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THERMODYNAMIC PERFORMANCES OF AN ABSORPTION DIFFUSION REFRIGERATION SYSTEM, EQUIPPED WITH AN EJECTOR-COMPRESSOR, USING THE THERMAL ENERGY OF THE EXHAUST GASES OF CEMENT KILNS

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ABSTRACT

The depletion and high cost of fossil energy sources are the main cause leading to the energy transition. Industrial processes are increasingly using renewable resources, and adapting the zero-waste policy, to improve their energy efficiency. This study investigates the thermodynamic performance of the diffusion absorption refrigeration (DAR) system, equipped with an ejector and a compressor. The system operates using the residual heat of the gases exiting the cement kiln chimneys, recovered from the high-performance heat exchangers. The system is modelled and optimized using the M2EP analysis method (mass, energy, exergy and performance) and the particle swarm optimization algorithm. The refrigeration machine generates cold by evaporating the strong solution of the H_2O+NH_3 mixture. Hydrogen circulates in the diffusion-absorption-compressor-ejector refrigerator circuit, facilitating the exchange between the evaporator and the absorber. A compressor and an ejector, placed between the evaporator and the absorber, increase the system pressure, therefore the coefficient of performance of the refrigeration machine. MATLAB and Excel software were used to solve the system of equations. The sensitivity of the model to variations in concentration, temperature and pressure was studied and analyzed. The results of this article serve as a decision-making tool for the installation of such a refrigeration system in a cement plant, to be able to valorize the gaseous waste generated.

Keywords: Thermodynamic Performance; DAR Cycle; Ejector-Compressor; Ammonia–Water; Waste Heat Recovery; Heating System.

I. INTRODUCTION

The dwindling and increasing scarcity of fossil fuel sources are the basis of the energy transition, where renewable resources are increasingly valued. The goal is to implement systems capable of recovering energy at various temperature levels at no additional cost. In the face of this energy transition, many industrial facilities are actively exploring systems to capture and recover energy otherwise lost to the environment. They integrate different cycles, such as Kalina, Organic Rankine, Brayton, absorption diffusion cycle, etc. into the residual hot gas evacuation circuit. Let's take the example of the cement industry: the gases emitted by the chimneys generally reach an average temperature of 250 °C, which places the cement sector among the industries with the highest heat losses in the world through its exhaust gases.

Numerous studies in the literature delve into diffusion–absorption refrigeration machines, exploring their utilization with diverse energy sources. For instance, Dhindsa [1] evaluated energy sources that can power thermochemical absorption solar hybrid refrigeration systems. This study shows that the so-called renewable sources can be used to operate such types of systems. Alcantara et al. [2] developed a mathematical model to simulate the behavior of absorption coolers with $NH_3/LiNO_3$ working fluid. An additional component known as a "rectifier" is essential to purify the refrigerant before entering the condenser. Given the volatility of the absorbent (water), it evaporates alongside ammonia (refrigerant). Without the rectifier, the water condenses and accumulates inside the evaporator, leading to diminished performance. Siddique et al. [3] examined the performance of four cascade refrigeration systems, with the aim of ensuring efficient low-temperature cooling and reducing energy consumption. The objective was also to address the problem faced by conventional systems, which have difficulty in exploiting high waste heat recovery. To overcome such limitations, a Vapor Compression Refrigeration (VCR) system integrated with an ejector is combined with absorption refrigeration cycles, incorporated with a refrigerant heat exchanger. This implies superior performance, with an improvement in COP of approximately 18% and 14% compared to the conventional double-effect compression absorption cycle. Dhahi Gharir and Garousi Farshi [4] studied the thermodynamic performance of a double ejector absorption refrigeration cycle. The results of this study revealed a significant increase in COP up to 56.8%, and the exergy efficiency is improved, reaching the value of 22.5%. Khalili and Garousi Farshi [5] designed and analyzed an absorption refrigeration system, equipped with two multi-pressure ejectors, in order to improve the performance of the ARC system. The maximum coefficient of performance and exergy efficiency of the system were improved, compared to the system without ejector.

