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THERMODYNAMIK
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# Comparison of Conventional and $CO_2$ Power Generation Cycles for Waste Heat Recovery

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# Overview

- Waste Heat Recovery
- cement plant Hatschek
- Steam Rankine Cycle
- Organic Rankine Cycle
- $sCO_2$ - advantages
- $sCO_2$ - Brayton Cycle ($sCO_2$-BC)
- $tCO_2$ - Brayton Cycle ($tCO_2$-BC)
- $tCO_2$ – Rankine Cycle ($tCO_2$-RC)
- Cycle Comparison
- Conclusions

# Waste Heat Recovery

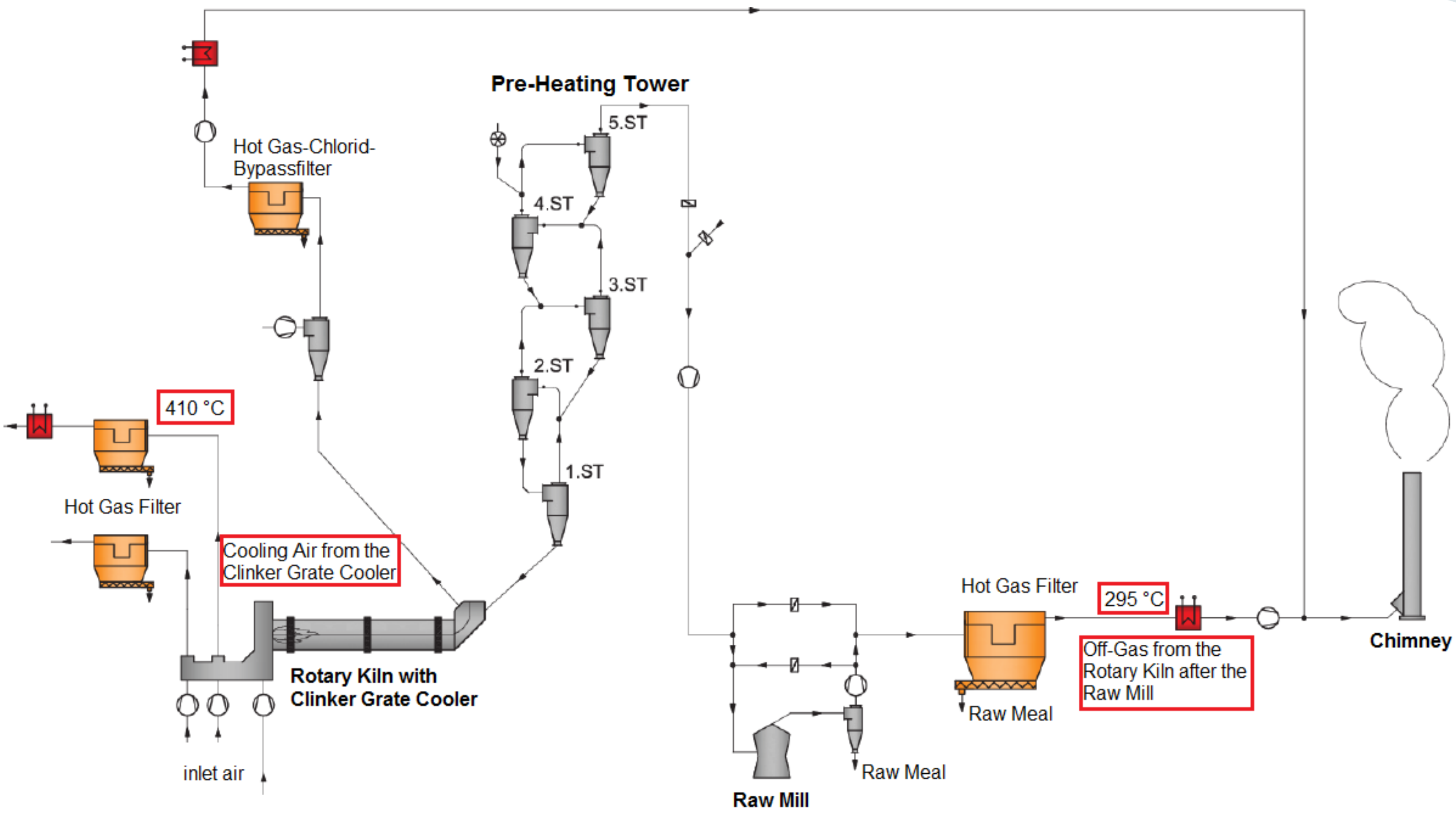
- waste heat recovery from industrial processes is of rising interest
  ➔ in terms of the Energy Efficiency Directive of the EU
  and Climate Change

- the efficiency of using waste heat is highly influenced by the used working fluid (e.g. water, organic substances, $CO_2$ ,...) and certain components of the cycle (compressor, pump, turbine,...)

