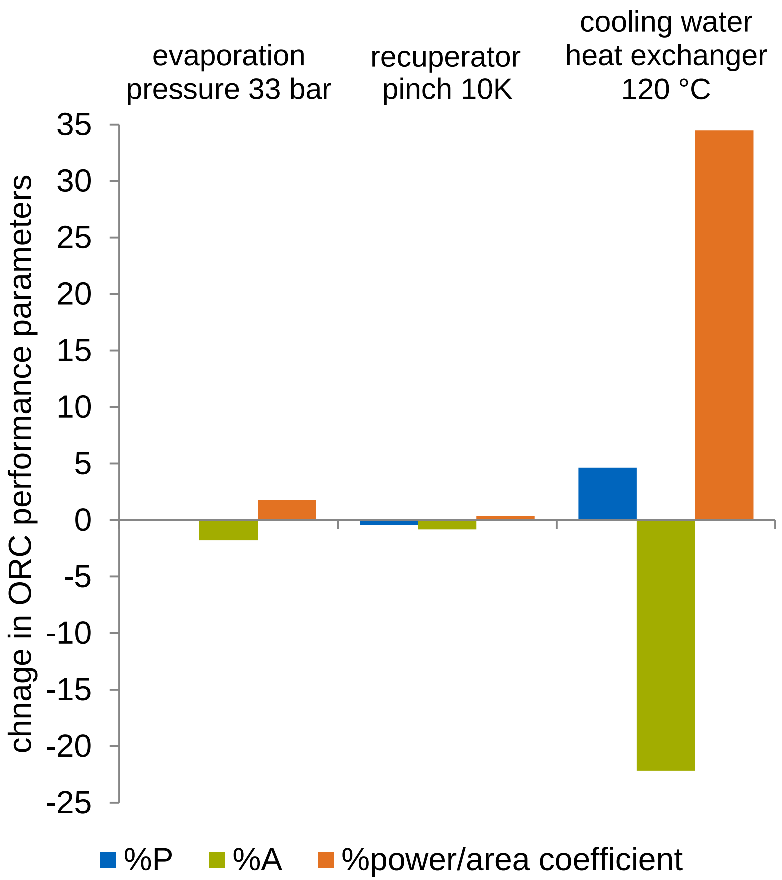
→ highest possible cooling of exhaust gas does not lead to the economically best performance

→ system optimization also has to take into account the engine not only the bottoming cycle



Discussion of optimal systems compared to basic configuration

- best economic performance for ORC with engine cooling water heat exchanger (120 ° C):
  - + 5 % net power output
  - + 35 % power/area coefficient
- optimization of evaporator pressure and recuperator pinch point around thermodynamic optimum does not have a great impact:
  - evaporation pressure: + 2 % power/area coefficient (but higher cost and safety efforts due to higher power !)
  - recuperator pinch: + 0.5 % power/area coefficient



Conclusion

- two-step approach:
  - thermodynamic optimization: ORC net power output
  - performance optimization: power/area coefficient as indicator for cost efficiency
- variation of important design parameters: evaporation pressure, recuperator pinch point, engine cooling water temperature

→ engine cooling water temperature has major influence on power/area coefficient

→ not only ORC internal optimization parameters, but overall system parameters, such as engine design parameters, have to be taken into account for an optimization approach

Outlook

further research topics:

- only qualitative results: optimization for specific case of application is necessary
- specific advantages of other fluids besides pentane (e.g. MDM → high exhaust gas temperatures → benefit for CHP applications)
- investigation of system performance during transient operation: specific requirements due to coupling of engine and ORC system at exhaust gas and cooling water side (e.g. engine cooling has to be ensured even when ORC is not running, different load change rates of engine and ORC)
- calculations are highly depending on the determination of heat transfer coefficients → easy and fast calculation procedures