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Experimental performance of a double-lift absorption heat transformer for manufacturing-process steam generation

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ABSTRACT

As widely known, some industrial processes produce a large amount of waste heat while others require a large amount of steam to heat the process flow. The main difference involves the temperature level of these heat quantities. Absorption heat transformers play a strategic role in waste heat recovery and heat supply to manufacturing processes due to their ability to utilize heat at a certain temperature level and release the enthalpy of mixing of the refrigerant at a different temperature level with a negligible amount of mechanical work input. However, given the lack of examples that find application as operative plants, the feasibility of the technology is questioned in academic and technical domains. In this study, the operability of a double-lift absorption heat transformer that generates pressurized steam at 170 °C is studied across a full range of operative conditions. The results demonstrate and clarify the manner in which the system can operate steadily and efficiently when driven by hot water temperature at approximately 80 °C while safely generating steam at a temperature exceeding 170 °C. The conditions yielding maximum system efficiency and capacity are identified, and the obtained experimental results are used to define an optimal control strategy.

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1. Introduction

In a manner similar to several other countries, Japan has developed a cautious awareness with respect to global environmental issues that has led to ecological strategies to drastically reduce CO_2 and air pollutant emissions and limit the effects of global warming. Industrial emissions and residual heat release are responsible to a significant extent for the fore-mentioned environmental issues. Conversely, addressing these problems with innovative, clean, and efficient solutions can significantly contribute in the realization of an environmentally compatible, technologically advanced, and economically rewarding industry. In May 2007, as a part of the Japanese environmental strategy against global warming, a plan termed as “Beautiful star 50 (Cool Earth 50)” was stipulated by stating the long-term goal of “having the global greenhouse emissions halved by 2050 as compared to the current situation” [1]. More recently in 2013, a survey performed by the Ministry of Economy [2] pointed out that over 40% of the national energy consumption is related to industrial processes. The development of steam generation heat pumps is cited as one of the most promising elements to reach this objective since it simultaneously addresses waste heat recovery and clean energy provision for industry.

Steam is widely used for several industrial processes with cross manufacturing procedures from heating to drying purposes. The process-steam is conventionally generated with boilers that then reject a large amount of waste heat as hot water between 40 °C and 100 °C and/or exhaust gases at 100 °C–250 °C [3–5]. In this context, heat pump technology represents a critical possibility of recovering and reutilizing this amount of heat as a source to generate steam that can be reintroduced in an industrial productive route and to further lower the release of heat and pollutants into the environment.

Parallely, this technology can be directed towards the utilization of heat available from renewable sources, such as solar or geothermal energy, at equivalent temperature levels. A previous study [6] indicated an effective solution to utilize solar thermal energy with an air-conditioning system that could be used throughout the year and being installed in a tropical country.

The refrigerant stability and compressor oil durability at high temperatures limits the employment of vapour compression type heat pumps for heat recovery purposes to condensation temperatures below 120 °C [7–9].

Absorption heat transformers are heat-driven heat pumps that function based on the possibility of utilizing the enthalpy of

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Nomenclature

Q	heat transfer rate (kW)
T	temperature (°C)
COP	coefficient of performance (–)
$\dot{m}$	solution mass flow rate (kg/s)
h	enthalpy (kJ/kg)
ε	temperature effectiveness

Subscript

AH	high temperature absorber
AL	absorption evaporator
C	condenser
EH	refrigerant separator
EL	evaporator
G	low temperature generator
in	inlet
out	outlet
s	solution
S	steam separator
SL	low temperature solution heat exchanger
SH	high temperature solution heat exchanger
RL	low temperature refrigerant heat exchanger
RH	high temperature refrigerant heat exchanger