- 5 different cycles investigated: Steam Rankine Cycle (SRC), Organic Rankine Cycle (ORC), supercritical $CO_2$-Brayton Cycle ($sCO_2$-BC), transcritical $CO_2$-Brayton Cycle ($tCO_2$-BC) and transcritical $CO_2$-Rankine Cycle ($tCO_2$-RC)

- waste heat source is the cement plant Hatschek in Gmunden (Austria)

# The cement plant Hatschek



2 major heat sources are available:

- the off-gas from the rotary kiln after the raw mill (295 °C, 78 kg/s)
- the cooling air from the grate cooler at the exit of the rotary kiln (410 °C, 14 kg/s)
- the hot gas from the chlorine bypass is not included (low mass flow)

# Steam Rankine Cycle

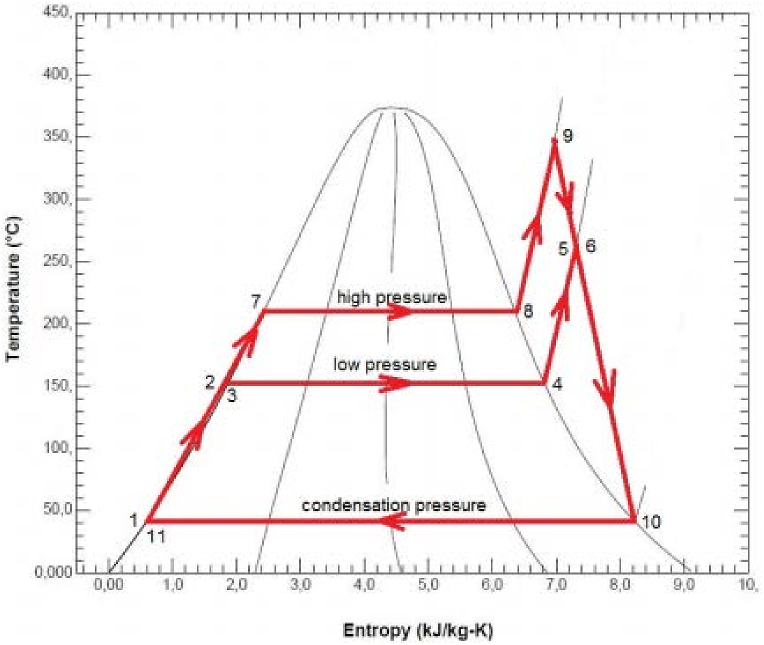
- \+ Frequently used and well developed system
- \+ Fluid characteristics
- \+ Pump consumption

- − Not suited for low temperature applications
- − Size of steam turbines
- − Water treatment system

**Two-pressure system**

- further cooling of the exhaust gas
- reduction of exergy losses

| Operating parameters | |
|---|---|
| High pressure level | 20 bara |
| Low pressure level | 6.5 bara |
| Max. steam temperature | 395°C |
| Min. allowed ΔT in HEX | 15°C |
| Turbine isentropic efficiency | 75% |



| Results | |
|---|---|
| Power output | 3297kW |
| Thermal efficiency | 22.39% |

# Organic Rankine Cycle

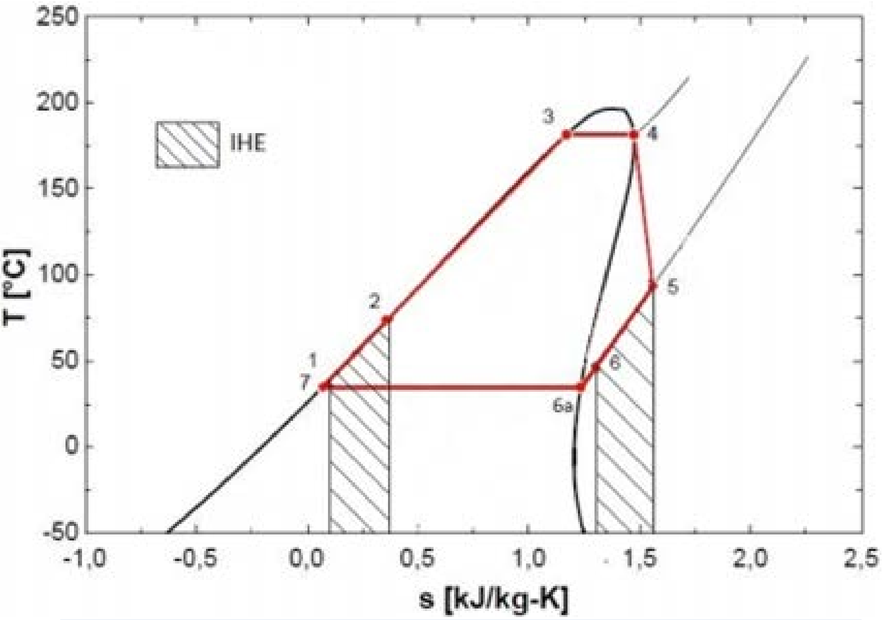
- + Suited for low temperature applications
- + Position of the critical point
- + No superheating

