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Development of an Ammonia/Water Absorption Heat Transformer to upgrade low-temperature industrial waste heat

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High Temperature Heat Pump, Absorption Heat Transformer, Ammonia absorption

Abstract

For numerous years, a drastic increase in energy demand has been observed worldwide, mainly originating from fossil fuels, despite an alarming need for a decrease in energy consumption and CO₂ emission. Numerous industries need heat at a high temperature while dissipating heat at moderate to low temperature. Answer this need in an environmentally friendly way is required to mitigate the impact of global warming. In this context, sorption systems are a promising solution able to valorise waste energy at a low electricity cost, up to ten times less electrical power compared to an equivalent vapour compression heat pump. Specifically, Absorption Heat Transformer (AHT) are a type of absorption machine able to recover low-level waste heat (~80°C) in order to provide higher-level heat (>100°C) necessary for vapour production or other industrial uses. In this study, a single stage AHT based on the NH₃/H₂O mixture is modelled and simulated. Results enable to evaluate the performances of the AHT fed by industrial waste heat and cooled by ambient air. The influence of both the waste heat and ambient air temperatures are evaluated. Different coefficients of performances based on the heat transferred and/or the electricity consumption are calculated as well as the expected output temperature of the hot heat sink. Finally, the range of valuable working conditions for the system are discussed.

Introduction

Approximately 32% of the global energy consumption is attributed to industrial energy demand, as reported by the International Energy Agency [1]. Over the past decades, this demand has consistently risen and is anticipated to continue on a similar trajectory in the future. This is concerning given the urgent need to reduce global energy consumption and curb CO₂ emissions [2]. Three quarters of industrial energy demand is in the form of heat, primarily derived from fossil resources. Unfortunately, a significant portion of this heat, around half, is released into the environment. A key challenge in harnessing this waste heat lies in its low temperature (<100°C), limiting the number of processes that can directly benefit from it. To address this issue, one potential solution is to elevate the waste heat to a higher temperature using methods such as heat pumps. Heat pumps, particularly sorption systems, are expected to play a crucial role in fulfilling industrial demand with minimal environmental impact in the coming years [3]. Specifically, sorption systems like absorption heat transformers (AHT) offer a promising approach to capitalize on waste energy with lower environmental costs compared to traditional vapour compression systems [4]–[6]. These systems have the capability to enhance the exergy

level of a heat source with minimal mechanical work input, primarily in the form of electricity consumption.

In this study, the modelling of a small scale $\text{H}_2\text{O}/\text{NH}_3$ simple effect single stage AHT system is described. The purpose of this modelling is to dimension a forthcoming 10 kW machine that will utilize plate heat exchangers. The primary objective of the machine is to enhance low-grade waste heat (ranging from 60°C to 90°C), leveraging insights from the group's prior research on the performance of plate heat exchangers [7]. A global model has been developed based on thermodynamical equilibrium, this model is able to give an estimation of the output temperature of the hot source after flowing through the absorber.

Methods

Architecture Description

The Absorption Heat Transformer (AHT) architecture considered in this paper is schemed in Figure 1 : Scheme of the AHT system used to upgrade low temperature waste heat source represented in a PT diagram. Figure 1. It is a simple effect single stage cycle including two internal heat exchangers based on the $\text{H}_2\text{O}/\text{NH}_3$ pair. The inclusion of a desorber, an absorber, an evaporator, and a condenser is standard and essential in any absorption machine, resulting in a total of six components. The two internal heat exchangers are the solution heat exchanger (SHX) and the refrigerant heat exchanger (RHX). These two exchangers are used to recover heat between two sections of their respective line, thereby enhancing the overall efficiency of the architecture. Two pumps are used to circulate the poor solution and the refrigerant, and an expansion valve allows the rich solution to lower its pressure.

