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Energetical, Technical and Economical considerations by choosing between a Steam and an Organic Rankine Cycle for Small Scale Power Generation

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1. ORC research objectives
2. The Steam Cycle
3. The Organic Rankine Cycle
4. Benchmark ORC vs Steam
5. Optimal use of a heat source
6. Calculation tool
7. Conclusions

Research Objectives

- To give an answer how to choose between a steam cycle and ORC for a given (waste) heat source related to small scale power generation
- Influence of all process parameters
- Effectiveness of a recuperater
- Influence of temperature profile heat source
- Economic analysis and comparison (not in this presentation)
- Selection criteria steam vs. ORC
- Elaborate industrial case studies
- Demonstrate ORC via a lab scale test rig

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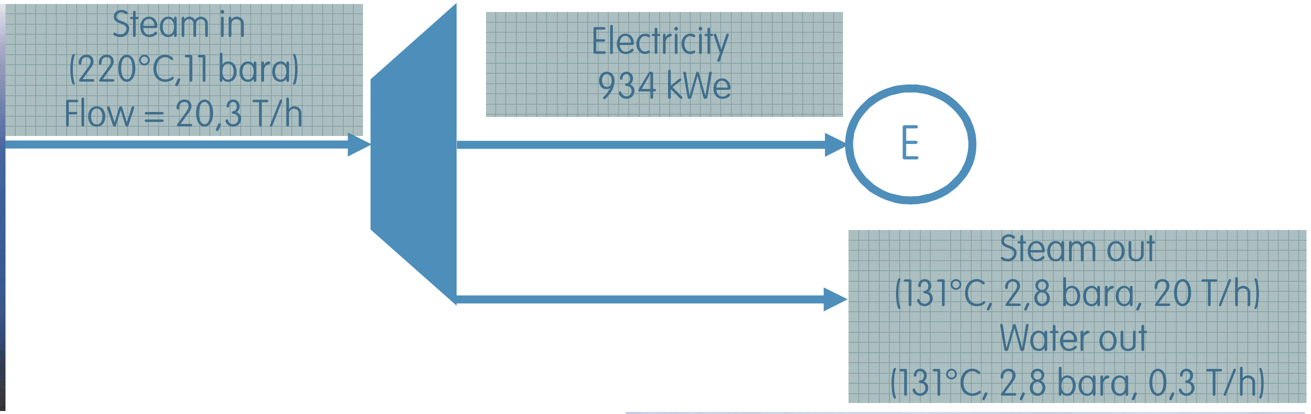
The Steam Cycle

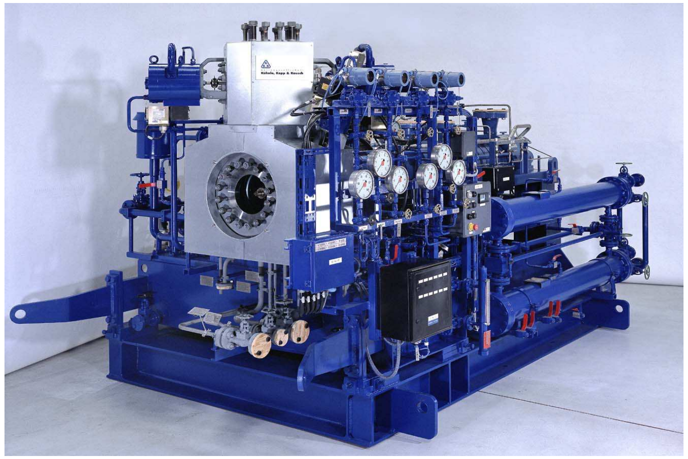
Wide range of steam turbines to recover waste heat and transform into electricity :

- impuls -, reaction turbine
- condensing -, backpressure turbine
- saturated -, superheated steam



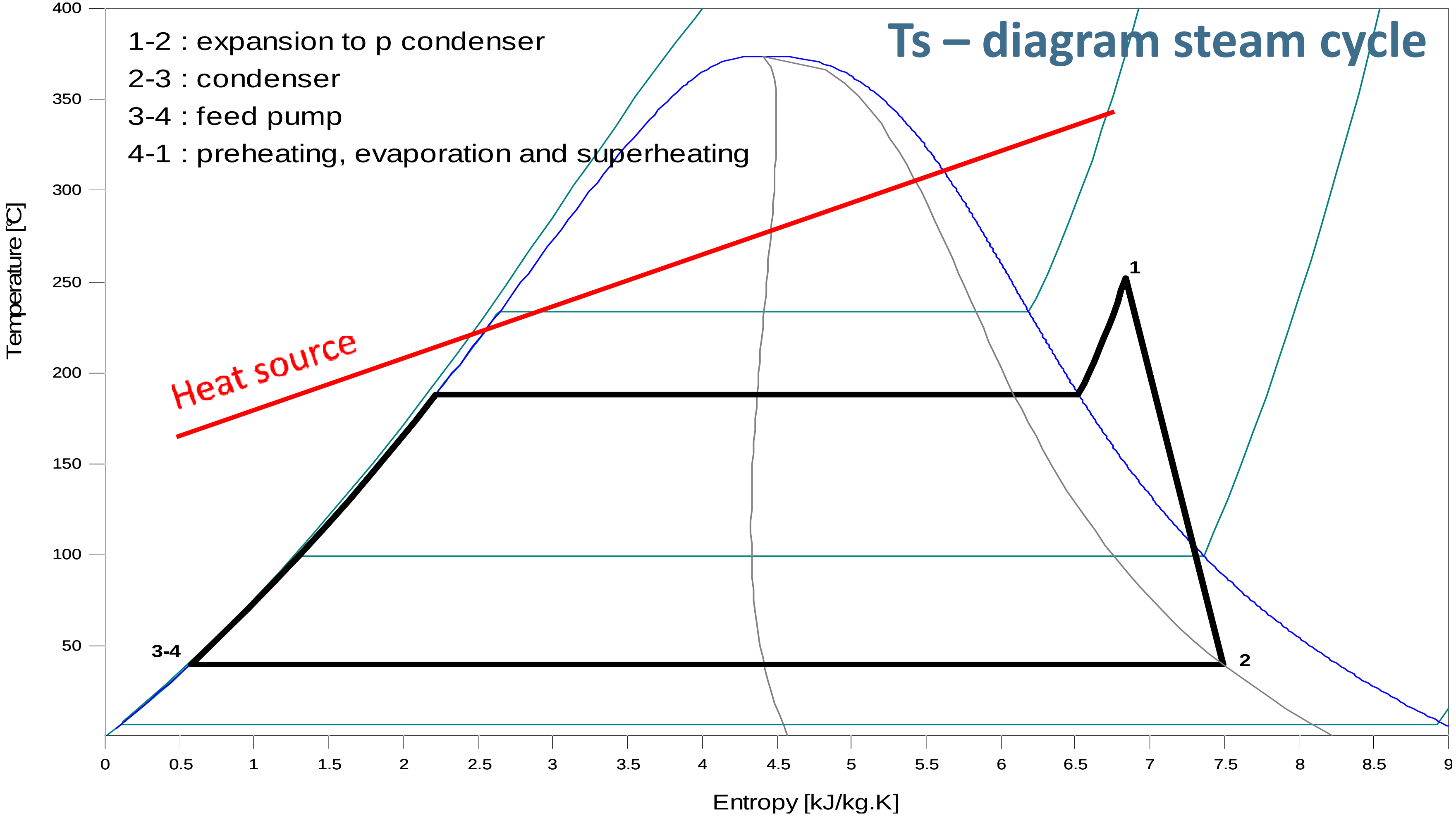
Example: Siemens SST series

Live steam pressure	: 3 – 130 bara
Live steam temperature	: dry sat. – 530°C
Exhaust steam pressure	: 0,08 – 29 bara
Speed	: 500 – 23000 rpm
Power	: 300 – 10000 kW



The Steam Cycle

- Superheating required to avoid condensation during expansion in turbine
- Only small part of total heat required on high t° level to superheat: no optimal use of the heat source, lower cycle efficiency