- − Expensive working fluids
- − Flammable
- − Global warming potential

### Fluid selection

- Critical temperature appropriate to the heat source
- High heat transfer capacity
- Best fit: Cyclopentane ($\theta_{crit}$=238.27°C)

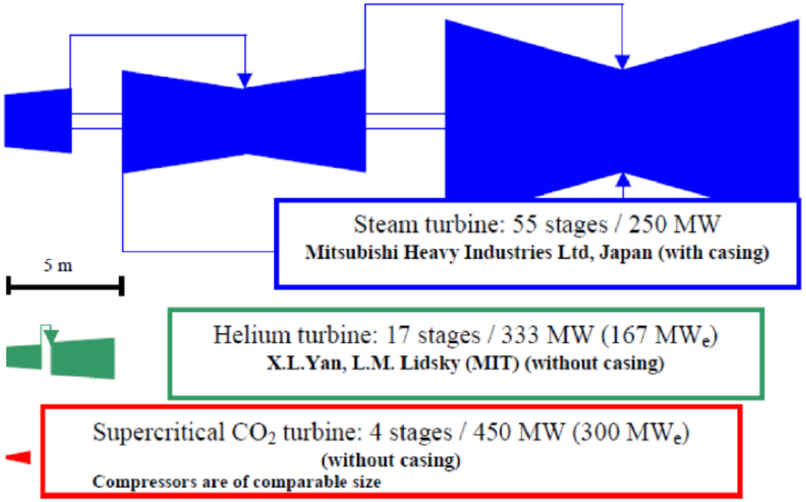
| Operating parameters | |
|---|---|
| Operating pressure | 34.6bara |
| Condensation pressure | 0.6 bara |
| Max. operating temperature | 217°C |
| Cooling water temperature | 15°C |
| Turbine isentropic efficiency | 75% |



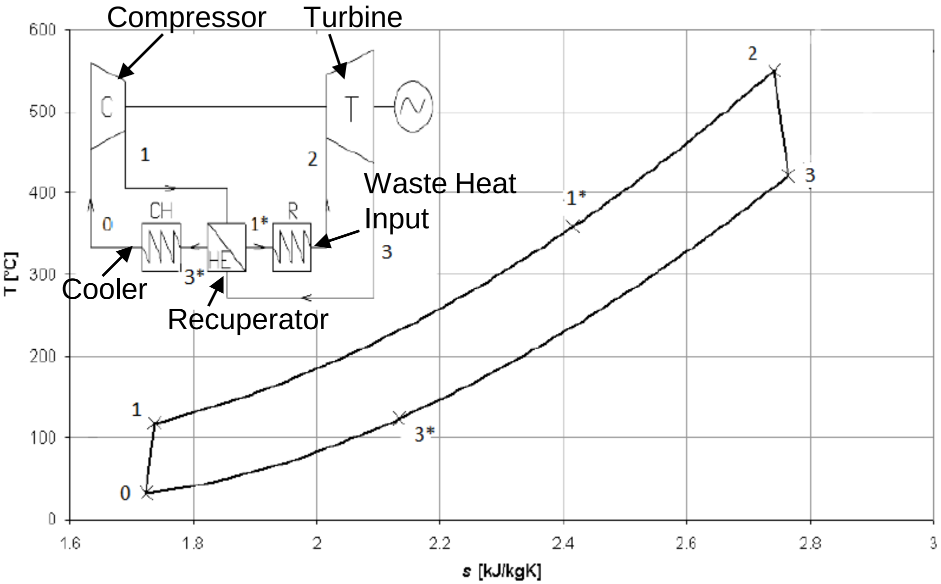
| Results | |
|---|---|
| Net power output | 3915kW |
| Thermal efficiency | 19.56% |

