Sensitivity analysis and robust controller design

– of an absorption compression high-temperature heat using oil free ammonia water as the working fluid based on a detailed dynamic numerical model.

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Introduction

Industrial processes and district heating systems often require temperatures above 100°C. High-temperature heat pumps bridge this gap, enabling the use of waste heat and renewable energy to replace fossil-fuelled boilers. The natural zeotropic ammonia-water mixture used as a working fluid in the absorption-compression heat pump (ACHP) offers a unique advantage: it enables a temperature glide during phase change. This improves efficiency by minimizing thermal losses and optimizing heat transfer [1]. Additionally, the mixture's vapor-liquid equilibrium properties allow the system to achieve high temperatures at moderate pressures. , as the presence of water reduces the partial pressure of ammonia
Integrating absorption into a Rankine-based cycle increases operational flexibility, enabling higher sink temperatures and temperature glide. However, this integration also introduces greater system complexity, making stability and control more challenging to maintain. Detailed simulations are an essential tool for understanding the sophisticated interactions and optimising performance under varying conditions.

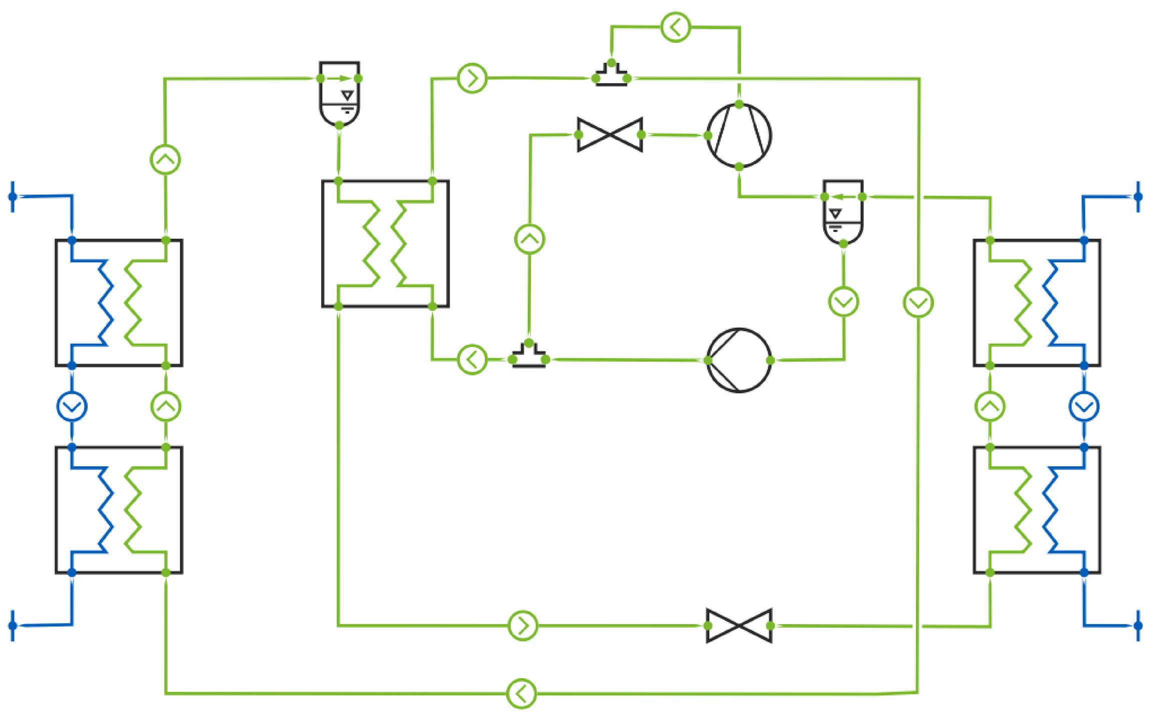

Figure 1: Flow diagram of the investigated ACHP system. A simple absorption compression cycle with a screw compressor was modelled, including the liquid injection line for cooling and lubrication, absorber/desorber heat exchanger and separator/receiver.

Methodology

The dynamic ACHP model, based on the NTNU laboratory setup, was implemented in Modelica using the Process Systems Library (PSL). Unlike previous steady-state or single-component models, this approach enables the dynamic simulation of the two-component mixture. It allows for high-resolution calculations of composition, phase behavior, and state variables at any point in the cycle under varying conditions.