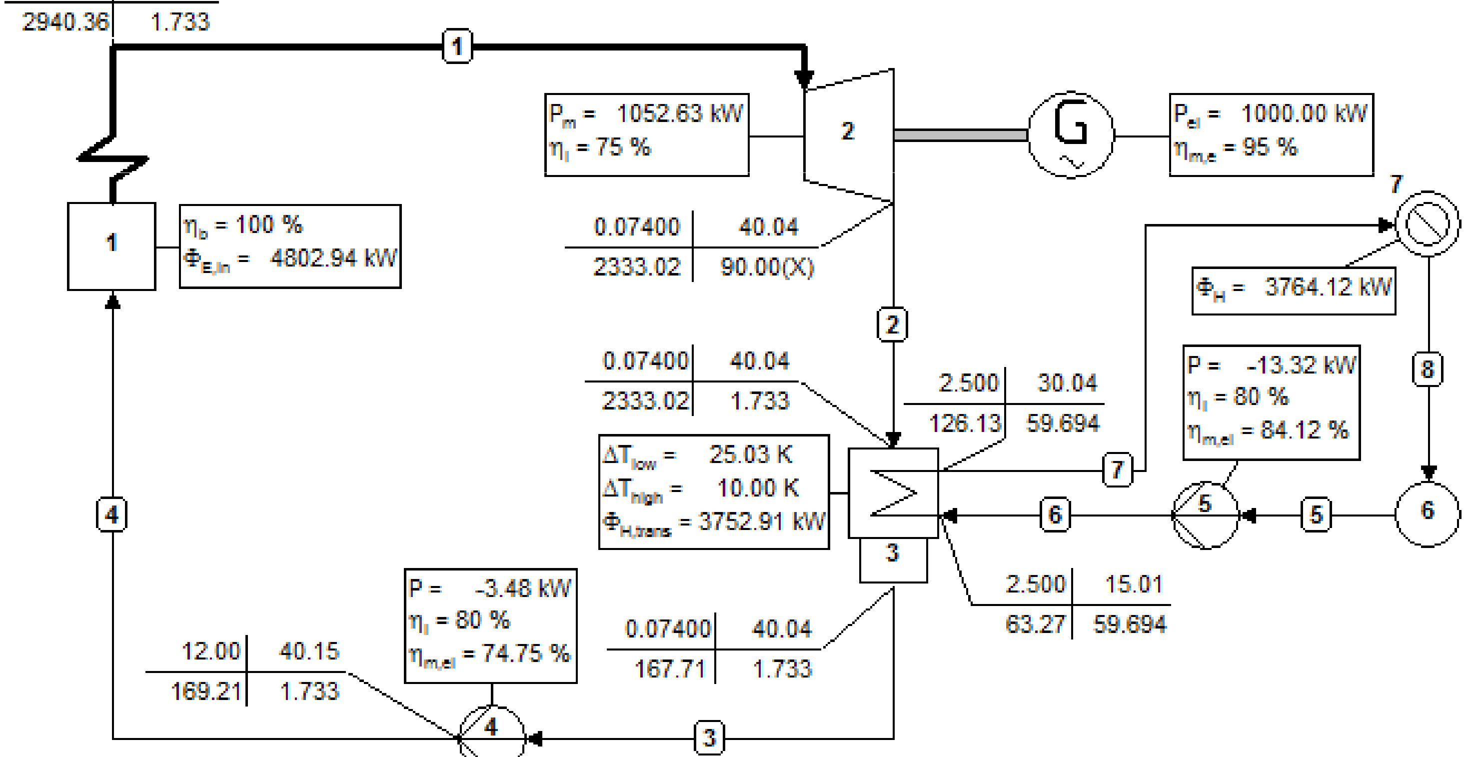
Disadvantages to the use of steam on low grade waste heat sources :

- Limited quantity of heat on high level restricts the evaporation pressure and superheating temperature and thus results in low cycle efficiencies.
- Low isentropic efficiency for single stage impuls steam turbine (60 – 65%)

p | T
h | Φ_m

p = Pressure [bar]
T = Temperature [°C]
h = Enthalpy [kJ/kg]
Φ_m = Mass flow [kg/s]
η_b = Boiler efficiency [%]
$\Phi_{E,in}$ = Energy input [kW]
P_m = Mechanical Power [kW]
η_i = Isentropic efficiency [%]
ΔT_{low} = Low end temp. diff. [K]
ΔT_{high} = High end temp. diff. [K]
$\Phi_{H,trans}$ = Transmitted heat flow [kW]
P = Power [kW]
$\eta_{m,e}$ = Mechanical*Electrical eff. [%]
X = Vapour quality [%]
Φ_H = Heat output [kW]
P_{el} = Electrical Power [kW]

Simulation Simple Steam Cycle



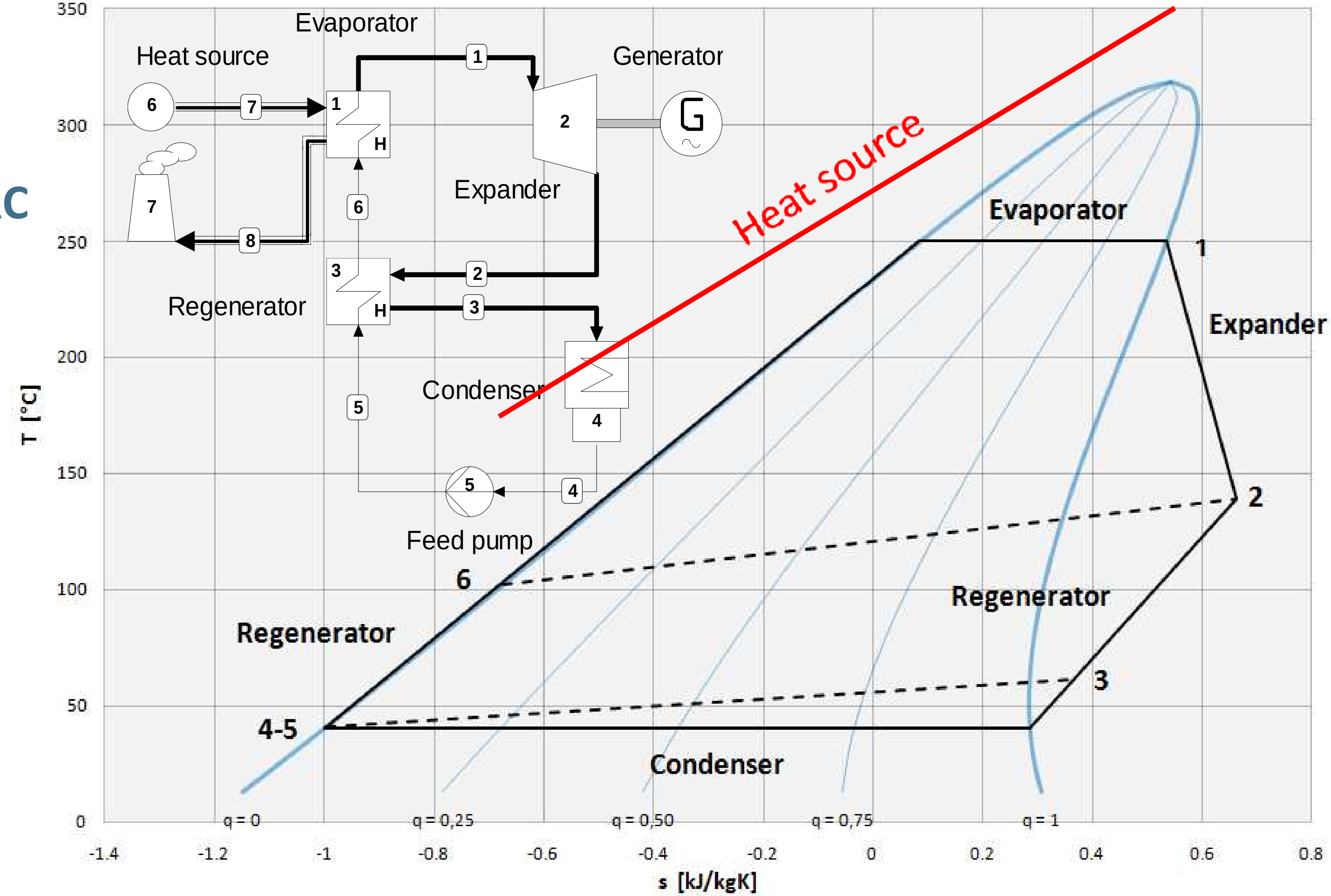
Simulation made in Cycle Tempo (TU Delft)

The Organic Rankine Cycle

- ORC uses similar technology as steam cycle : evaporator - expander – condenser
- But organic work fluid is being used instead of water/steam
- Advantages : smaller quantity of evaporation heat and no superheating needed

Commonly used ORC work fluids :

- Toluene
- (Cyclo)-pentane
- Ammonia
- Butane
- Refrigerants (R245fa)
- Solkatherm
- Siloxanes (silicone oils)