# $sCO_2$ - advantages

- $sCO_2$ cycles achieve high efficiencies at low temperatures
- the high operating pressure enables smaller size components
- well known thermodynamic properties
- stability, non-toxicity, non-flammable
- low critical temperature (31°C)
- high power density
- low surface tension (reduced effects of cavitation in the machinery)
- abundantly available
- low cost
- easy handling
- plant personnel accustomed to $CO_2$



# $sCO_2$-Brayton - Cycle ($sCO_2$-BC)



<u>Concept of a simple Brayton Cycle:</u>

- 0-1: compression of the fluid
- 1-1*: heating up in the recuperator
- 1*-2: heating up with the waste heat
- 2-3: expansion in the turbine section
- 3-3*: cooling in the recuperator
- 3*-0: cooling with water

**Operating parameters**

| | |
|---|---|
| High pressure level | 221.4 bara |
| Low pressure level | 73.8 bara |
| Lowest cycle temperature | 34 °C |
| Turbine inlet temperature | 302 °C |
| Cooling water temperature | 12 °C |
| Turbine isentropic efficiency | 91 % |
| Compressor isentropic efficiency | 89 % |

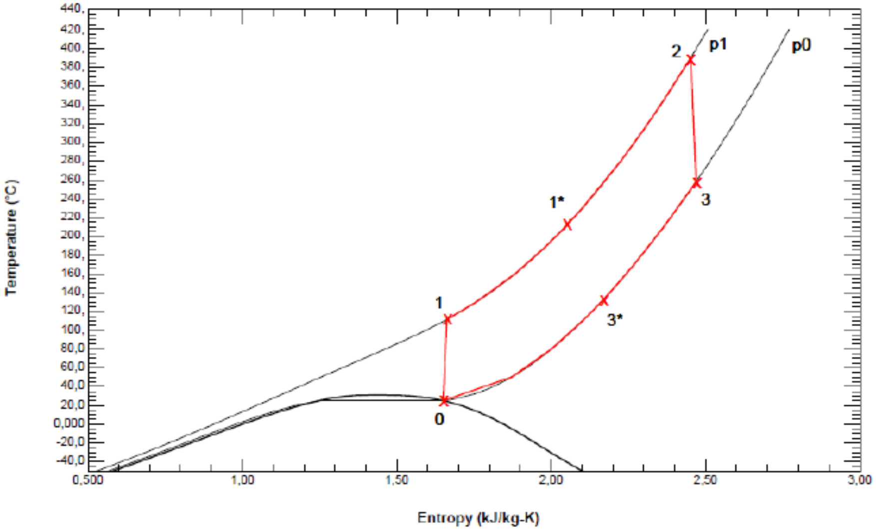
**Results**

| | |
|---|---|
| Net power output | 4007 kW |
| Thermal efficiency | 20.8 % |

# $tCO_2$-Brayton - Cycle ($tCO_2$-BC)

- ➢ very similar to the $sCO_2$-BC, but conditions at the entry to the compressor below the critical point conditions ➔ $CO_2$ still in gaseous state on the saturated vapor line

- ➢ less power consumption for compression because of lower pressure ➔ smaller compressibility factor



| Results | |
|---|---|
| Net power output | 4295 kW |
| Thermal efficiency | 22.3 % |

| Operating parameters | |
|---|---|
| High pressure level | 221.4 bara |
| Low pressure level | 64.34 bara |
| Lowest cycle temperature | 25 °C |
| Turbine inlet temperature | 302 °C |
| Cooling Water temperature | 12 °C |
| Turbine isentropic efficiency | 91 % |
| Compressor isentropic efficiency | 89 % |