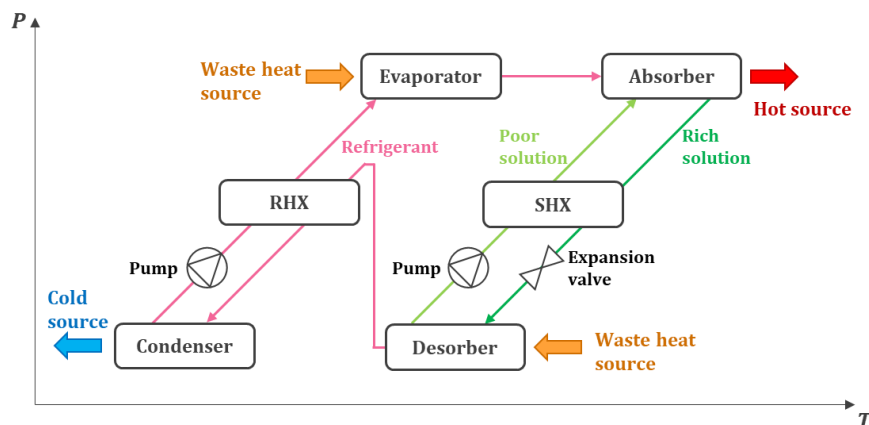


Figure 1 : Scheme of the AHT system used to upgrade low temperature waste heat source represented in a PT diagram.

The machine is fuelled by three heat sources: a cold source is employed at the condenser to facilitate the condensation of the refrigerant vapour, an intermediate source, characterized as waste heat, is divided between the generator and the evaporator, serving to generate the refrigerant and vaporize it, respectively. The hot source flows through the absorber, where it accumulates the heat generated during the exothermic absorption process.

Modelling of the AHT and of its absorber

The behavior and performances of the absorption heat transformer were modelled using steady state thermodynamics equilibrium equations applied to each component of the system. To assess the fluid's condition at various points within the system, energy, mass, and species balance equations were applied to the pertinent components. The full set of calculations can be condensed into the following set of equations:

$$Q_i = \sum_f \dot{m}_f h_f \quad (1)$$

$$W_i = \dot{m}_f (h_{f,outlet} - h_{f,inlet}) \quad (2)$$

$$\sum_f \dot{m}_f = 0 \quad (3)$$

$$\sum_f \dot{m}_f x_f = 0 \quad (4)$$

where i is the considered component, thus, depending on the nature of i , Q_i is the power exchanged at a heat exchanger and W_i is the work of a pump. \dot{m}_f is the mass flow rate of the fluid f , h_f is the enthalpy and x_f is the mass fraction. For the two internal exchangers, the RHX and the SHX, an effectiveness model has been applied with fixed efficiency of 80%. For the other heat exchangers, a temperature pinch of 5°C has been applied. It is assumed that the solution is saturated at the outlet of the desorber, absorber and condenser. The system has been modelled and computed in the equation solver EES.

To evaluate the performances of the system, two different Coefficients Of Performance (COP) are calculated. They are the thermal COP eq.(5) and the electrical COP eq.6, which respectively evaluate the performance of the machine in respect to the absorbed waste heat and in respect of the absorbed electrical power.

$$COP_{th} = \frac{|Q_{abs}|}{|Q_{des}| + |Q_{evap}|} \quad (5)$$

$$COP_{elec} = \frac{|Q_{abs}|}{\sum |W_{pumps}|} \quad (6)$$

This particular model, somewhat conventional, has been extensively utilized to assess the performances of diverse absorption heat pumps [8]–[10], demonstrating its reliability. However, applying this straightforward model to an Absorption Heat Transformer (AHT) has its limitations. While it can evaluate performances and exchanged heat power, determining the temperature at which the hot source exits the absorber poses a challenge. To comprehensively characterize an AHT, it becomes imperative to not only assess the heat flux absorbed by the hot source but also its temperature increase. In order to address this uncertainty, the absorber is divided into two sections: an adiabatic absorption section and a heat exchange section, illustrated in Figure 2. The assumption between these sections is that the solution is saturated, signifying that a portion of the refrigerant vapour has been absorbed by the solution, resulting in an elevation of the solution temperature above that of the hot source inlet.