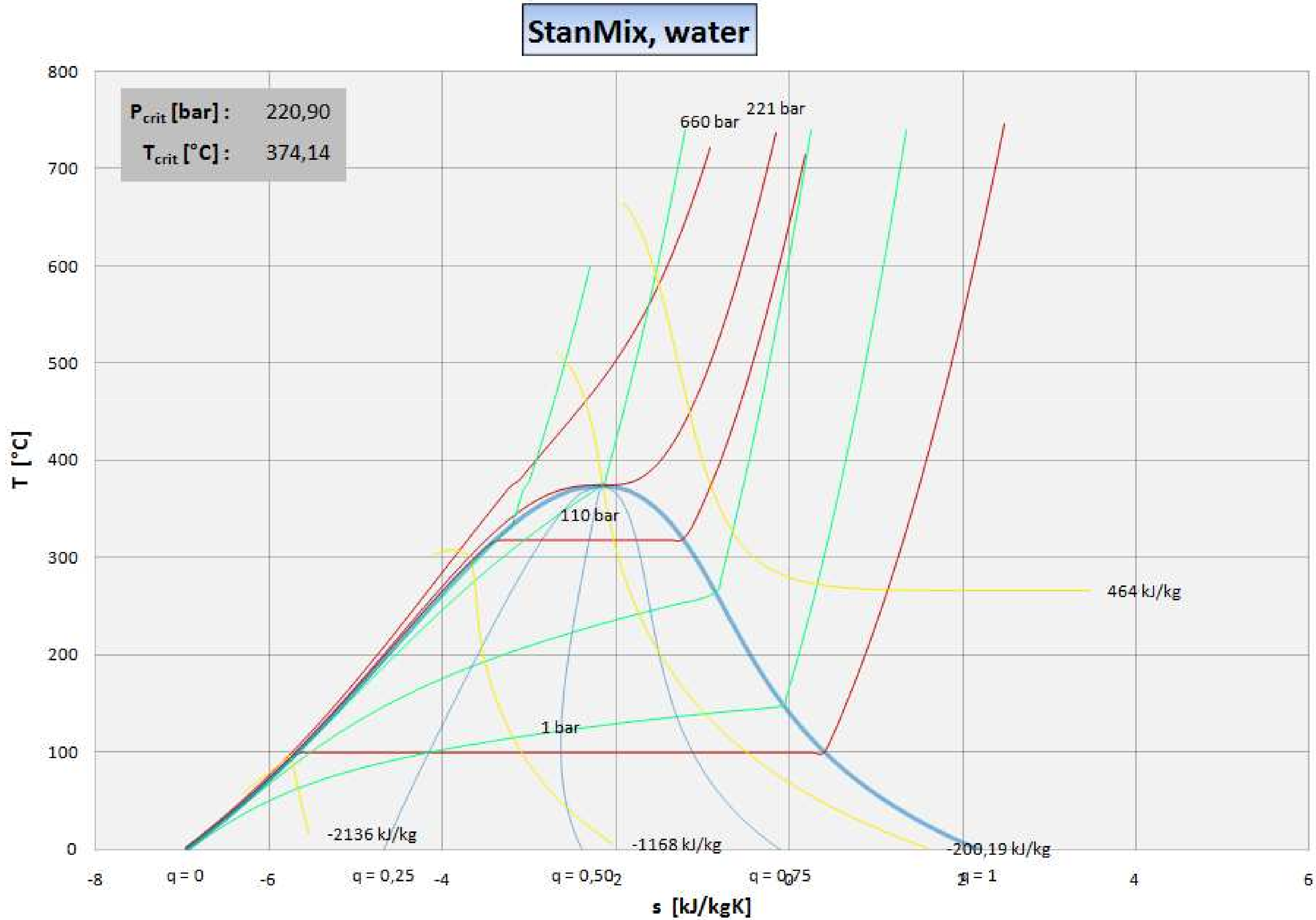


Properties ORC media vs. Steam

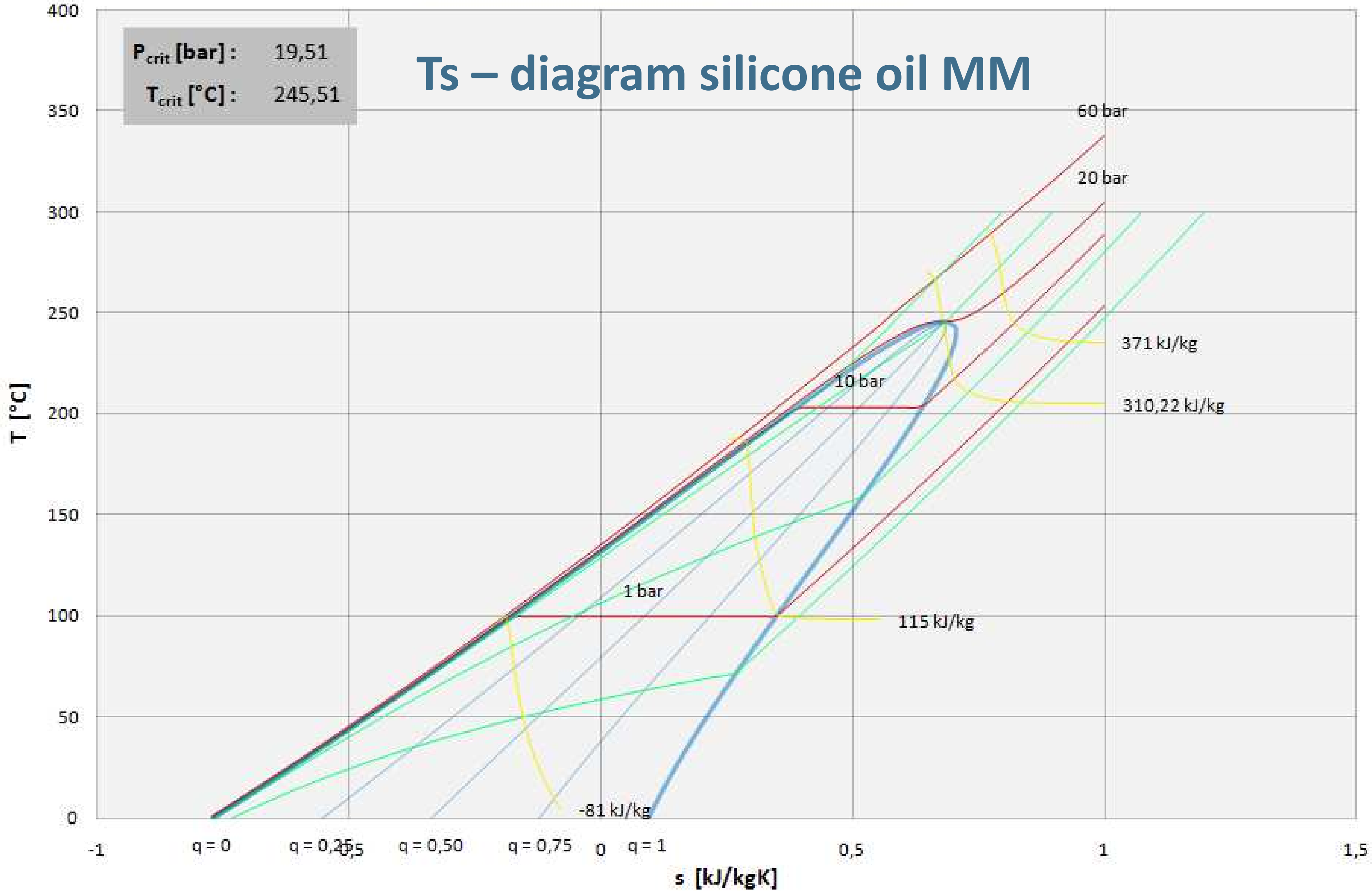
		T_{crit}	p_{crit}	Boiling Point	E_{evap} (1bar)
Fluid	**Formula / name**	**[°C]**	**[bar]**	**[°C]**	**[kJ/kg]**
Water	H20	373.9	220.6	100.0	2257.5
Toluene	C7H8	318.7	41.1	110.7	365.0
R245fa	C3H3F5	154.1	36.4	14.8	195.6
n-pentane	C5H12	196.6	33.7	36.2	361.8
cyclopentane	C5H10	238.6	45.1	49.4	391.7
Solkatherm	solkatherm	177.6	28.5	35.5	138.1
OMTS	MDM	291.0	14.2	152.7	153.0
HMDS	MM	245.5	19.5	100.4	195.8

- Water : wet fluid < > ORC media : dry fluids (positive slope saturated vapour)
- Dry fluids : no superheater required
- Application area in function of T_{crit} and p_{crit}
- High BP -> high specific volume at low T condensation
- Low evaporation heat -> high mass flow -> bigger feed pump

The Organic Rankine Cycle



StanMix, Hexamethyldisiloxane

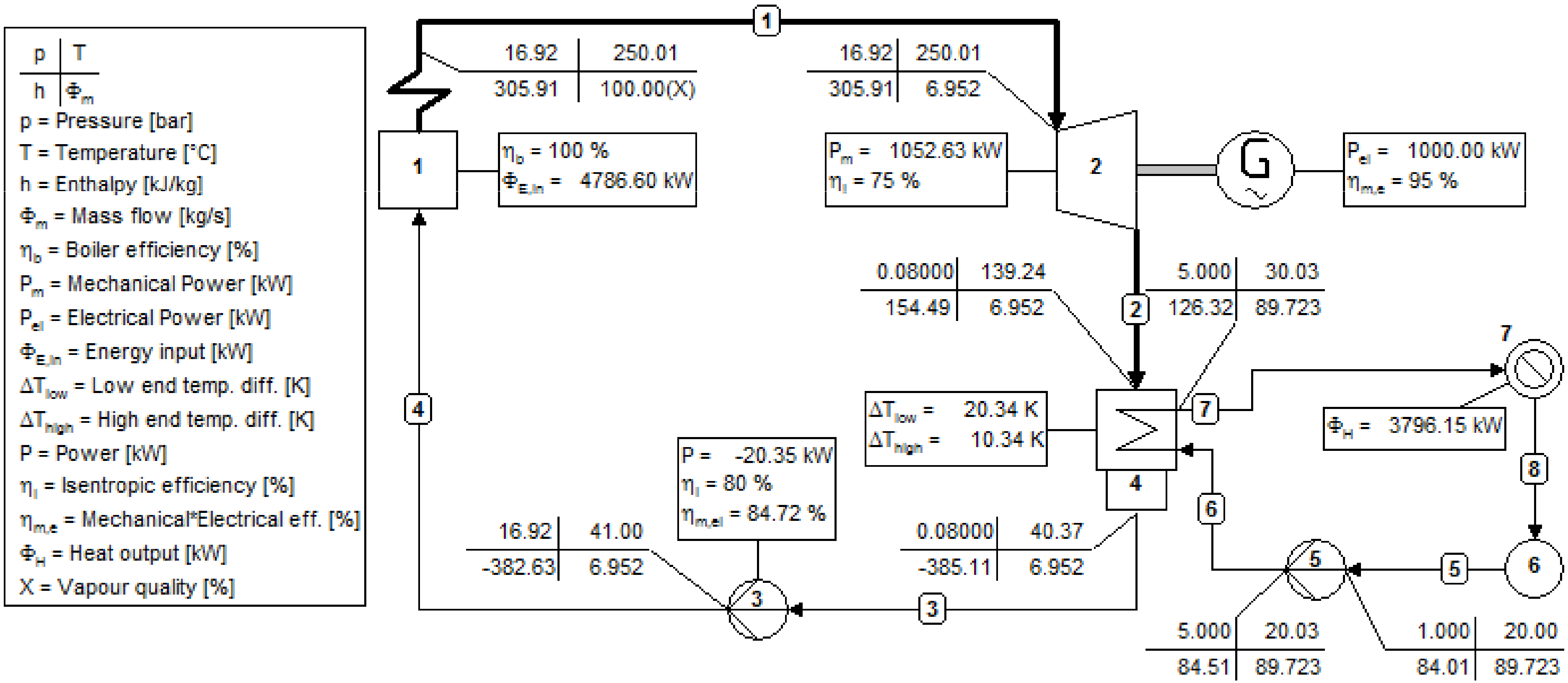


The Organic Rankine Cycle

- In simple ORC without regenerator : high quantity of sensible heat after expanders to reject, has negative effect on cycle efficiency.
- Dedicated design of ORC turbines have isentropic efficiency >85%

