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Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C

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Cascade multi-stage steam compression, Decarbonization, High-temperature heat pump, Process heat, Reversed Brayton cycle, R718, R744.

Introduction

The ambitions to reduce greenhouse gas emissions do inevitably require sustainable alternatives to fossil fuel-based combustions for supply of process heat to industrial processes. Electricity-driven heat pumps imply the general potential to operate emission free and do thereby represent a sustainable long-term solution for emission free process heat supply.

Currently available heat pump technologies are however limited to supply temperatures of 100 °C to 150 °C, while electric boilers and biomass boilers are often mentioned as alternatives in energy transition strategies. The overall feasibility for heat pump systems in such applications is among others limited by technical component constraints as well as limited thermodynamic performances, resulting in limited operating performances.

Zühlsdorf et al. [1] have therefore analyzed the possibilities for heat pump-based process heat supply at large capacities and temperatures above 150 °C. They evaluated the technical and economic feasibility of two heat pump systems for two case studies. The main results from [1] are summarized by this extended abstract. The article focused on large-scale applications and considered components as known from oil- and gas applications, as these are capable of operating in more challenging conditions and enable exceeding the limitations known from available refrigeration equipment [2]. In addition, the focus was on applications, in which the plant owners have access to electricity at low costs or the possibility to invest in own renewable electricity generators, such as wind farms and photovoltaics, as these are ensuring low levelized cost of electricity [3].
Methods

The study considered two different heat pump systems, namely a cascade multi-stage steam compression system and a reversed Brayton cycle. The cascade multi-stage steam compression system is shown in Figure 1 and consists of bottom cycles that are recovering the heat from the heat sources while providing heat to the evaporator of the top cycle, in which the steam from the evaporator is compressed in several stages. The steam is cooled by liquid injection after each compression stage. The system can supply steam at every pressure level to the system, ensuring an optimal integration into the process and thereby maximum performances.

Figure 1: Flow sheet of a cascade heat pump with a multi-stage R-718 cycle for steam generation or closed loop heat supply at different temperature levels (B-HP = Bottom heat pump, IC = Intercooler, P = Pump, TC = Turbocompressor).

The less complex layout of the reversed Brayton cycle is shown in Figure 2. The cycle consists of three heat exchangers, as well as a turbocompressor and a turboexpander, which are mounted on the same shaft. The cycle uses CO₂ as working fluid and operates completely in the gas phase.

The cycles were modelled with energy and mass balances. Design variables, such as pinch points in the heat exchangers or pressure levels were defined or optimized under consideration of common limitations. The investment cost of the equipment was estimated with cost correlations and validated with estimations obtained from manufacturers.
Both cycles were evaluated for two case studies. The first case study was alumina production in which 50 MW were supplied to heat thermal oil from 140 °C to 280 °C, while heat was recovered between 110 °C and 60 °C. The second case study was a spray dryer for milk powder production in which an air stream was heated up from 64 °C to 210 °C with a capacity of 8.2 MW, while a heat source at 50 °C was recovered.

Both technologies were evaluated in both cases for a set of economic boundary conditions. Three economic scenarios were considered that corresponded to the fuel cost in Norway, Germany and Denmark in 2020 and one scenario was considered corresponding to the acquisition and operation of own renewables.

Results

The heat pump systems were designed and optimized for both case studies. Table 1 shows the COP and the total capital investment TCI for both cases and both technologies. It may be seen that the COP for the cascade system was estimated to be 1.9 in both cases, while it was 1.7 for the reversed Brayton cycle in the alumina production and 1.6 in the spray dryer case. The investment cost were relatively similar for the two technologies, while the economy of scale yielded considerably lower specific investment cost for the alumina production.