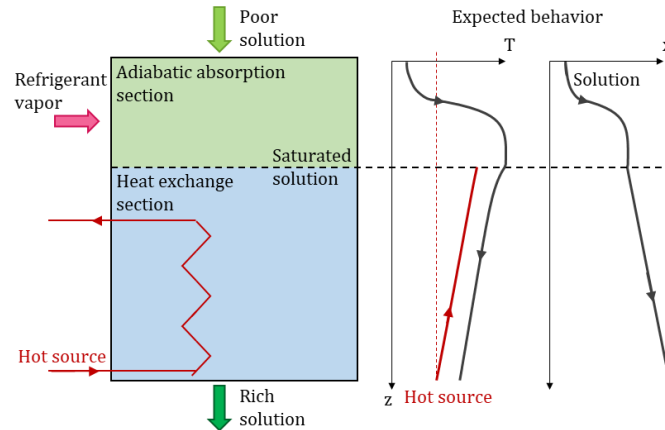


Figure 2 : Scheme of the considered heat and mass transfers behavior for the thermodynamical equilibrium model used to estimate the transfers inside the absorber, where the to-be-heated hot source enters the exchanger at a higher temperature than the solution. The assumed temperature T and solution mass fraction x behaviors allow for the introduction of a saturated equilibrium point inside of the absorber in order to estimate the maximum temperature reached by the solution.

Results and Discussion

The performance of a single-stage Absorption Heat Transformer (AHT) was assessed using the steady-state equilibrium model. The results detailing the performance indexes can be observed in Figure 3. The figure illustrates the variation of both performance indexes concerning the temperatures of the cold and waste sources. In the graph, solid lines represent the thermal coefficient of performance (COP_{th}), while dotted lines represent the electrical coefficient of performance (COP_{elec}). The findings indicate a general decrease in both performance indexes as the temperature of the cold source rises. For a specific cold source temperature, as depicted in Figure 3, the AHT system demonstrates a finite working range for waste heat temperature that becomes narrower with higher cold source temperatures. For instance, at $T_{cold} = 15^\circ\text{C}$, the AHT is effective within the waste heat temperature range of 61°C to 98°C . At a constant T_{cold} , the performance indexes exhibit a slight shift of around 20°C with respect to the waste heat source temperature. Despite the overall decline in performance with increasing T_{cold} , the maximum COP_{th} remains relatively high, ranging from 0.7 to 0.6 within the studied region. However, the COP_{elec} displays more variability with T_{cold} , with its local maximum decreasing from 120 to 40 as T_{cold} increases. This indicates a significant influence of the working conditions on the pump's work. Nevertheless, under comparable conditions, these performance indexes compare favourably with classical vapour compression heat pumps, where the only analogous value, COP_{elec} , reaches a maximum of 10 at best [11].

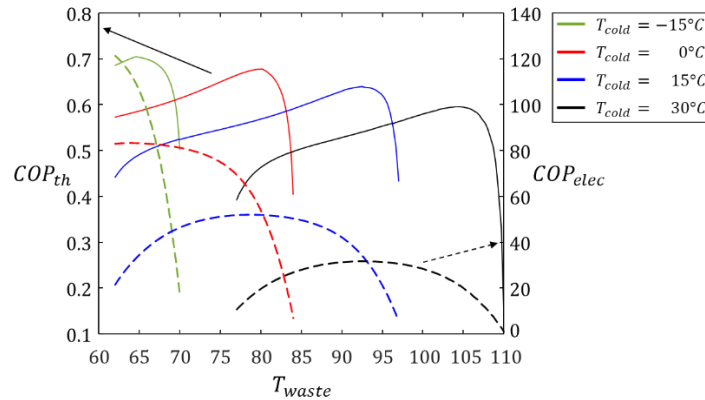


Figure 3 : Estimated performances of the machine depending on the temperature of the cold and waste heat sources. The colors represents different cold source temperatures. Full lines corresponds to COP_{th} the thermal performance index and the dotted lines corresponds to COP_{elec} the electrical performance index.