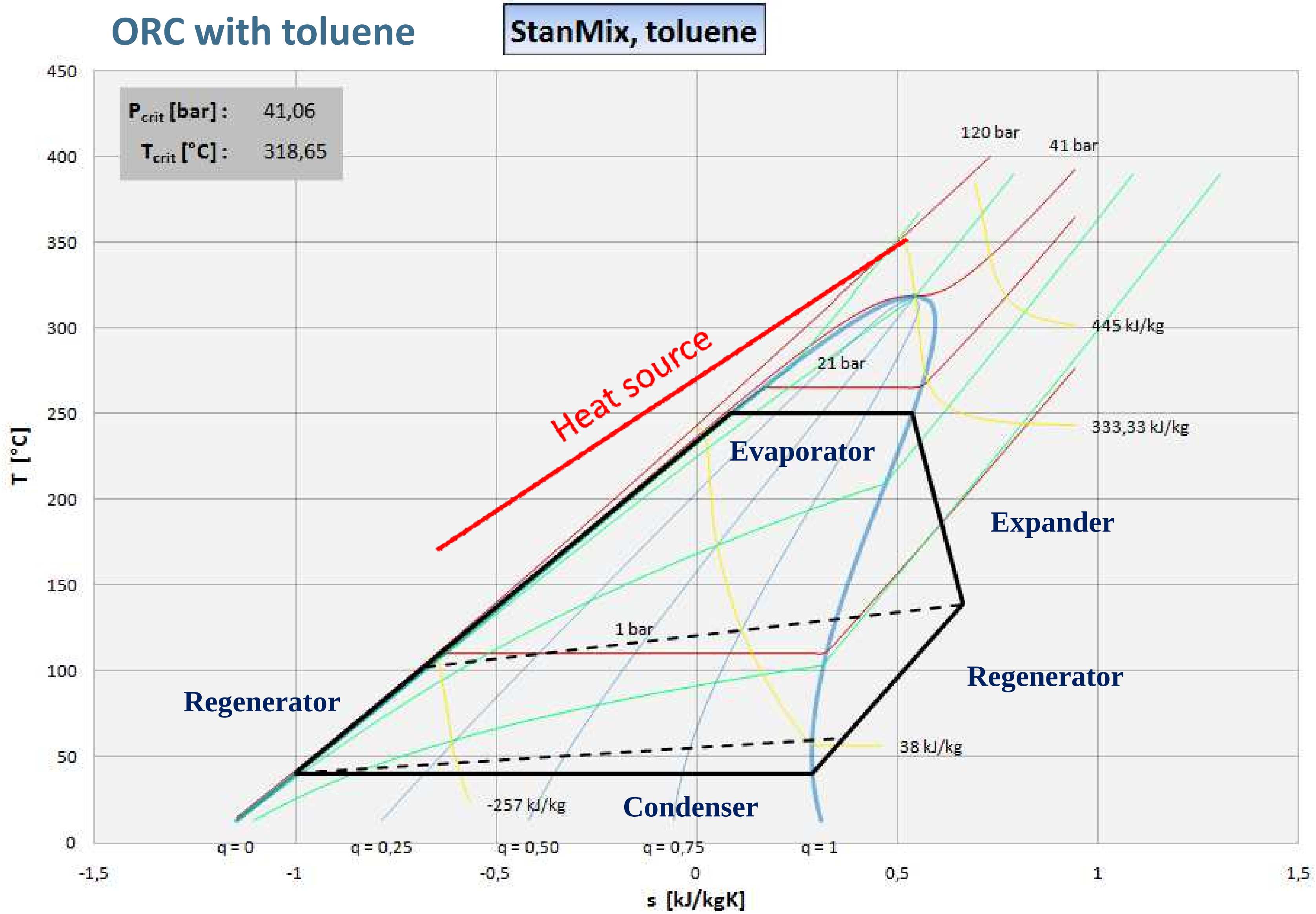
Simulation ORC

Toluene without regenerator



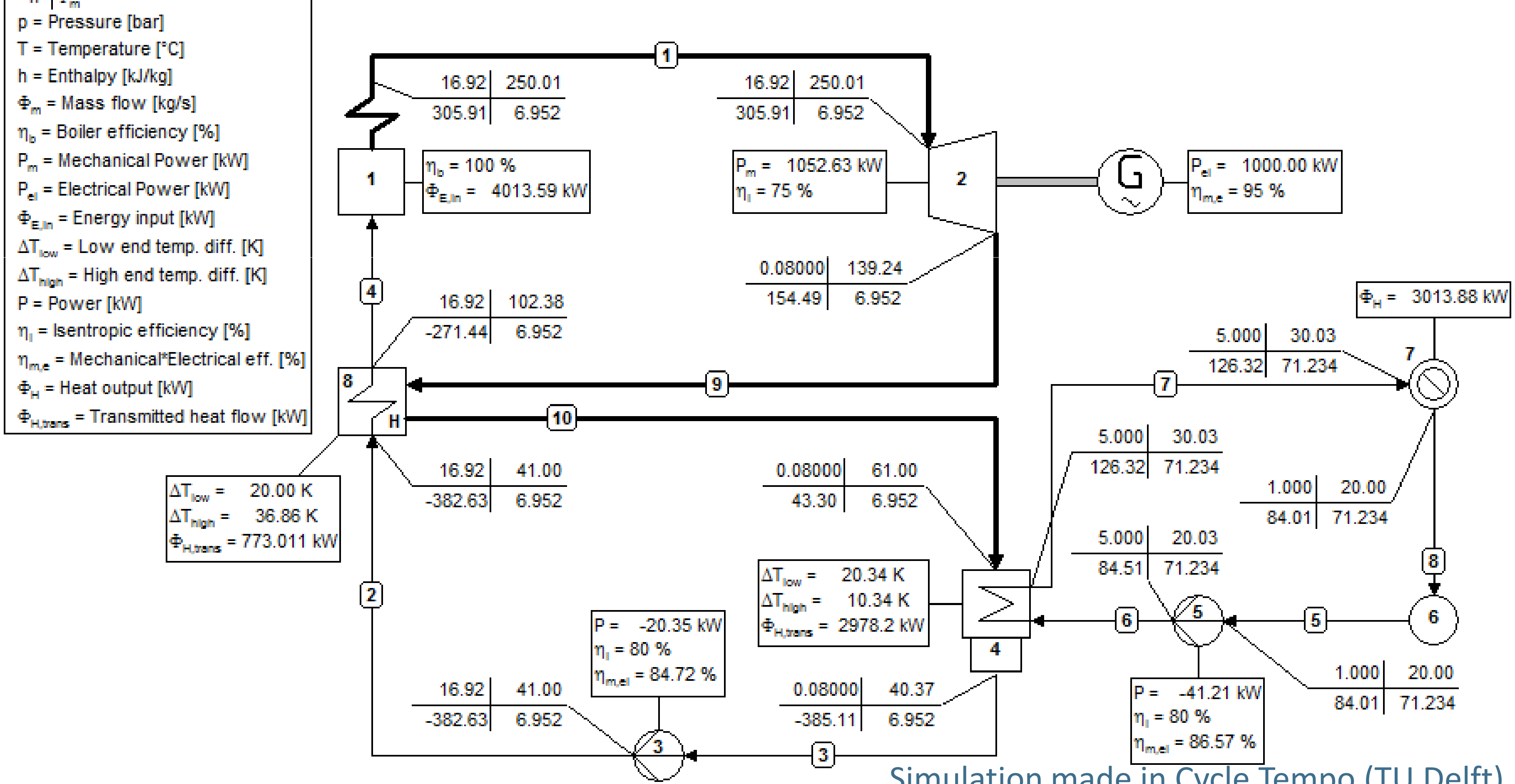
Simulation made in Cycle Tempo (TU Delft)