Table 1: COP and Total capital investment TCI for both cases and cycles [1]

|                      | Alumina production | Spray dryer |
|----------------------|--------------------|-------------|
|                      | Cascade multi-stage system | Reversed Brayton cycle | Cascade multi-stage system | Reversed Brayton cycle |
| Coefficient of performance COP, - | 1.92 | 1.72 | 1.92 | 1.61 |
| Total capital investment TCI, Mio. € | 47.3 | 48.3 | 16.4 | 15.4 |
| Specific total capital investment TCI(spec), €/kW | 946 | 966 | 1,997 | 1,868 |
Figure 3 shows the levelized cost of heat for both technologies and both case studies for all economic scenarios and compares them to the alternative heat supply technologies. The levelized cost of heat is divided into the contributions accounting for the investment, the fuel cost and an exemplifying CO\textsubscript{2} tax of 50 €/ton to indicate the impact of a potential tax. In the case of the alumina production, the levelized cost of heat reaches as low as 31 €/MWh to 33 €/MWh under consideration of own renewable electricity facilities, while it is between 44 €/MWh and 46 €/MWh for the spray dryer case. In the spray dryer case, the heat pump-based solutions are competitive with a biomass boiler and a natural gas boiler under consideration of the assumed CO\textsubscript{2} tax. In the alumina production case, the lowest levelized cost of heat are obtained for the heat pump systems.

![Figure 3: Specific levelized cost of heat for both case studies including the reversed Brayton cycle, the multi-stage steam compression cycle, an electrical boiler and combustion-based boiler using natural gas, biogas and biomass. The cost scenarios are as defined in [1] while the ranges for the cost for electricity from renewables, natural gas, biogas and biomass are indicated by the black bars [1]](image)

Conclusions

The study analyzed a reversed Brayton cycle and a cascade multi-stage steam compression for large-scale process heat supply at temperatures above 150 °C. It was pointed out that these temperatures might be reached by components from oil- and gas industries and that low electricity prices, as typically accessible for energy intensive industries or obtainable from acquiring and operating own renewable facilities, may improve the economic performance considerably. The levelized cost of heat for the heat pump-based systems were competitive to the biomass boilers and natural gas boilers for the spray dryer case study and outperformed both for the alumina production case study. This study has accordingly demonstrated, that heat pump systems are a viable alternative for process heat supply in industrial processes at temperatures of up to 280 °C.
1.2 Analysis of technologies and potentials for heat pump-based process heat supply above 150°C, Benjamin Zühlsdorf, DTI

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Motivation and Potential

Process heat demand in Denmark, 2012
- Oil
- Food
- Wood
- Chemical
- Building
- Metal

Energy demand for heating and cooling in industry in Europe
- Space heating 14%
- Process heating <100 °C 9%
- Process heating 100-200 °C 21%
- Process heating >200 °C 9%

Alternatives:
- Electrical heater
- Biomass/Biogas
- Natural gas (+ compensation of emissions)

Role of high-temperature heat pumps?

*Based on data from Bühler, F., Nguyen, T. V., & Elmegaard, B. (2016). Energy and exergy analyses of the Danish industry sector. Applied energy, 184, 1447-1459.*
Motivation and Potential

Challenges for HTHPs
- Limited performance (COP\textsubscript{Lor})
- High investment cost $\rightarrow$ Economic performance
- Component constraints

Motivation for electrification: Changing boundary conditions
- Decreasing LCOE from renewables
- Cost of emission increasing
- Limitations of biomass/biogas
- Political/industrial strategies to become carbon neutral

Possibilities
- Components from e.g., oil & gas industries operate in more challenging conditions (up to $>400 \, ^\circ \text{C}$)
- Combination of heat pumps and own renewable electricity utilities

Agenda
- Considered case studies
  - Alumina production case study
  - Spray dryer case study
- Technical concepts
  - Cascade multi-stage compression cycle (R718)
  - Reversed Brayton cycle (R744)
- Economic Analysis
- Summary and outlook
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Considered Case Studies

- **Alumina production**
  - \( \dot{Q}_{\text{Demand}} = 50 \text{ MW} \)
  - \( n = 8000 \text{ h/year} \)
  - Heat sink: Thermal oil
  - Heat source: Air
  - Heat sink: 280°C, Heat source: 140°C
  - Process: 110°C, 60°C

- **Spray dryer for milk powder production**
  - \( \dot{Q}_{\text{Demand}} = 8.2 \text{ MW} \)
  - \( n = 7000 \text{ h/year} \)
  - Heat sink: Drying air
  - Heat source: Moist excess air (fixed mass flow)
  - Heat sink: 210°C, Heat source: 64°C
  - Process: 50°C, 20–25°C