# tCO2-Rankine - Cycle (tCO2-RC)

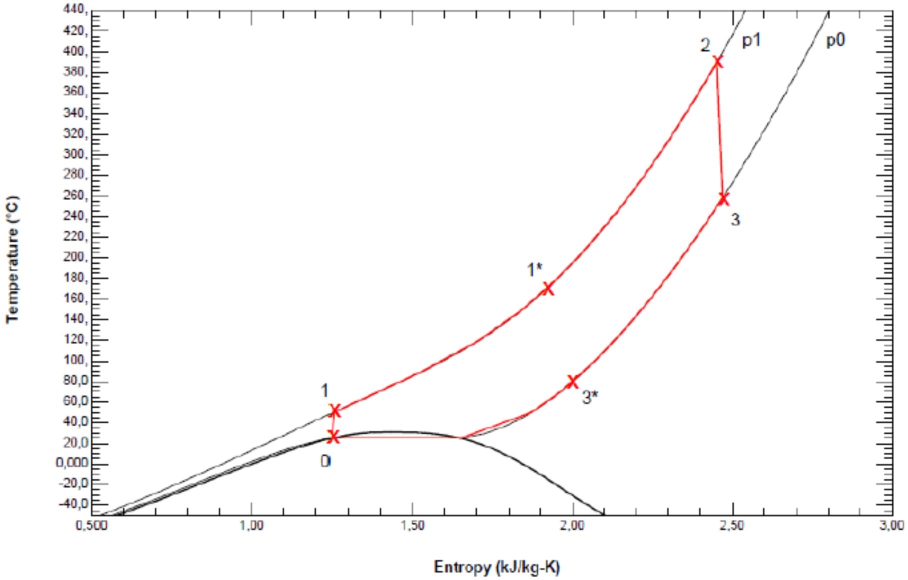
- is like the SRC a condensation process ➔ two phase region is passed, $CO_2$ completely liquified

- a pump is used (instead of a compressor)

- the entry in the pump is on the saturated liquid line, below critical point

- notable less energy for compression ➔ $CO_2$ in the liquid state (high density)

- possible problems with the cooling, depending on ambient conditions (e.g. water sources) ➔ high water mass flow is needed (420 kg/s)



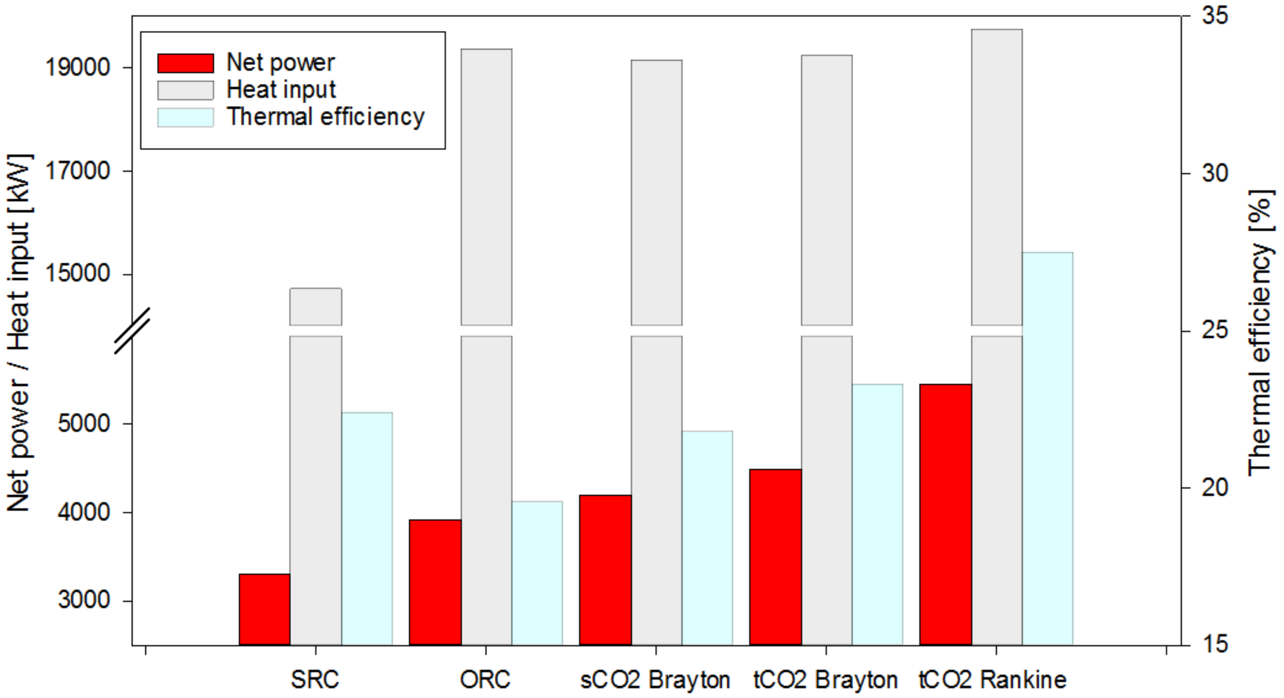
**Results**

| | |
|---|---|
| Net power output | 5192 kW |
| Thermal efficiency | 26.3 % |

**Operating parameters**

| | |
|---|---|
| High pressure level | 221.4 bara |
| Low pressure level | 64.34 bara |
| Lowest cycle temperature | 25 °C |
| Turbine inlet temperature | 302 °C |
| Cooling Water temperature | 12 °C |
| Turbine isentropic efficiency | 91 % |
| Compressor isentropic efficiency | 89 % |

