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Internal energy and exergy recovery in high temperature application absorption heat transformers

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HIGHLIGHTS

- Triple absorption heat transformer internal heat recovery dissected and optimised.
- Optimised designs created using heat exchange network modelling.
- One heat exchanger in conventional unit proven almost irrelevant at high GTLs.
- Rearranging heat exchangers increases COP by 11.7% and reduces exergy losses by 21%.
- One extra heat exchanger increases COP by 16.4% and reduces exergy losses by 28%.

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ABSTRACT

In this paper, the design of a triple absorption heat transformer (TAHT) using the working fluids water and lithium bromide is dissected and reassembled using heat exchange network modelling in order to determine the optimum number and locations of internal heat exchange units within the system. It is found that the conventional design of the TAHT does not employ heat exchangers effectively, and that thus by rearranging these units system COP may be increased by 11.7% while exergy destruction within the system (its irreversibility) can be reduced by 21%. Strategically adding an extra one or two heat exchangers increases the COP by 16.4% and 18.8% while decreasing exergy destruction by 28% and 31.5% respectively compared to a conventional TAHT design.

1. Introduction

As the price of fuel increases, and concerns regarding global warming and atmospheric pollution become more and more widespread, the efficient usage of energy is an issue which is of particular concern to industry. Technologies such as absorption heat transformers (AHTs) which allow for the recycling of waste heat energy are very attractive methods of improving performance in this area. A heat transformer is a closed cycle system which upgrades a fraction of the energy contained by an intermediate temperature waste heat stream to a higher temperature so that it may be reused. These cycles require almost no mechanical or electrical work and thus have very low running costs.

For smaller temperature augmentations, such as 50 °C, a single stage heat transformer (SSHT) is generally used. This type of system, generally using a lithium bromide and water ($LiBr - H_2O$) working fluid combination, can achieve coefficients of performance (COPs) of 0.5 meaning that approximately half of the energy supplied to the system is recovered as higher entropy product [1]. In order to achieve a greater gross temperature lift (GTL) however, more sophisticated types of cycles are required. A double absorption heat transformer (DAHT) can achieve GTLs of about 80 °C while maintaining a COP of roughly 0.36 [2]. However if even higher GTLs are required, a triple absorption heat transformer (TAHT) must be utilised. Such triple stage systems are capable of achieving GTLs of 140 °C, and can thus be a very useful tool in an industrial setting involving high temperature processing.

In order to attempt to optimise a thermodynamic cycle such as a heat transformer, it should be examined using both the first and second laws of thermodynamics. While the first law is required to determine the energy flows to and from the system, the second law allows for the quantification of irreversibility within the cycle and the identification of sources of loss through the use of an exergy analysis. Such exergy analyses have been previously conducted on SSHT cycles, showing that the absorber has the lowest

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Nomenclature

COP	coefficient of performance of the system
dT_{Hx}	minimum pinch temperature (heat transfer gradient) utilised in all system heat transfer operations (°C)
ECOP	exergetic coefficient of performance of the system
E_D	total exergy destruction within the cycle (W)
FR	flow ratio of the system
GTL	difference in temperature between the absorber and the generator (°C)
GTL1	difference in temperature between absorber-evaporator-1 and the generator (°C)
GTL2	difference in temperature between absorber-evaporator-2 and the generator (°C)

Temperatures

T_c	temperature of the condenser (K)
T_e	temperature of the evaporator (K)
T_g	temperature of the generator (equal to T_e in this study) (K)
T_{ae1}	temperature of the salt solution in absorber-evaporator-1 (K)
T_{ae2}	temperature of the salt solution in absorber-evaporator-2 (K)
T_a	temperature of the salt solution in the absorber (K)

Pressures

P_0	pressure of the condenser and the generator. Equal to the vapour pressure of water at T_c (Pa)
P_1	pressure of the evaporator and absorber-evaporator-1. Equal to the vapour pressure of water at T_e (Pa)
P_2	pressure of absorber-evaporator-2. Equal to the vapour pressure of water at $T_{ae1} - dT_{Hx}$ (Pa)
P_3	pressure of the absorber. Equal to the vapour pressure of water at $T_{ae2} - dT_{Hx}$ (Pa)