- Focus on industries with:
  - Large capacities
  - Access to cheap electricity
  - High number of operating hours
  - Possibility to acquire own renewable electricity
  - Acceptance of process equipment

Cascade multi-stage R-718 cycle

[Diagram of the Cascade multi-stage R-718 cycle]

Alumina production

- Heat sink: 280°C, Heat source: 140°C
- Process: 110°C, 60°C

[Graph showing specific enthalpy vs. log(\(p/\text{bar}\)) with data points at various specific enthalpies]
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Cascade multi-stage R-718 cycle

Reversed Brayton cycle using R-744
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**Reversed Brayton cycle using R-744**

Alumina production

- 140 °C → 280 °C
- 60 °C → 110 °C

**Performance:**
- \( \text{COP} = 1.72 \)
- \( \text{TCI} = 48.3 \text{ Mio. €} \)
- \( \text{TCI}_{\text{spec}} = 966 \text{ €/kW} \)

**Note:** Conservative assumptions for turbomachinery (\( \eta_{\text{is}} = 75\% \))

**Cascade multi-stage R-718 cycle**

Spray Dryer

- 64 °C → 210 °C
- 20-25 °C → 50 °C

**Performance:**
- \( \text{COP} = 1.92 \)
- \( \text{TCI} = 16.4 \text{ Mio. €} \)
- \( \text{TCI}_{\text{spec}} = 1,997 \text{ €/kW} \)
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**Reversed Brayton cycle using R-744**

**Performance:**
- COP = 1.61
- TCI = 15.4 Mio. €
- TCI\_spec = 1,868 €/kW

**Note:** Conservative assumptions for turbomachinery (η\_is = 75 %)

**Economics – Levelized cost of heat**

|                      | Investment | Electricity | Combustion Fuel | Exemplifying CO2-Tax: 50 €/t of CO2 |
|----------------------|------------|-------------|-----------------|-------------------------------------|
| **Spray Dryer** Case Study | 59.6       | 56.0        | 47.1            | 32.9                                |
| **Alumina Production Case Study** | 74.9 | 73.1 | 61.5 | 67.8 |
| Denmark 2020          | 56.0       | 54.6        | 56.1            | 44.5                                |
| Germany 2020          | 41.1       | 41.5        | 31.2            | 46.2                                |
| Norway 2020           | 61.5       | 66.3        | 67.8            | 66.3                                |
| Renew. El 2020        | 51.0       | 43.7        | 51.0            | 47.2                                |
| **Reversed Brayton Cycle** | 59.6 | 56.0 | 47.1 | 32.9 |
| Denmark 2020          | 61.5       | 67.8        | 61.5            | 67.8                                |
| Germany 2020          | 41.5       | 44.5        | 41.5            | 44.5                                |
| Norway 2020           | 67.8       | 66.3        | 67.8            | 66.3                                |
| Renew. El 2020        | 51.0       | 43.7        | 51.0            | 47.2                                |
| **Steam Compression System** | 56.0 | 54.6 | 56.1 | 44.5 |
| Denmark 2020          | 67.8       | 66.3        | 67.8            | 66.3                                |
| Germany 2020          | 51.0       | 43.7        | 51.0            | 47.2                                |
| Norway 2020           | 74.9       | 73.1        | 74.9            | 73.1                                |
| Renew. El 2020        | 67.8       | 66.3        | 67.8            | 66.3                                |
| **Electrical Boiler** | 51.0       | 43.7        | 51.0            | 47.2                                |
| **Combustion Boiler** | 59.6       | 56.0        | 56.0            | 56.0                                |
Discussion

• Different scenarios possible for balancing fluctuating renewables
  - Variable renewable electricity
  - Stabilization of electricity supply
  - Power to heat
  - Thermal storage
  - Process

• Large investments feasible?

Conclusions

• Technical feasibility:
  • Supply temperatures of up to 280 °C analyzed
  • COPs between 1.6 to 1.9

• Economic feasibility:
  • Economy of scale → lower specific investment at increasing capacities
  • Levelized cost of heat strongly dependent on electricity cost
  • Heat pump solutions competitive to natural gas and biomass boilers

• Future work and potentials:
  • Component optimization
  • Optimization of investment cost
  • Demonstration