ORC with toluene

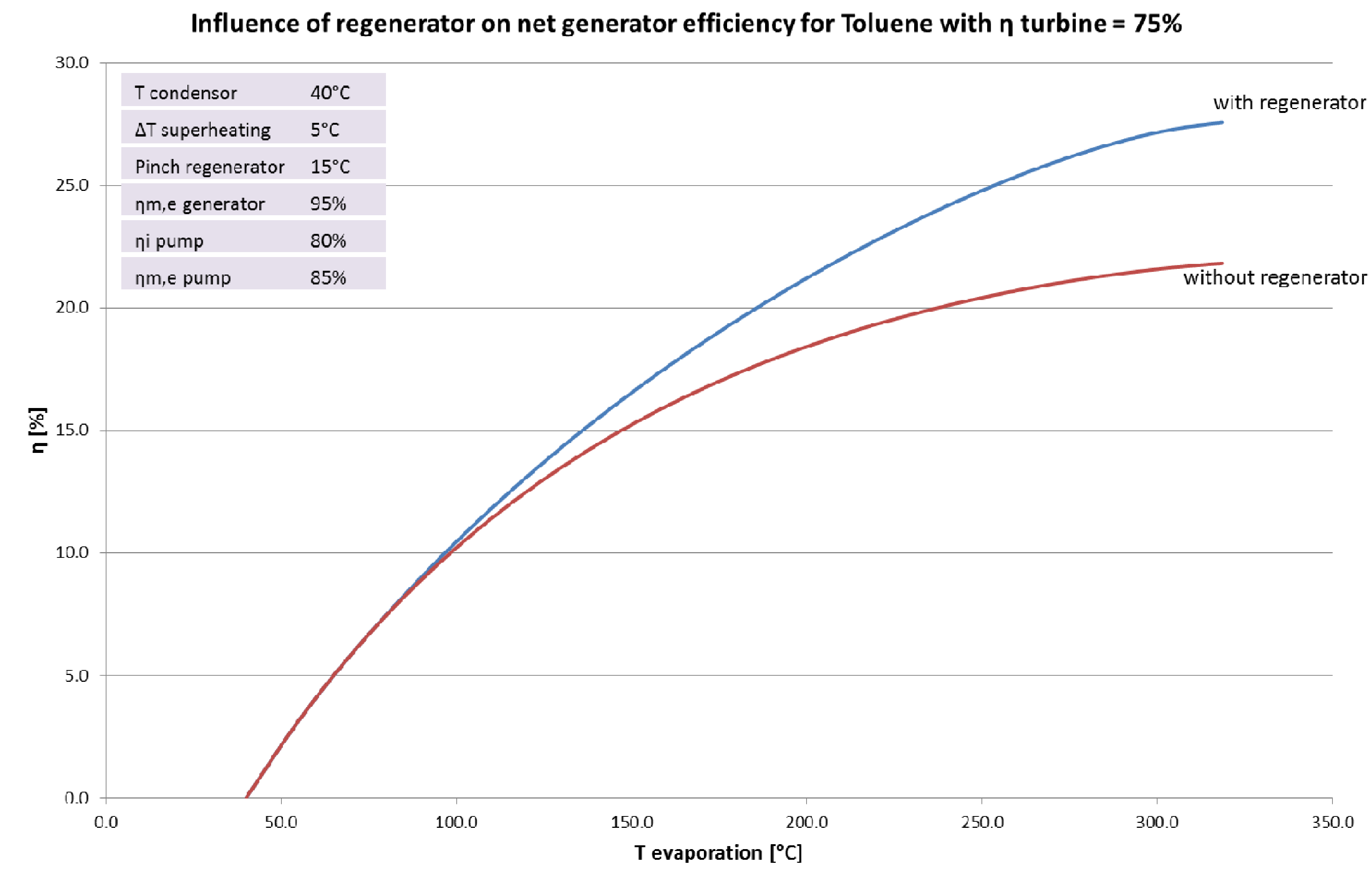


ORC with regenerator: Sensible heat after expander is used to preheat ORC liquid fluid in regenerator

Toluene with regenerator



Simulation made in Cycle Tempo (TU Delft)


Influence of regenerator on net generator efficiency for Toluene with η turbine = 75%
T condensor 40°C
ΔT superheating 5°C
Pinch regenerator 15°C
ηm,e generator 95%
ηi pump 80%
ηm,e pump 85%
with regenerator
without regenerator
η [%]
T evaporation [°C]
30.0
25.0
20.0
15.0
10.0
5.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0

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Comparison application area ORC fluids and water/steam

Simulation assumptions in stationary conditions :

Table 2 : ORC and steam cycle data

Cycle data		
Isentropic efficiency turbine	[%]	75
Pump efficiency	[%]	80
T_{cond}	[°C]	40
q steam outlet turbine	[%]	90
Inlet turbine ORC		Saturated
Inlet turbine steam		Superheated
T_{in} turbine	[°C]	60-500

- no pressure drops or energy losses taken into account
- compare theoretical gross cycle efficiency P_{mech} at turbine shaft
- efficiency gear box, generator not taken into account

Assumptions and remarks:

Comparison application area ORC fluids and water/steam

- Compare gross cycle efficiency of ORC with regenerator vs. simplified steam cycle (results presented on next graph)
- same T inlet turbine for steam cycle as for ORC cycle
- No restrictions on temperature level and thermal power of the heat source

Remarks :

- in reality cycle efficiency will be lower due to pressure drops and energy losses
- Isentropic efficiency depends on used expander type, all simulations are made for η isentropic of 75%
  - Dedicated designed ORC turbines : η isentropic >85%
  - Impuls turbine saturated steam : η isentropic <60%

Benchmark ORC vs Steam

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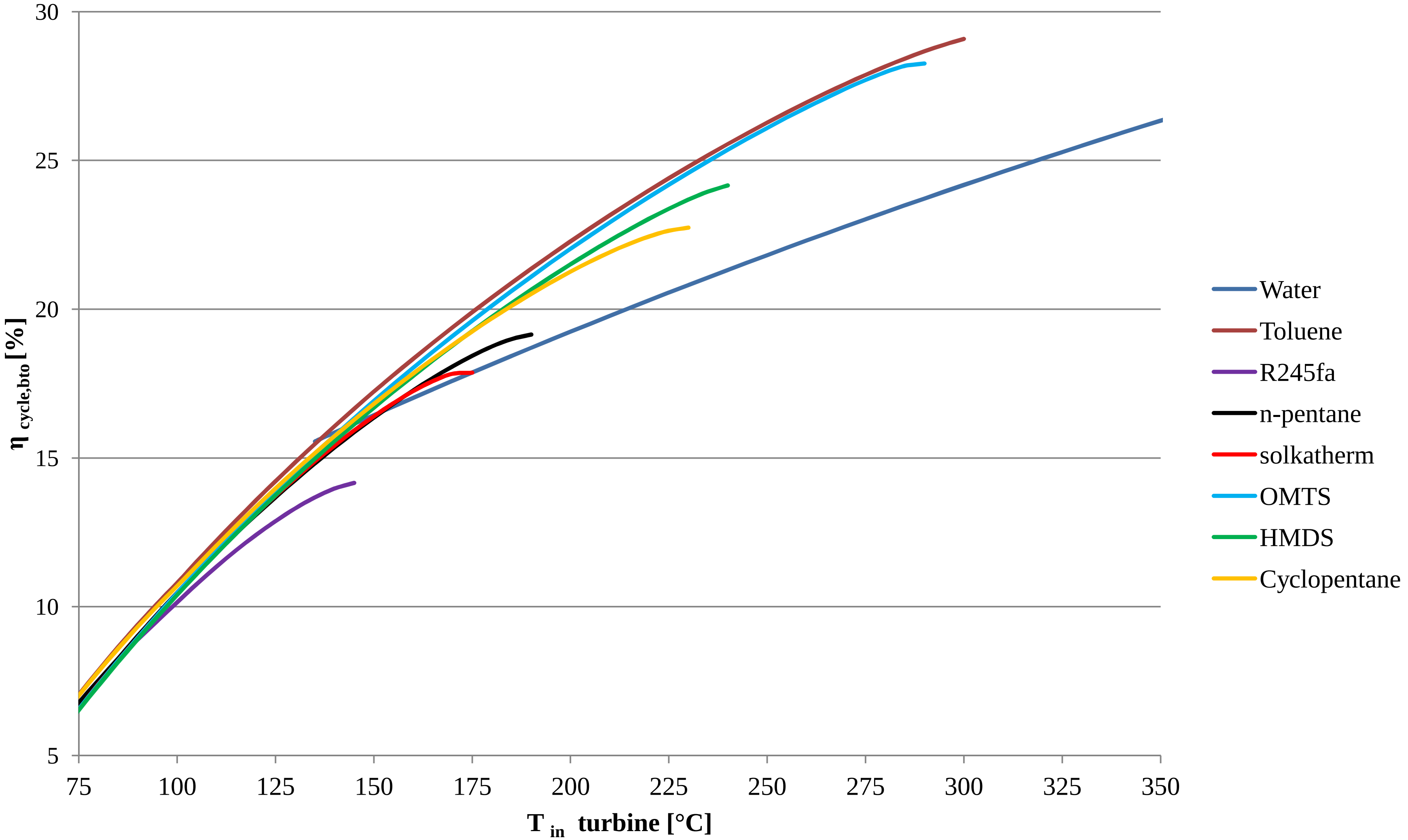
Gross cycle efficiency ORC with regenerator vs simplified steam cycle



Conclusions ORC fluids:

- ORC fluids : higher efficiency achievable than simplified steam cycle (considering the assumptions and restrictions made)
- Temperature range ORC fluids limited < 300°C (without superheating)
- Efficiency ORC at 300°C comparable to simplified Steam cycle at 400°C, so ORC can be applied on waste heat sources at lower temperatures
- Heat source with T >400°C : steam cycle has higher performance
- Highest cycle efficiency achievable using ORC with toluene (theoretically)

