

## ABSTRACT

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Industrial processes often consume large quantities of heat, while often dissipating large quantities of waste heat to the ambient. The main energy source for industrial heat supply is fossil fuels, either oil or natural gas. Thus, the heat consumption of industrial processes often entail large CO<sub>2</sub> emissions as well as emission of other harmful pollutants. As heat pumps can upgrade low temperature waste heat to a high temperature heat supply using only a fraction of primary energy, heat pumps may be applied to improve the energy efficiency of industrial processes. Further, Replacing oil or gas burners with heat pumps could lead to a reduction of the emissions, especially in a future energy system with a high penetration of renewable energy sources.

Many industrial heat pumps have been installed with a heat supply temperature ranging from 50 - 90 °C. The lack of installation in the temperature domain in excess of 90 °C is believed to be caused by the lack of cost efficient heat pumps, rather than a limited demand. Commercial components for industrial heat pumps are limited to a working pressure of 28 bar, although high pressure alternatives do exist for ammonia (50 bar) and CO<sub>2</sub> (140 bar). Most commercial compressors are not durable at compressor discharge temperature above 180 °C. Using these components, vapour compression heat pumps (VCHP) are limited to heat supply temperatures between 80 - 90 °C. Developing heat pumps that are capable of delivering temperatures above 90 °C may therefore allow heat pump implementation in more industrial processes than is currently possible.

The ammonia-water hybrid absorption-compression heat pump (HACHP) is of specific interest for development of high temperature heat pumps due to two properties inherent to the zeotropic working fluid: 1. Increased efficiency due to the reduction of thermal irreversibilities in the heat transfer processes between the working fluid and the external streams. 2. The reduction of vapour pressure compared to the vapour pressure of pure ammonia. The HACHP can therefore deliver higher temperatures at higher efficiencies than conventional VCHP.

To investigate the possibility of developing high temperature HACHP, numerical models are developed for the one-stage cycle and several identified two-stage compression configurations. The design of the HACHP is governed by two extra degrees of freedom compared to the VCHP. These can be set by many criterion but is in this study set by the choice of the rich ammonia mass fraction and the circulation ratio. The influence of these parameters on the performance and size of the system is investigated. The performance and size of the identified two-stage compression configurations are compared to the one-stage cycle. One two-stage compression cycle performs better than the remaining, both in terms of increased efficiency, reduction of discharge temperature and needed compressor volume.

For the one-stage and the best two-stage cycle the constraints of commercial com-

ponents are imposed on the choice of rich ammonia mass fraction and the circulation ratio at a number of supply temperatures. This showed that the 28 bar one-stage HACHP allow temperatures up to 111 °C, 50 bar up to 129 °C, and 140 bar up to 147 °C. For the two-stage HACHP, 28 bar components allow temperatures up to 126 °C, 50 bar up to 145 °C, and 140 bar up to 160 °C.

To determine the sources of thermodynamic irreversibilities as well as the formation of cost and environmental impact an advanced exergy-based analysis is applied to the HACHP. An exergy-based analysis consists of three steps: an exergy analysis is conducted to identify the exergy streams in the system and the thermodynamic irreversibilities (exergy destruction). Subsequently, an economic analysis is conducted and combined with the exergy analysis such that cost is associated with each stream of exergy and consequently, the cost of exergy destruction is determined. This is known as an exergoeconomic analysis. Further, a life cycle assessment is performed and combined with the exergy analysis to associate environmental impact to all streams of exergy and thereby determine the environmental impact of exergy destruction. This is known as an exergoenvironmental analysis. The advanced exergy-based analysis differs from the conventional analysis by accounting for component interdependencies as well as reduction potential. The highest rate of avoidable exergy destruction was associated with the desorber while the highest rate of avoidable cost was associated with the absorber. It is found that the cost of most components are evenly distributed between operational and capital investment cost. The highest rate of avoidable environmental impact stems from the compressor. It is shown that the environmental impact of construction, transportation and disposal was negligible compared to the environmental impact related to the operation of the HACHP.

The working domain of the HACHP is investigated by imposing all technical constraints of commercial components to a variation of the heat supply temperature and temperature lift. An economic analysis is applied to the same variation such that the net present value in all points is attained. For all combinations it is evaluated whether the solution complies with the technical and economic constraint (net present value > 0) and thus whether the heat pump implementation is feasible. A similar analysis is conducted for VCHP, which allows a comparison, not only on which temperature levels and lift are attainable by the two technologies but also which technology is the more viable solution in the domain where both compete. This showed that the HACHP can be used to heat supply temperatures of 150 °C and temperatures up to 60 K. This increases the working domain of industrial heat pump. For the temperature range where the HACHP competes with ammonia VCHP: the HACHP is the most viable solution at low temperature lifts while VCHP are more profitable at high lifts. For the range where the HACHP competes with iso-butane or CO<sub>2</sub> the HACHP is always the more viable solution.