condensation of a refrigerant into an appropriate absorptive solution. This enables a system to realize the operative pressure jump of the refrigerant at a liquid state with low mechanical power requirements. Several extant studies involved theoretical and experimental investigations on different configurations and applications. A previous study [10] discussed the effectiveness of these systems with under different criteria to attain meaningful comparison terms. A more recent study [11] defines a thermodynamic criterion for a preliminary design of optimized three-thermal heat transformers and a method to perform the diagnostics of existing plants to provide guidelines for their performance improvement. An extant study [12] presented a thermodynamic model for irreversible heat transformers operating between four source-temperatures and included the effect of heat leaks, heat resistance, and internal irreversibility given a Newtonian heat transfer law. This was followed by a more general model [13] that was developed by considering a generalized heat transfer law to study the relation between coefficient of performance (COP) and heating load. New fluid pairs [14] were proposed to alleviate some of the main technical problems of the well-established lithium-bromide/water pair and different applications for achieving efficient waste heat recovery and broadening the application field of the technology (for further details refer to Ref. [15]). The possibility of using heat sources at lower temperatures to generate high-temperature steam would significantly enhance the usefulness and broaden the implementation field of these systems. However, multiple-lift configurations are needed to achieve temperatures above 120 °C, and except for [16], research effort in this area is limited to a theoretical standpoint in which the performance of different configurations are investigated with lumped parameters models [17–23]. Thus, given the lack of examples that find application as operative plants or prototypes, the feasibility and reliability of the technology is questioned in academic and technical domains. The technical and economic feasibility of single-effect heat transformers were demonstrated by early studies. However, more advanced configurations encounter various technical challenges, and it is necessary to overcome the same before they can be operationalised as market alternatives.

The present study demonstrates the real performance of a double-lift heat transformer operated with a lithium bromide-water mixture. The prototype overcomes the main technical challenges that have limited the application cases of this technology, showing that the system can operate steadily and efficiently when driven by hot water at approximately 80 °C while reaching output steam temperatures above 170 °C. The experimental performances are analysed with respect to the main operative parameters and control variables in a manner that is useful in indicating the best condition for a system recovering from heat discharged from a real plant and to clarify the functioning of the main components.

2. System description

Vapour absorption is among methods of refrigeration that were initially used widely. Therefore, given that absorption refrigeration machines are used for a long time, this technology has a broad albeit inconclusive theoretical background [24–26]. Absorption heat transformers, or absorption second type heat pumps achieve their final objective by means of the same thermo-chemical processes as those of an absorption chiller albeit occurring with a diverse rearrangement of the same components. Given this viewpoint, single- and multiple-lift heat transformers can be studied and developed as an extension of the fore-mentioned well-rooted counterpart. A single-stage heat transformer can raise the temperature of hot water from 90 °C to 120 °C, and actual machines have tested the same [27].

2.1. Basic cycle

An initial systematic assessment of the ideal performance of these systems constitutes the starting point for a comparative evaluation of the experimental performance of an actual plant. Preliminarily, a steady endo-reversible single-stage absorption heat transformer (Fig. 1a) is considered based on a systematic approach presented in a previous study [28] wherein heat transfer through the heat exchangers occurs isothermally, with zero temperature difference and heat losses towards the external environment. The effects of potential and kinetic energies of the refrigerant are neglected, the circulating solution amount is assumed to be infinite, and the Dühring rule (Eq. (4)) is applicable yielding a linear relationship between the temperature and saturation temperature of the solution.

A second type absorption heat pump (heat transformer) is driven by the intermediate temperature level heat delivered to a generator Q_G. Refrigerant vapour extracted is subsequently condensed at a lowest temperature source Q_C, whereas the rich liquid solution is pumped to a higher pressure level at low work expense. In which the refrigerant evaporated at the same pressure level (requiring Q_E as an input) can be absorbed by lowering the solution concentration (intended as the lithium-bromide mass fraction) and releasing heat Q_A at a higher equilibrium temperature T_A.

The efficiency of the resulting combination of endo-reversible cycles is defined as follows:

$$COP = \frac{Q_A}{Q_G + Q_E} \quad (1)$$

The algebraic form of first and second laws of thermodynamics can be expressed as Eqs. (2) and (3), respectively, as follows:

$$Q_G + Q_E = Q_A + Q_C \quad (2)$$

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