Thus, the objective of this paper is to study and examine the thermodynamic performance of the diffusion-absorption refrigeration (DAR) system, equipped with an ejector and a compressor (DAR-EC). The DAR-EC system uses residual heat from the gases leaving the cement kiln chimneys and recovered by high-performance heat exchangers to heat the ammonia solution. A comparison of the performance elements of the DAR-EC system with that of DAR from previous works [6], is discussed in the results and discussions section. The originality of this manuscript lies in the fact that the DAR-EC system is designed for low-cost high- and low-temperature heat recovery in a cement rotary kiln. Although powered by a relatively low-temperature energy source, the DAR-EC system produced acceptable efficiency, and a good coefficient of performance compared to the configuration without an ejector-compressor.

II. Materials and Methods

A. System description

This paper is devoted to the energy performance study of the DAR system, equipped with an ejector and a compressor (DAR-EC). The system receives the residual gas of 109°C, coming from the Kalina cycle cogeneration circuit, dedicated to the production of electricity. The residual gases heat the water-ammonia mixture (H_2O+NH_3), at the generator level, thus allowing the formation of the vapor phase. The paper is also devoted to the study of the comparison of the performance elements of the present model with those of the DAR system, from our previous work [6]. The DAR system introduced in the work of Mazouz et al.[7]. was modified by the integration of a compressor and an ejector, to have a diffusion absorption refrigeration machine system, equipped with an ejector and a compressor (DAR-EC). The DAR-EC system consists of a rectifier, a condenser, an absorber, an evaporator, a compressor, an ejector, two heat exchangers (gas heat exchanger GHX and solution heat exchanger SHX) and a generator designed as two externally heated coaxial tubes. The inner tube functions as a bubble pump, receiving heat indirectly from the solution circulating in the annular space, thus acting as a boiler. The heat $\dot{Q}_{gen}$ supplied to the generator facilitates the degassing of a fraction of the ammonia from the rich solution of the absorber. The resulting ammonia vapors are then purified in the rectifier by partial condensation of the remaining water vapors, the heat rejected in the rectifier being denoted $\dot{Q}_{rec}$. The nearly pure ammonia then condenses in the condenser, releasing heat $\dot{Q}_{cond}$ to the surroundings. The condensate undergoes subcooling in the gas heat exchanger before evaporating at low temperature in the evaporator, producing a useful cooling capacity $\dot{Q}_{evap}$. The gas mixture leaving the evaporator, before heading to the absorber, passes successively through the compressor and the ejector, to be able to increase the pressure and speed of the mixture, consequently the coefficient of performance (COP) of the system. At the inlet of the ejector, the gas mixture meets the weak solution coming from the generator, which is then sent to the absorber at a high speed. The exothermic absorption of ammonia in the aqueous solution is accompanied by a heat rejection $\dot{Q}_{abs}$ to the environment [7]. And the cycle begins again.

B. Absorption Working Fluids Selection

Selecting the appropriate working fluid or solution is crucial in operating a heat recovery system. The thermophysical properties of the chosen working fluid significantly influence the system's performance. Factors to consider include the rate of evaporation at the saturation point, safety considerations (harmfulness in case of accidents or leaks in the installation), and global warming potential (GWP) values. Different fluids exhibit varying characteristics in evaporation rates, safety profiles, and environmental impact, making the choice of the working fluid a pivotal aspect of system design and operation. Typically, the thermodynamic properties of working fluids are presented in diagrams. According to Cefarin [8], critical thermodynamic properties crucial for designing an absorption system include pressure, temperature, mass fraction, enthalpy, specific volume, and entropy. Various studies have employed the water–ammonia mixture in the literature due to its efficacy in the absorption machine cycle. This mixture is recognized for harnessing heat sources at low temperatures (80–200 °C). In the current study, the ternary water–ammonia–hydrogen mixture is utilized. This choice is motivated by the mixture's performance characteristics, particularly its suitability for exploiting low-temperature heat sources.

III. Modeling of DAR-EC

This section presents the physical modeling of different systems constituting the overall system. Firstly, the hypotheses used are presented, then the mathematical equations reflecting the operation of these systems are modeled. Finally, the mixing model of the fluids used is presented. The system is modeled and optimized using the M2EP (mass, energy, exergy and performance) analysis method and the particle swarm optimization algorithm.