Merely examining performance indexes falls short of providing a complete characterization of an Absorption Heat Transformer (AHT). This is because the useful effect results from the absorption process occurring within the absorber, where the hot source enters at a temperature already higher than that of the solution, as illustrated in Figure 2. Consequently, deducing the output temperature of the hot source from the solution inlet temperature is not straightforward. To address this uncertainty, the maximum temperature attained by the solution was determined by assuming perfect absorption of the refrigerant vapour until saturation at the absorber inlet. The maximum achievable solution temperature, denoted as $T_{f,max}$, as depicted in Figure 4, has been estimated for various cold and waste heat source temperatures. As anticipated, an increase in either the cold source or the waste heat source temperature leads to an increase in $T_{f,max}$. According to the model, for $T_{cold} = 30^\circ C$ and $T_{waste} \leq 100^\circ C$, $T_{f,max}$ reaches $130^\circ C$, which aligns with the critical temperature of NH_3 and thus imposes a limit on the operational capabilities of an AHT. While it is possible to surpass this critical temperature due to the presence of water vapour mixed with ammonia in the refrigerant, it drastically alters the machine's working conditions, necessitating a specific architecture to accommodate supercritical fluids. Hence, the combination $T_{cold} = 30^\circ C$ and $T_{waste} \leq 100^\circ C$ represents a soft limitation for any simple effect single-stage H_2O/NH_3 AHT system. Since both T_{cold} and T_{waste} affect the system's response, the optimal working condition couple, in terms of maximum solution temperature, is almost never the one where COP_{th} is higher. For instance, at $T_{waste} = 95^\circ C$, where the COP_{th} reaches its maximum at $T_{cold} = 15^\circ C$ (as shown in Figure 3), and is lower for $T_{cold} = 30^\circ C$, the second case yields the maximum solution temperature. Consequently, depending on the hot source heating requirements, it is often preferable to design an AHT at a point where performance is slightly inferior but where the recoverable heat is of higher quality. Nonetheless, under any conditions, the maximum temperature attained by the solution within the absorber is at best $T_{waste} + 30^\circ C$ for this simple effect single-stage H_2O/NH_3 AHT architecture.

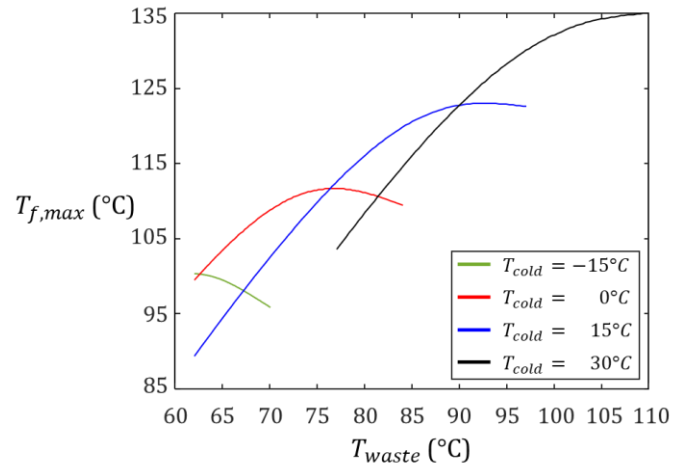


Figure 4 : Evolution of the maximum solution temperature that can be reached inside of the absorber thanks to the absorption process until it reaches saturation depending on the cold and waste heat source temperatures. The colors represents different cold source temperatures.

Conclusion

This study investigates the sizing of a 10 kW H₂O/NH₃ simple effect single stage Absorption Heat Transformer machine designed for elevating heat temperature from an intermediate waste heat source to a hot source. The selected operational range is $-15^\circ C \leq T_{cold} \leq 30^\circ C$ and $60^\circ C \leq T_{waste} \leq 110^\circ C$. To gauge the system's performance, a steady-state thermodynamic equilibrium model was developed. However, conventional assumptions fall short in fully characterizing the machine, particularly in assessing the temperature of the hot source output. In order to estimate the maximum temperature within the absorber, it was assumed that it is composed of an adiabatic absorption section and of a heat exchange section. The solution between these sections is treated as saturated. This set of assumptions and equations were implemented to compute the maximum temperature reached by the solution in the absorber, thus determining the quality of the heat that can be transferred to the hot source. This model provided insights into both the potential and limitations of an AHT architecture.

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