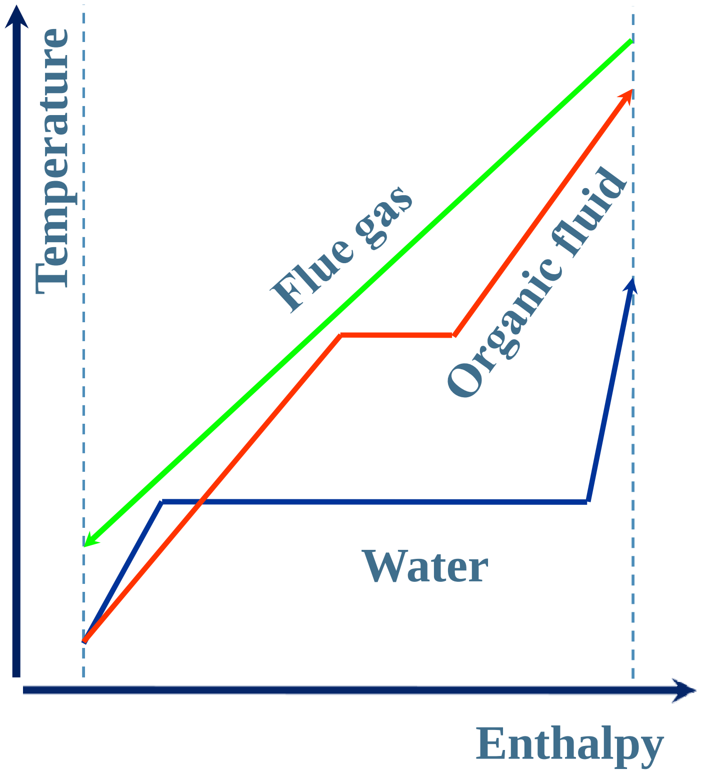
Influence temperature profile of a (waste) heat source

Temperature profile represents the thermal power available according to the temperature level

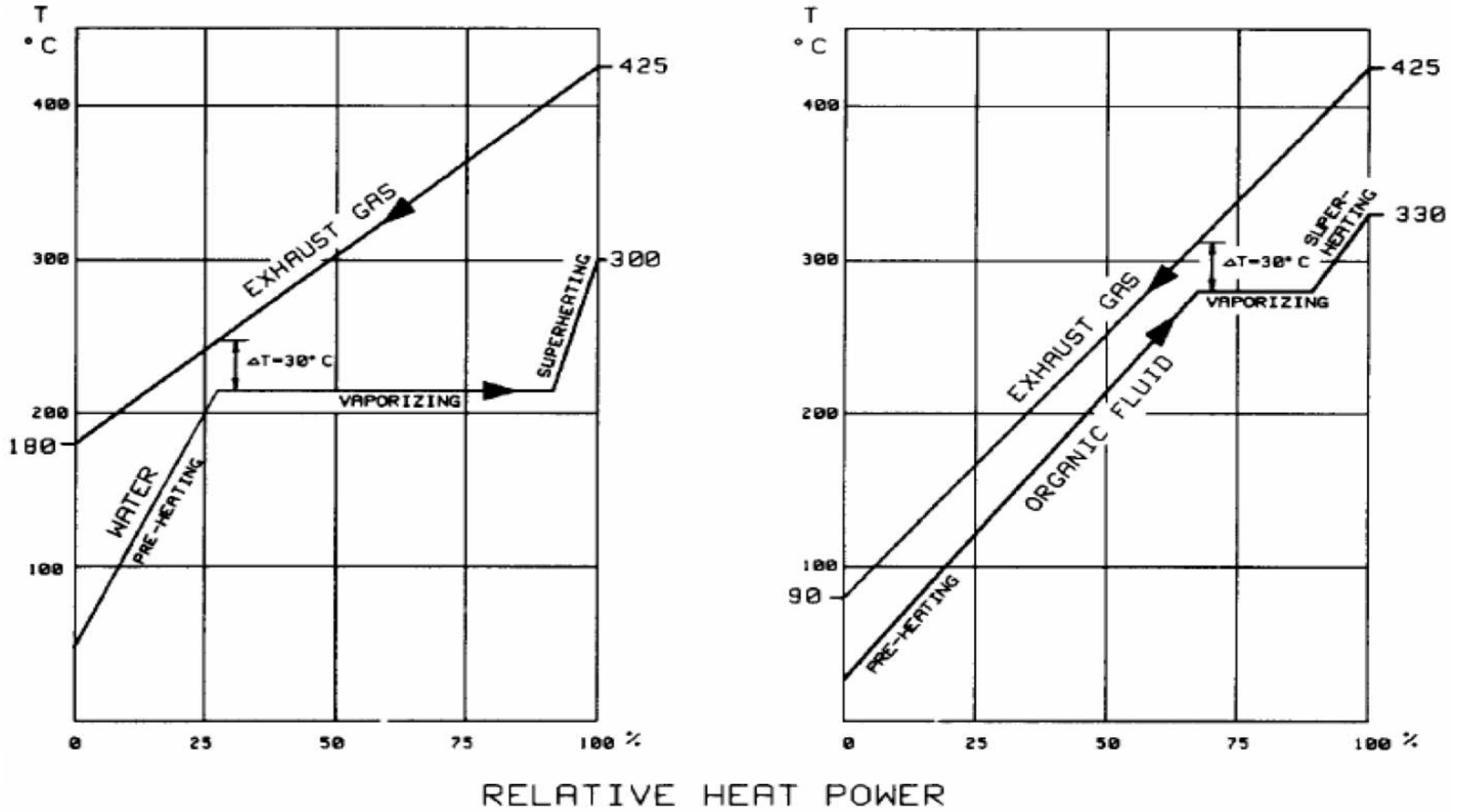
Calculation tool: optimal ORC and steam cycle

- Optimal power generated by generator
- Optimal evaporation pressure
- Influence considered parameters on efficiency
  - T_{in} heat source
  - T_{out} heat source
  - P_{th} heat source
  - ORC medium
  - T condensor
  - T evaporator
  - ΔT superheating
  - η_i turbine, pump
  - $\eta_{m,e}$ pump, generator
  - Steam quality
  - With / without regenerator

ORC: Organic Fluid vs Water



Optimal use of a heat source

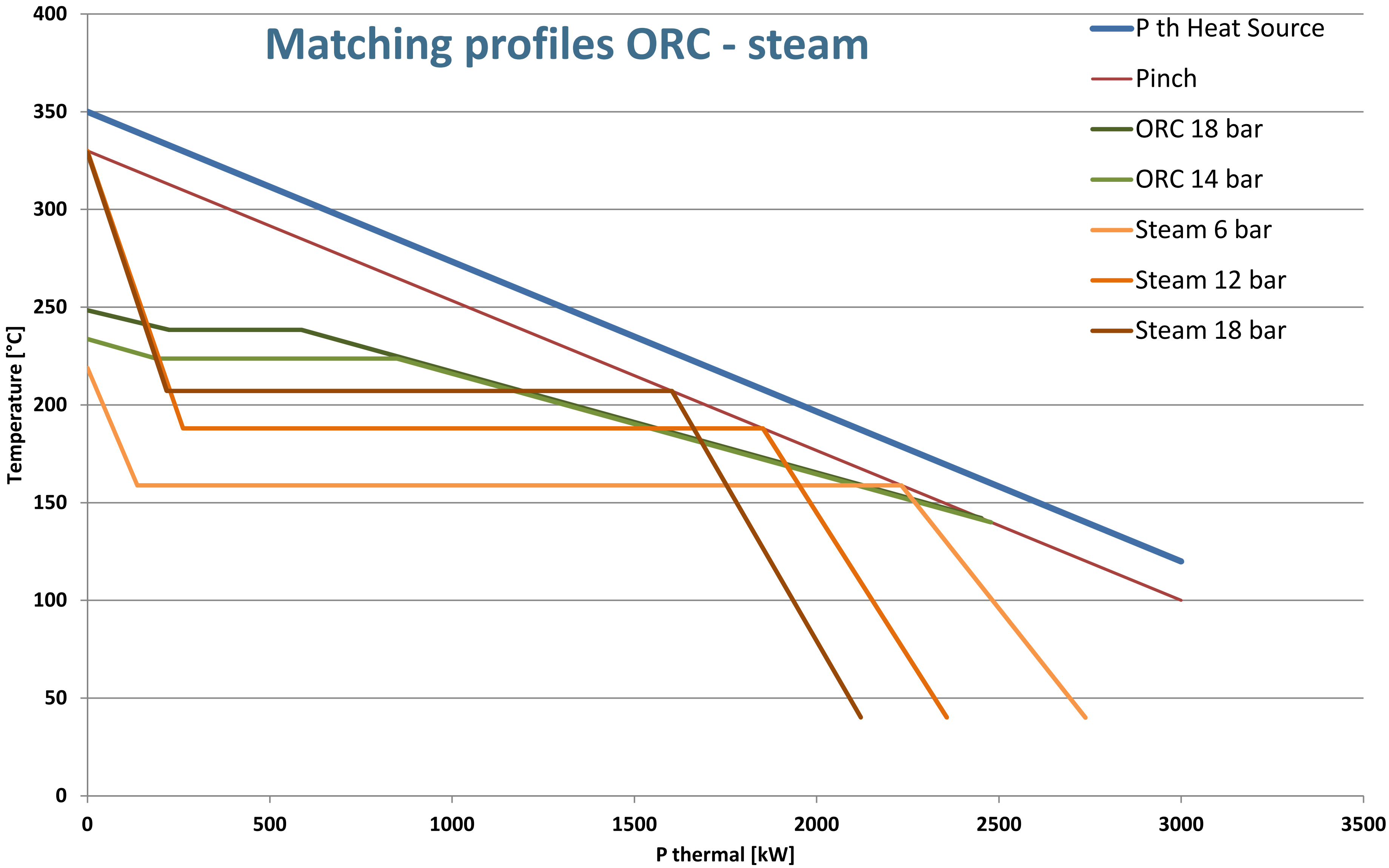


Comparison of temperature profiles and pinch points for a gas turbine exhaust and water (left) versus R114 (right) as working fluids