Energy flows

Q_a	useful, high temperature enthalpy removed by a cooling stream from the absorber (W)
Q_c	enthalpy removed by a cooling stream (or generally ejected to the environment) from the condenser (W)
Q_e	enthalpy added to the evaporator by a heating stream (generally a waste heat stream) (W)
Q_g	enthalpy added to the generator by a heating stream (generally a waste heat stream) (W)

thermodynamic efficiency [1], and that optimum pressure and concentration ratios exist within the cycle to minimise this total non-ideality [3]. It is demonstrated that the mass flow rates and temperatures of the heat source used by the SSHT are more influential than those of the cooling source with respect to maximising the system's COP and total useful enthalpy output, and that both of these outputs can be increased during off-design operating conditions by maintaining a constant flow ratio [4]. Artificial neural networks have been trained to predict the total irreversibility within the SSHT as a function of input temperatures to the cycle [5], while the use of energy utilisation diagrams have shown that much of the exergy destruction in the absorber occurs during the pre-mixing stage and may be reduced by utilising a multicompartment absorber design [6]. Similarly in double stage systems, the use of split absorption and split generation has been shown to increase the exergy coefficient of performance (ECOP) by 6.8% [7], while a detailed exergy analysis determined that the generator is the greatest source of irreversibility within the cycle accounting for almost 40% of these losses [2]. It is demonstrated that almost identical results are achieved if the entropy generated within the system is used to quantify irreversibility instead of the conventional exergy method and that DAHT cycles only achieve roughly 51% of their reversibly achievable performance due to these losses [8].

Several combined first and second law studies have also been conduced on SSHT cycles utilising alternate working fluids. It is found that the ECOP of a SSHT operating with $LiBr - H_2O$ may be increased by up to 100% if 400 ppm of 2-ethyl-1-hexanol is added to the solution [9]. It also demonstrated that similar thermodynamic performance to $LiBr - H_2O$ may be achieved with some physical benefits such as lower corrosivity and higher solubility etc. if the ionic liquid 1-ethyl-3-methylimidazolium dimethylphosphate combined with water is used as working pair [10].

In general, the design of multi-stage absorption heat transformers utilising $LiBr - H_2O$ builds on that of the SSHT by adding an absorber-evaporator and an extra heat exchanger to the cycle [11]. It has been shown however that the issue of internal heat recovery is critical to the performance of the heat transformer, and studies have demonstrated that an increase in the effectiveness of the internal heat exchangers within the system leads to a distinct increase in the overall thermodynamic output from the cycle [2]. Thus especially as the systems' number of stages increase and gross temperature lifts become greater, these designs should be critically examined in order to determine whether they are in fact maximising the output of the cycle. Certain aspects of internal heat transfer have been analysed to date, such as replacing conventional shell and tube heat exchangers in the generator, evaporator, condenser and internal solution heat exchanger with brazed plate units in order to increase the heat transfer coefficient and thus reduce capital cost [12]. However this does not influence the thermodynamic output of the cycle. A second heat exchanger is incorporated into a SSHT by a study which aims to analyse the effect of including an ejector into such a system [13], while in contrast it is demonstrated that due to the very low flow ratio employed in a SSHT being installed in a particular sugar mill, a very good performance may still be achieved even without any internal solution heat exchanger [14]. Generally double absorption heat transformers have two internal solution heat exchangers [8]. However other methods of achieving heat recovery in such cycles has been shown to be possible requiring only one such heat transfer unit by allowing the hot dilute salt solution leaving the absorber to act as the concentrated salt solution entering the absorber-evaporator [15]. This method eliminates the need for a cold salt solution stream entering the absorber-evaporator.

As can be seen from the above review, no complete dissection of the design of multi-stage absorption heat transformers has been conducted to date. This provides a motivation for this work. A full dissection of the design of a triple stage absorption heat transformer is conducted which aims to determine the optimum utilisation of internal heat transfer units within the cycle in order to maximise the system's thermodynamic output.

2. Conventional system description

The conventional triple absorption heat transformer (TAHT) refers to the TAHT which is assembled using the same design as the more common double absorption heat transformer (DAHT) and illustrated in Fig. 1. In this figure all of the units are arranged vertically according to their temperature (as shown by the axis on the left