# Cycle Comparison

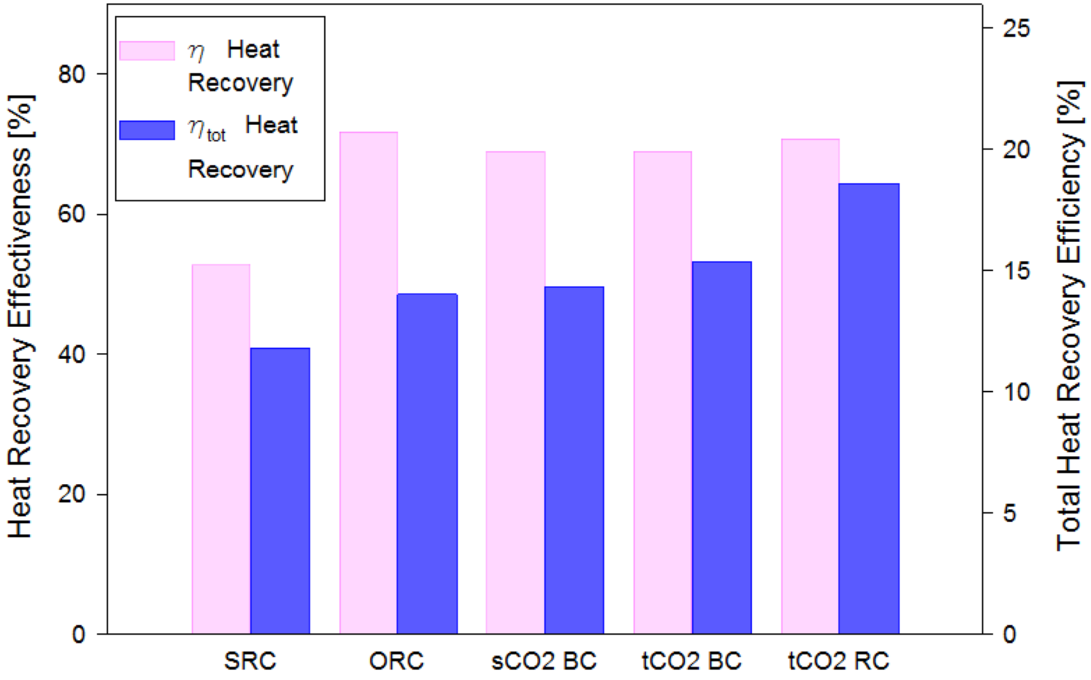


➢tCO$_2$-RC supplies the highest electrical power ➔ low specific work rate of the pump but potential cooling problems (tCO$_2$-RC 420 kg/s, tCO$_2$-BC 130 kg/s, sCO$_2$-BC 70 kg/s)

➢SRC has significantly less heat input (about 5000 kW) ➔ thermo-physical properties of water not sufficient for using low temperature waste heat

➢tCO$_2$-RC has best thermal efficiency, SRC better therm. eff. than ORC and sCO$_2$-BC ➔ less power output, but also less heat input

# Waste Heat Recovery - Analysis



- ➢Heat recovery effectiveness: ratio between heat input and available heat
  Total heat recovery efficiency: ratio between net power output and available heat

- ➢Heat recovery effectiveness of the SRC significantly lower than all other investigated cycles due to decreased heat input

- ➢$tCO_2$-RC yields the highest total heat recovery efficiency since it amounts to the highest produced net power at about equal heat input

# Conclusions

- potential waste heat recovery systems for a cement plant were analyzed
- different power cycles were simulated, aim was the comparison between currently used cycles and new supercritical $CO_2$ concepts
- transcritical $CO_2$ Rankine cycle delivers best results, but possible problems with cooling
- all $CO_2$ cycles perform better than the currently used power cycles for waste heat recovery (SRC, ORC)
- ORC approaches the results of the $CO_2$ cycles, but organic working fluids have several disadvantages (flammable, expensive, harmful to the climate,…)
- supercritical/transcritical power cycle technology should be further developed – they could be an economic alternative in waste heat recovery

Thank you very much for your attention !