Simulation data for example temperature profile :

Table 3 : Data case study temperature profile heat source

Parameter data			
Waste Heat source :		Components	
T profile	350 – 120 °C	η_i pump	80%
P_{th}	3000 kW_{th}	$\eta_{m,e}$ pump	90%
Pinch	20°C	$\eta_{m,e}$ generator	90%
ORC-cycle		Simplified steam cycle	
medium	HMDS	T_{cond}	40°C
ΔT_{sup}	10°C	η_i turbine	70 – 80%
T_{cond}	40°C	q	93%
η_i turbine	70 – 80%	ΔT_{sup}	$=f(p_{evap}, T_{cond}, q, \eta_i$ turbine)


Matching profiles ORC - steam
P th Heat Source
Pinch
ORC 18 bar
ORC 14 bar
Steam 6 bar
Steam 12 bar
Steam 18 bar
Temperature [°C]
400
350
300
250
200
150
100
50
0
0
500
1000
1500
2000
2500
3000
3500
P thermal [kW]

Optimal use of a heat source

Table 4 : Results case study temperature profile heat source

		ORC with regenerator			
p_{evap}	[bar]	17.6		14	
η_i turbine	[%]	70	80	70	80
T_{sup}	[°C]	248	248	234	234
$P_{th,reco}$	[kW_{th}]	2388	2452	2479	2540
$P_{gen,bto}$	[kW_e]	509	578	506	574
$\eta_{cycle,bto}$	[%]	21.3	23.6	20.4	22.6
$P_{gen,nto}$	[kW_e]	487	556	488	556
$\eta_{cycle,nto}$	[%]	20.4	22.7	19.7	21.9
Case		1	2	3	4

Table summarizes results for ORC with HMDS for different parameters
Realistic expected ORC power (η_i turbine = 80%) : **>500 kW_e**
(Example : Turboden HR 6 : 2850 kW_{th} – 545 kW_e)

Table 4 : Results case study temperature profile heat source

		Simplified steam cycle					
p_{evap}	[bar]	6		12		18	
η_i turbine	[%]	70	80	70	80	70	74
T_{sup}	[°C]	219	267	272	330	305	329
$P_{th,reco}$	[kW_{th}]	2737	2715	2386	2357	2134	2121
$P_{gen,bto}$	[kW_e]	440	509	442	509	426	450
$\eta_{cycle,bto}$	[%]	16.1	18.7	18.5	21.6	19.9	21.2
$P_{gen,nto}$	[kW_e]	439	508	441	508	424	449
$\eta_{cycle,nto}$	[%]	16.0	18.7	18.5	21.5	19.9	21.2
Case		5	6	7	8	9	10

Table summarizes results for steam cycle with different parameters
Realistic expected power simplified steam cylce : **~440 kW_e** (~ -10 à -15% ORC) (η_i turbine = 70%)

Some conclusions for case study on temperature profile heat source :

- ORC can be operated even a with low evaporation pressure on low grade heat sources, and still achieve an acceptable cycle efficiency compared to a (simplified) steam cycle
- ORC’s require higher mass flows, and therefore bigger feed pumps which have a negative impact on net electric power
- The heating curves of ORC’s can be better matched to the temperature profile of a low grade heat source, resulting in a higher cycle efficiency and in a higher recovery ratio for the thermal power.

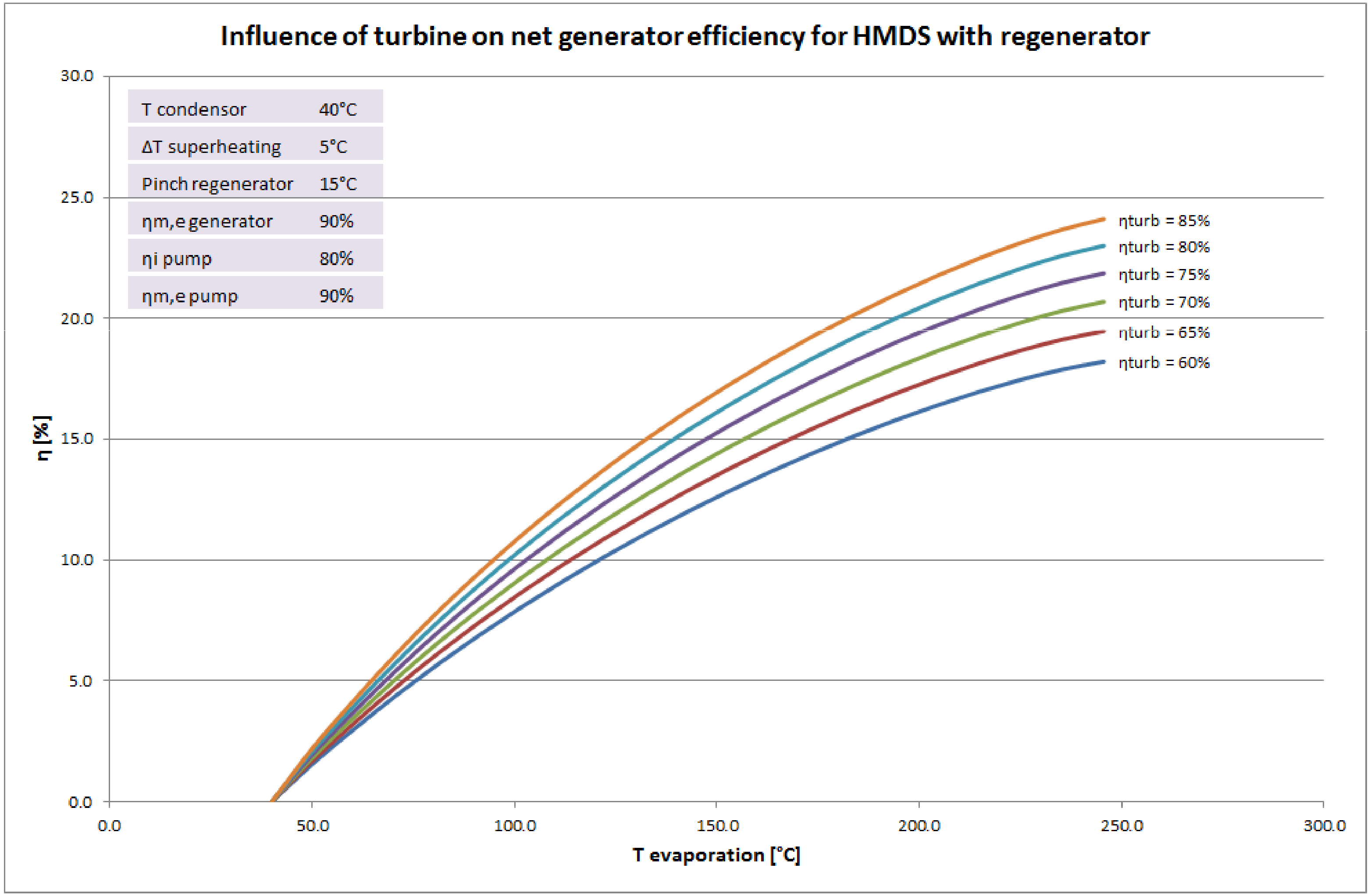
Tools :

- Calculation tool for cycle efficiency and generated power for ORC
- Calculation tool for cycle efficiency and generated power for steam cycle
- Calculation tool for optimal net generated power for any given temperature profile of a waste heat source

Tools output :

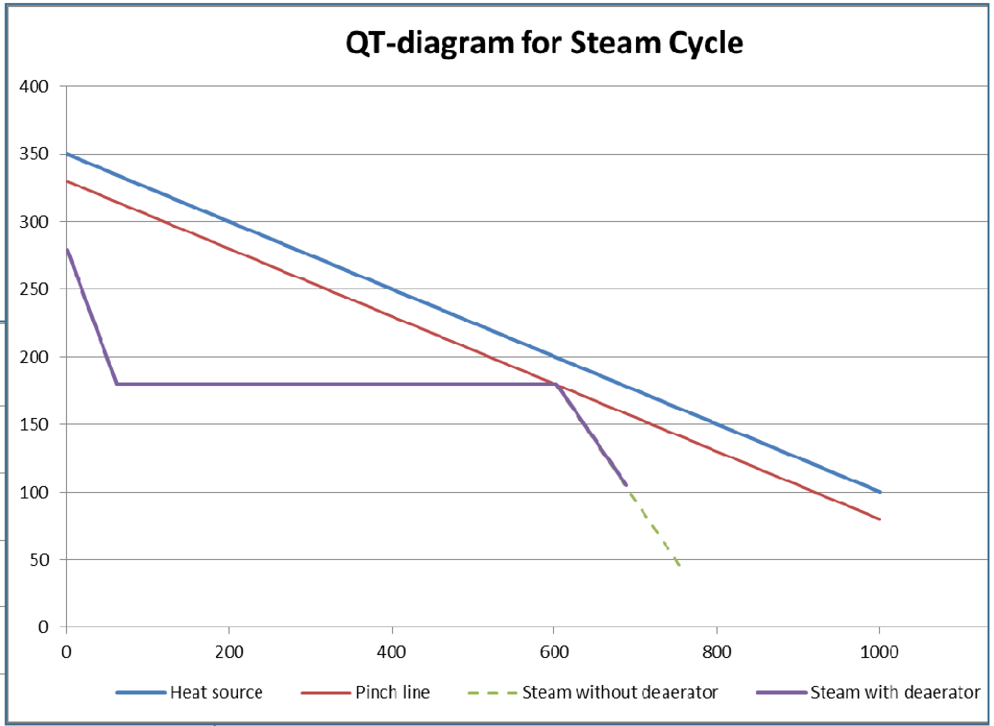
- Charts with influence of all parameters on cycle efficiency and generated power
- Optimal heating profile for ORC and steam cycle matching any heat source (optimal T evaporator, p evaporator, T superheating)
- Automatic generation of QT-diagram
- Automatic representation of ORC and steam cycle on Ts-diagram