- **Component Development**: While standard components were taken from the PSL, specific units—most notably the oil-free screw compressor—were newly implemented**.**
- **Compressor Model**: To account for the liquid injection of the weak solution (used for lubrication and cooling), a new efficiency-based compressor model was created. This model allows for spatial discretization, enabling the simulation of the evaporation process of the injected weak solution.
- **Fluid data**: Since the initial PSL version utilized NASA polynomials (assuming ideal mixtures), adjustments were necessary to account for the strong negative deviation of the ammonia-water mixture.

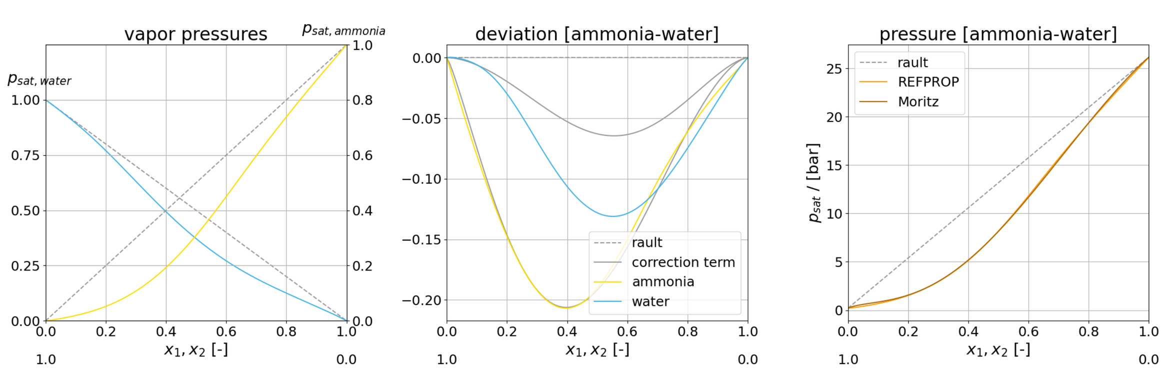

Figure 2: (a) Partial pressure of ammonia and water (b) Deviation from Raults' law (c) Partial pressure compared to REFPROP data, including a correction term.

Results

Based on the implemented ACHP model, several simulations were conducted to answer the following research questions:

What effect does the temperature glide of the zeotropic refrigerant have, and how can it be modified in dynamic behaviour?

How does the system respond to variations in the source and sink temperatures, and how can it be adjusted to achieve the best possible response?

How can heat exchangers achieve highly efficient absorption and desorption? What is the optimum ratio for achieving efficient, safe and stable operating conditions?

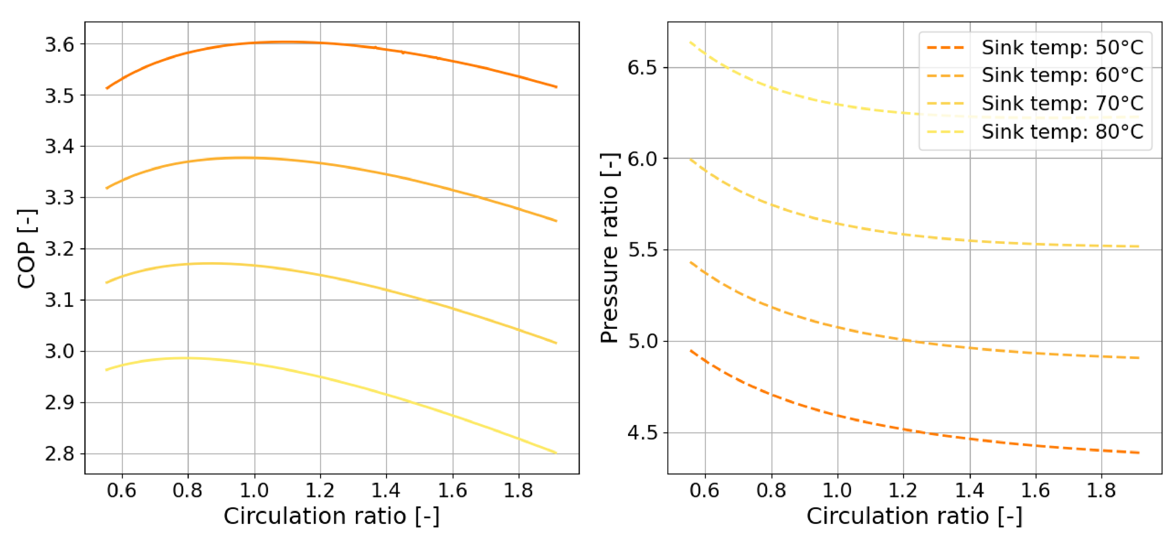

Figure 3:On the left, the COP is shown as a function of the circulation ratio for different sink temperatures at 35 kW thermal output. On the right is the corresponding pressure ratio.

