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Detailed thermodynamic analysis of a diffusion-absorption refrigeration cycle

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ABSTRACT

This paper proposes an advanced simulation model for a Diffusion-Absorption Refrigerator DAR using ammonia/water/hydrogen as working fluids, and developed to describe and predict the behavior of the device under different operating conditions. The system is supposed to be cooled with ambient air and actuated with solar hot water available at 200 °C. The DAR is first simulated for a set of basic data; a *COP* of 0.126 associated to a cooling capacity of 22.3 W are found. Basing on the obtained results an exergetic analysis of the system is performed which shows that the rectifier contribution to the exergy destruction is the most important with 34%. In a second step, the thermal capacities of all heat exchangers of the DAR are evaluated and the mathematical model so modified that the calculated capacities are now used as input data. A parametric study of the cycle is then carried out. The *COP* is found to exhibit a maximum when the heat supplied to the boiler or to the bubble pump is varied. Similar behavior is observed for variable submergence ratio. It is further noted that the *COP* is very sensitive to the ambient air temperature and to the absorber efficiency.

1. Introduction

The Diffusion Absorption Refrigerator (DAR) invented by Platen and Munters in 1928 [1] has been recognized as one of the most encouraging sustainable technologies for production of cold. The cycle of the machine operates at constant total pressure and uses environment compatible working fluids: ammonia as refrigerant, water as absorbent and hydrogen or helium as non-absorbable auxiliary inert gas. This inert gas is necessary to reduce the partial pressure of the refrigerant in the evaporator to allow the process of evaporation to take place in the uniform pressure device.

The main characteristic of DAR is that it has no moving parts, hence its good reliability. The circulation of the liquid solutions is driven by a bubble-pump and that of the gas loop between absorber and evaporator by gravity. This system has been now used for over 80 years [2]. The first commercial diffusion–absorption refrigerator was introduced to the market by Electrolux Company in Sweden (also known as Dometic) [3], and since then millions of such refrigerators have been built and used mainly in domestic and niche applications as in camping and caravans. The DAR operates only with thermal energy, no mechanical and then no electric power is needed. This energy can be provided by fossil fuel combustion (gas, fuel, etc.), but also, for temperatures varying between 90 and 200 °C, by solar thermal energy, or thermal discharges, etc. The growing concerns about worldwide energy and environmental sustainability in recent years enlarge the development of the DAR.

There are many theoretical and experimental studies on the performance analyses of the DAR system operated by different energy sources [4–8]. Chen et al. [9] designed a modified generator including a heat exchanger that reuses the rejected heat in the rectifier to pre-heat the rich solution from the absorber. The new configuration of the cycle showed a significant improvement in the cooling *COP*, as much as 50% compared to the original system for the same cooling capacity.

Zohar et al. [10] considered two configurations of a DAR, with and without refrigerant condensate sub-cooling. The results showed that the *COP* of the cycle without sub-cooling is higher by approximately 14–20% than that of the cycle with sub-cooling. The best system performances were obtained for ammonia mass fraction in rich solution varying in the range (0.25–0.4).

The search for alternative working fluids to the standard ammonia-water system has also been the focus of investigations.

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Nomenclature

A	Heat exchange area (m^2)
d	Diameter of bubble pump tube (m)
E	Efficiency (absorber), effectiveness (SHX)
H	Height (m) in Fig. 2
h	Height (m) in Fig. 2
$\dot{I}$	Irreversibility (W)
M	Molar mass (g mol^{-1})
$\dot{m}$	Mass flow rate (kg s^{-1})
$\dot{n}$	Molar flow rate (mol s^{-1})
N	Ratio of ammonia and hydrogen molar flow rate
$P\ sys$	Total pressure (bar)
p^*	partial pressure of ammonia (bar)
$\dot{Q}$	Thermal flow rate (W)
r	Molar flow ratio
Re	Reynolds number
$S, \dot{S}$	Entropy (J K^{-1}), entropy creation (W K^{-1})
s'	Slip ratio
T	Temperature (°C)
$\tilde{T}$	Mean temperature (°C)
ΔT	Heat-exchanger thermal pinch (K)
u	Velocity (m s^{-1})
UA	Overall thermal conductance of HX (W/°C)
$\dot{V}$	Volume flow rate (cm^3 s^{-1})
We'	Weber number
X,Y	Molar ratio of ammonia in liq. and vap
$.x$	Ammonia mole fraction in liquid
y	Ammonia mole fraction in vapor
y_{H2}	Hydrogen mole fraction in gas
z	Ammonia charge in hydrogen