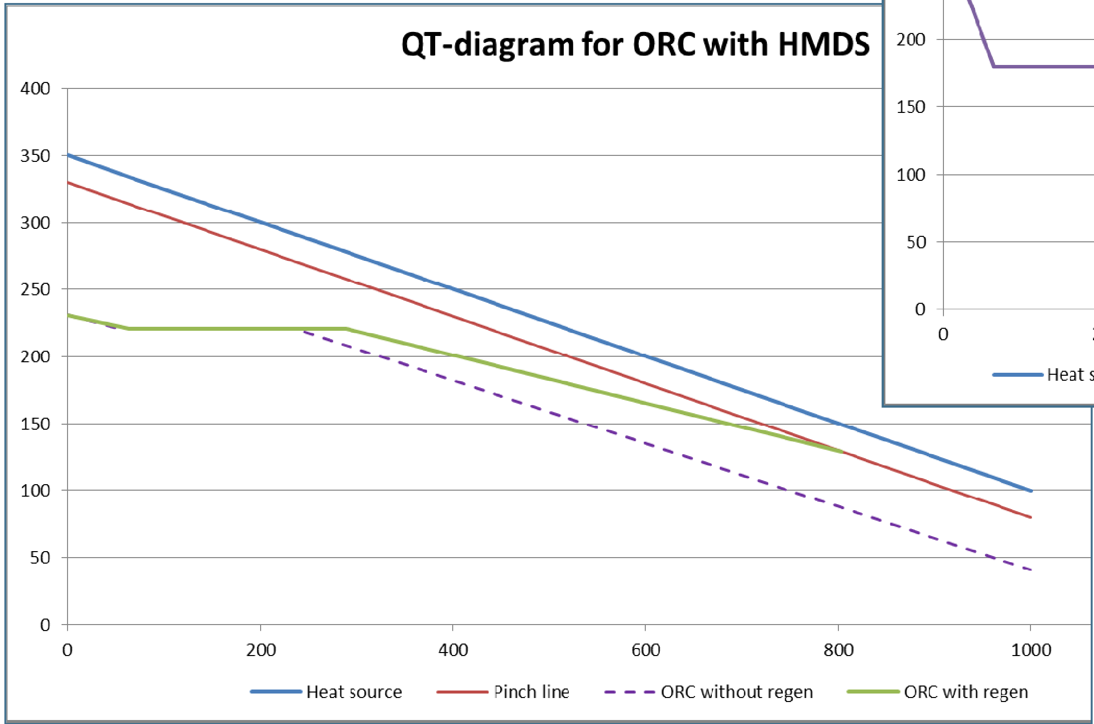
- **Influence charts for all parameters on cycle efficiency and generated power**



Calculation Tool

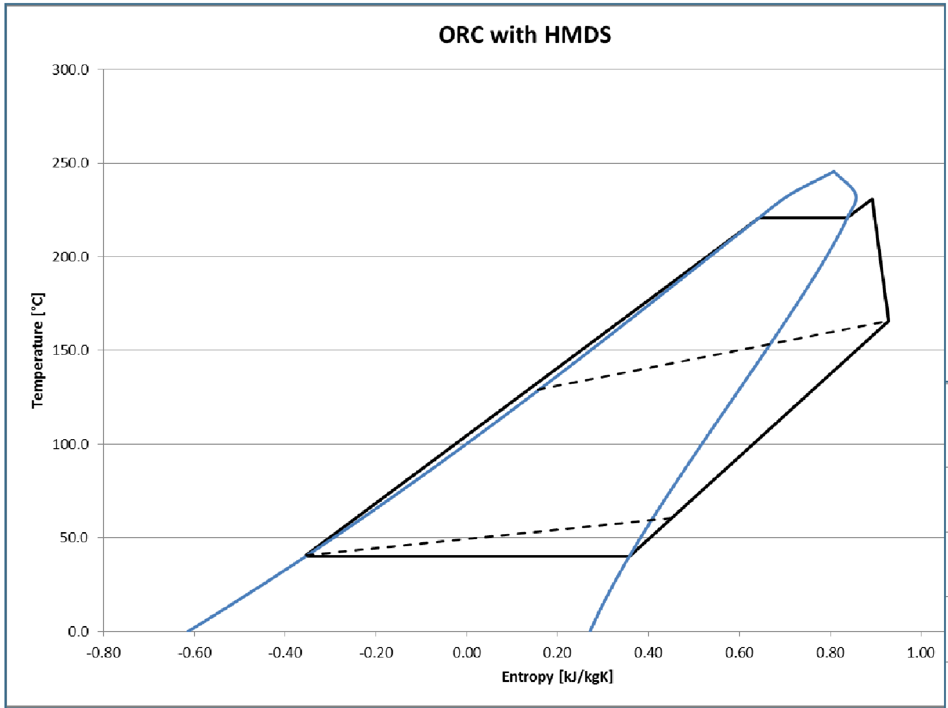
- Optimal heating profile for ORC and steam cycle matching any heat source (optimal T evaporator, p evaporator, T superheating)
- Automatic generation of QT-diagram

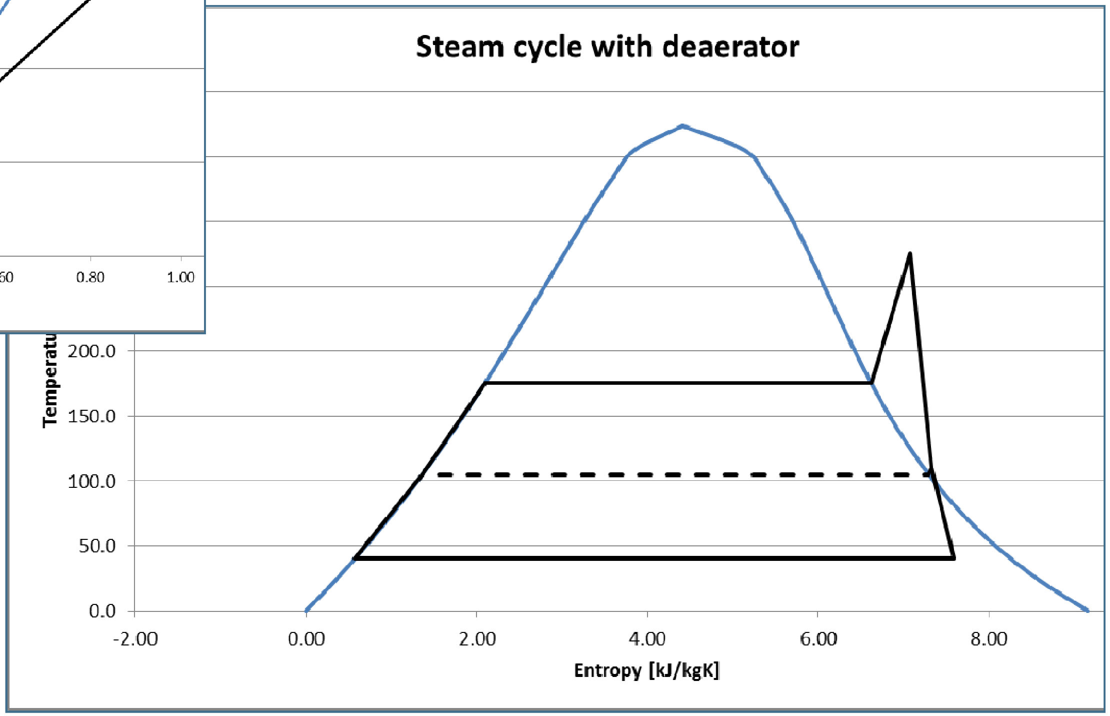




Calculation Tool

- **Automatic presentation of ORC and steam cycle on Ts-diagram**





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Conclusions

ORC

Pro:

- low t° heat sources usable
- lower pressure in the system
- less complex installation
- no superheater needed
- easy to operate (“one button” start)
- small scale (from 0,3 kWe) available
- better part load efficiency

Contra:

- often thermal oil intermediate
- working fluid probably toxic, flammable

Steam cycle

Pro:

- “standard” technology
- more flexibility in power/heat ratio
- water/steam as working fluid
- direct evaporation in HR exchanger

Contra:

- needs higher t° sources (from ca 150°C)
- more complex installation (water treatment, deaerator…)
- higher system pressure
- only “higher” power range (from ca 300 kWe)

Thanks to all of you for your attention

Time for questions…discussion ?

ing. Bruno Vanslambrouck

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