To analyze the performance of the ACHP, the system's characteristic parameters were varied to evaluate their impact on overall efficiency. One characteristic parameter is the circulation ratio, which is defined as follows [2] [3] :

$$\text{circulation ratio } (CR) = \frac{\dot{m}_{weak}}{\dot{m}_{strong}}$$

- The **pressure ratio** was identified as the primary factor influencing system efficiency.
- The pressure level dictates the ammonia-water equilibrium. This determines the ratio of refrigerant transported by the compressor versus the solution pump.

→ A higher pressure ratio increases compressor work but simultaneously counteracts ammonia volatility, creating a complex trade-off for system optimization.

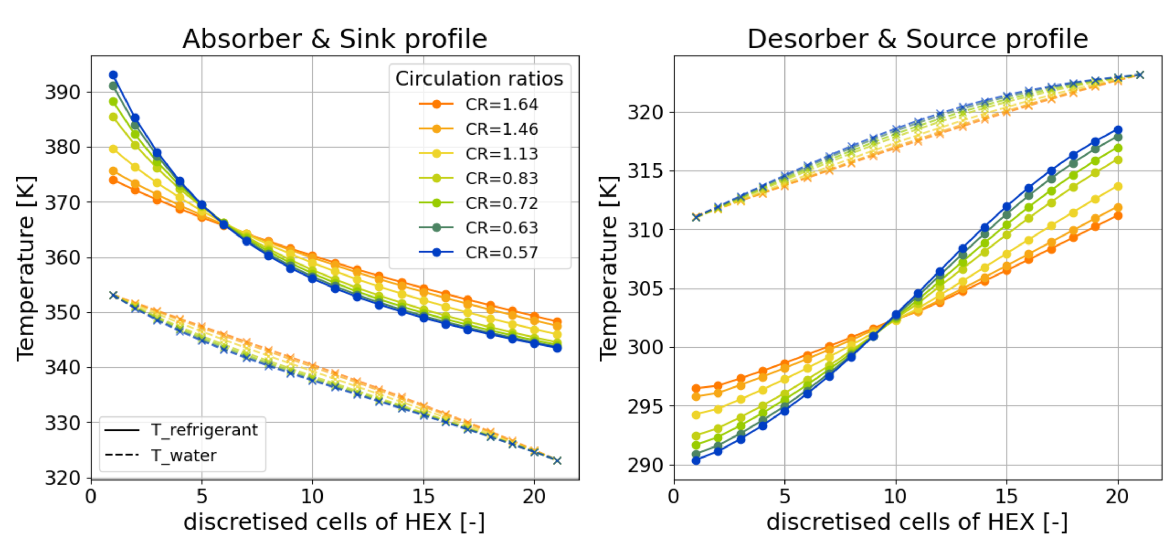

Figure 4: illustrates the behavior of the temperature curve over the length of the heat exchanger. Shown for different states with varying amounts of absorption or desorption (CRs).

The simulation utilizes a detailed Heat Exchanger (HEX) model to precisely analyze the temperature glide. A key finding is that minimizing exergy losses by matching the glide to the source/sink profiles is highly dependent on the circulation ratio. This highlights that the circulation ratio serves as an additional degree of freedom, allowing the ACHP to achieve optimized, high-efficiency control under varying conditions.

A significant advantage of this modeling approach is the ability to monitor ammonia-water concentrations at every point within the cycle. Especially in dynamic simulations, this enables:

- **Refrigerant Shift Evaluation**: Tracking how the mixture composition redistributes during transient operations.
- **Local HEX Analysis**: Visualizing exactly how absorption and desorption progress along the length of the heat exchangers.