Greek symbols

α	Vapor fraction in liq.-vap. Mixture
η	Liquid-phase viscosity (kg m^{-1} s^{-1})
μ	Chemical potential
ρ	Density (kg m^{-3})
σ	Surface tension (N m^{-1})
τ	Void fraction
ϕ	Slope ratio of actual, τ_{POL}, and minimum operating lines, τ_{MOL} (absorber), $\phi = \tau_{POL}/\tau_{MOL}$

Indices

A	Absorber
AW	Ammonia-water mixture
B	Boiler
C	Condenser
CF	Cool chamber
cv	Control volume
EC	Hot inlet
E	Evaporator
gen,cv	Entropy generated in control volume
hw	Hot water
j	Component j
L	Liquid phase
lm,i	Mean logarithmic temperature difference in machine component i
P	Bubble pump
R	Rectifier
SR	Liquid sub-cooling
V	Vapor phase
0	Temperature of surrounding

List of abbreviations

COP	Coefficient of performance, $COP = \dot{Q}_E/\dot{Q}_P + \dot{Q}_B$
CISE	Computer and Information Science and Engineering
DAR	Diffusion-absorption refrigerator
GHX	Gas heat exchanger
HX	Heat exchanger
SHX	Solution heat exchanger
VLE	Vapor liquid equilibrium

The objective is to reduce the temperature level of the driving heat supplied to the generator, so that solar thermal energy from flat plate or evacuated tube collectors can be used to this purpose [11–16]. Ben Ezzine et al. [17] reported that the *R*124–DMAC mixture could yield higher *COP* at lower driving heat temperatures in comparison with the NH_3–H_2O system. They also experimentally investigated a DAR using C_4H_{10}–C_9H_{20} as working fluid in association with helium [18], and demonstrated the feasibility of solar cooling with this system.

Maiya [19] showed that helium was more advantageous than hydrogen as inert gas, although a larger quantity of it is needed because of its larger viscosity. In the same study it was demonstrated that a higher pressure of operation decreases the *COP*.

The recent review of diffusion cooling systems by Rodríguez-Muñoz and Belman-Flores [20] pointed out that the actual investigation trend is the search for alternate working fluid systems that make the DAR be driven by residual or solar heat.

Srikhirin and Aphornratana [21] carried out an experimental study on an NH_3–H_2O DAR using helium as auxiliary gas. They developed also a mathematical model to determine the appropriate operating conditions for optimal performance, and observed that mass transfer rates in evaporator and absorber have a crucial effect on the system performance. The *COP* of the machine was found to vary in the range 0.09–0.15.

Starace and De Pascalis [22] elaborated a thermodynamic model of the DAR cycle without any assumption concerning the purity of the refrigerant exiting the rectifier. This model predicts higher performances than those found in Ref. [13]. In another study, Starace and De Pascalis [23] experimentally validated their model using a prototype with a bubble pump coupled to a domestic magnetron to reduce the starting transient of the circuit. The validation was carried out by varying the heat power supplied to the thermal pump of a commercially available DAR.

Yildiz and Mustafa [24] proposed a simulation model of a DAR and evaluated the energy and exergy losses in each component of the machine. The model was then validated by comparing calculated results with measurements. It was found theoretically as well as experimentally that the largest energy and exergy losses occured in the solution heat exchanger.

In the present paper a thermodynamic model for ammonia-water diffusion absorption refrigeration with hydrogen as inert gas is developed. The performances of the cycle are theoretically evaluated and analyzed. The effect of bubble pump characteristics and operating conditions (heat input, temperature, submergence ratio, etc.) is investigated. Further, an exergy analysis is performed in order to evaluate the contribution of each element of the DAR to