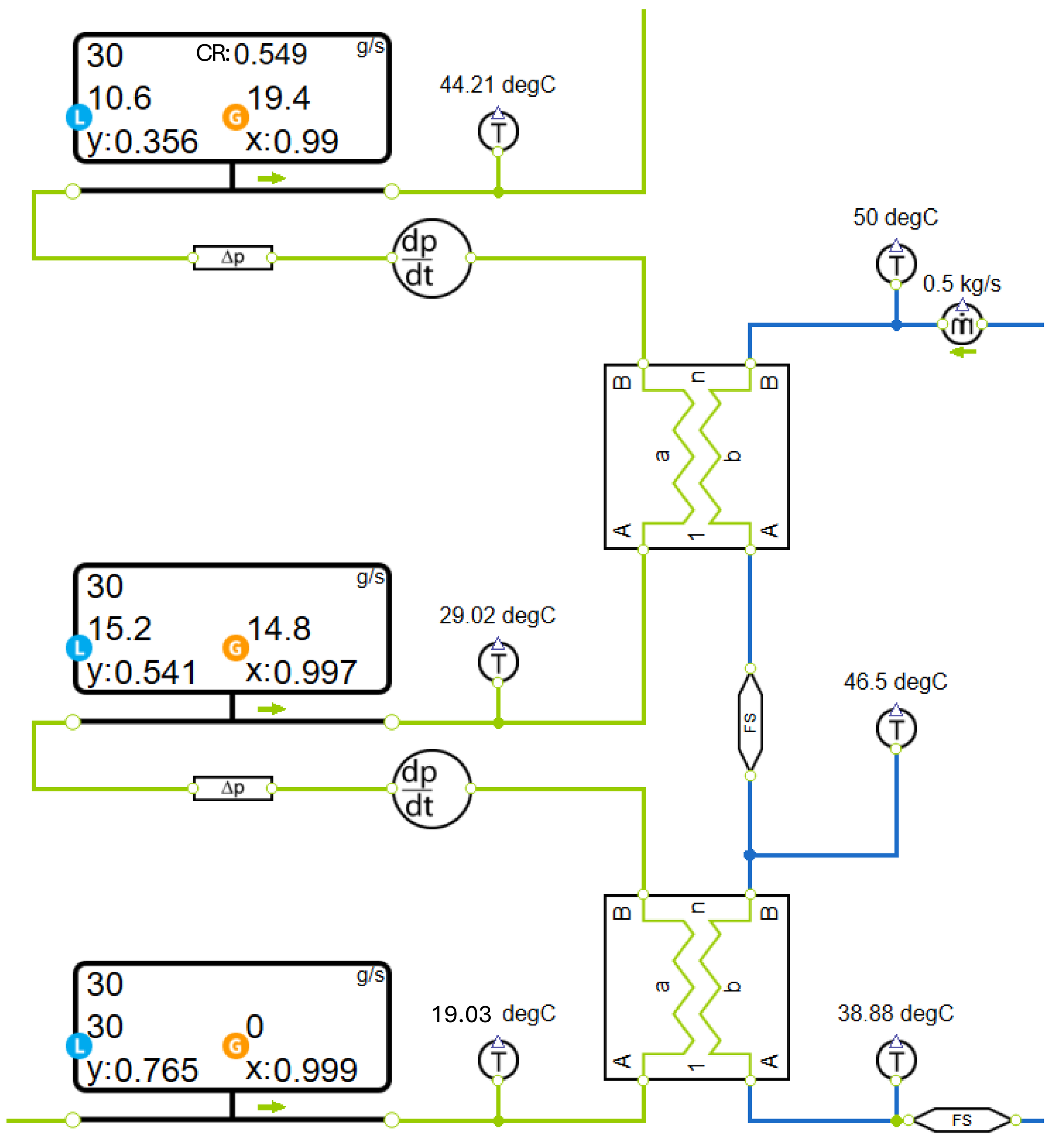

Figure 5: Screenshot from the simulation with measured values for concentration and temperature across the desorber of the ACHP.

Limitations

While the model provides a robust framework for dynamic analysis, the following limitations should be considered for further refinement:

- The **fluid data** is currently optimized for specific operating points. Future work should integrate the Tillner & Roth model to ensure higher accuracy [4].
- The simulation assumes a **constant isentropic efficiency** for the compressor. In real-world operation, efficiency varies drastically with pressure ratios.
- **Constant heat transfer coefficients** are currently assumed. To better reflect the complex physics of the ACHP, these should be replaced by dynamic correlations specifically tailored for absorption and desorption processes.

Outlook

Following detailed **calibration against experimental data**, this model serves as a high-fidelity digital twin of the physical ACHP plant. This enables:

- **Control Strategy Optimization**: Virtual testing and refinement of control algorithms before implementation on the real system.
- **System Optimization**: Seamless evaluation of hardware modifications and operational parameter adjustments in a risk-free environment.
- **Advanced Monitoring**: Enhanced process insights through "virtual sensors" that provide detailed data on internal states, such as local concentrations and phase behavior.

References

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