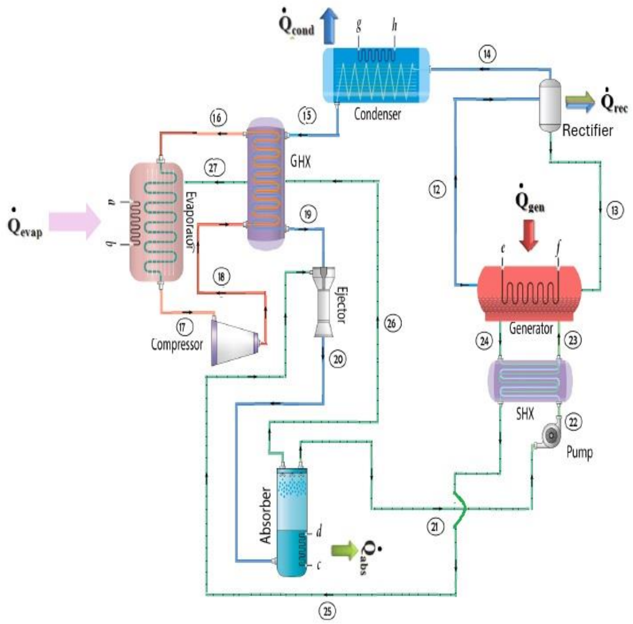

Figure 1. Scheme of DAR-EC cycle.

A. *Data of Study*

The data and operating conditions from an existing cement kiln located in Congo-Kinshasa facilitate the development and simulation of the multigeneration system. These technical and industrial data are used to simulate the system studied. Detailed information on the operating parameters of the Kalina cycle is given in [9], and that of the DAR-EC cycle is given in Table 1.

Table 1 – Operating parameters of the DAR-EC system.

Operating Parameters	**Values**
Gas temperature at generator inlet ($T_{gas\text{-}gen}$)	109.5 °C
The mass flow rate of working fluid (H_2O+NH_3)	22.32 kg/s
The mass flow rate of H_2	14.83 kg/s
Ambient temperature	30 °C
Rectifier pinch-point temperature difference	10 °C
The efficiency of the absorber	80% [10]
The efficiency of evaporator	80%
The efficiency of heat exchangers	70% [11]
The concentration of NH_3 in the mixture at the pump discharge	30% [9]
Evaporator pinch-point temperature difference	10 °C [12]
SHX efficiency	70% [11]
Efficiency of nozzle (ejector)	90% [13]

B. *Mathematical modeling*

The thermodynamic equations characterizing the multigeneration system are given in the following tables (Tables 2 and 3). These equations are based on the two main laws of thermodynamics.

Table 2 – Mass, energy, and exergy balance of multigeneration system.

Components	**Mass Balance Equations**	**Energy Balance Equations**	**Exergy Balance Equations**
DAR-EC SYSTEM			
Bubble Pump	$\dot{m}_{22}+\dot{m}_{13}=\dot{m}_{12}+\dot{m}_{23}$	$\dot{Q}_{gen}=\dot{m}_{22}h_{22}+\dot{m}_{13}h_{13}-\dot{m}_{12}h_{12}-\dot{m}_{23}h_{23}$	$\dot{Ex}_{13}+\dot{Ex}_{22}=\dot{Ex}_{12}+\dot{Ex}_{23}+\dot{Ex}_{gen}^{D}$
Rectifier	$\dot{m}_{12}=\dot{m}_{13}+\dot{m}_{14}$	$\dot{Q}_{rec}=\dot{m}_{12}h_{12}-\dot{m}_{13}h_{13}-\dot{m}_{14}h_{14}$	$\dot{Ex}_{14}+\dot{Ex}_{13}=\dot{Ex}_{12}+\dot{Ex}_{rec}^{D}$
Condenser	$\dot{m}_{14}=\dot{m}_{15}$	$\dot{Q}_{cond}=\dot{m}_{14}(h_{15}-h_{14})$	$\dot{Ex}_{15}=\dot{Ex}_{14}+\dot{Ex}_{Cond}^{D}$
GHX Exchanger	$\dot{m}_{15}=\dot{m}_{16}$ $\dot{m}_{18}=\dot{m}_{19}$ $\dot{m}_{26}=\dot{m}_{27}$	$\dot{Q}_{GHX}=\dot{m}_{15}(h_{16}-h_{15})=\dot{m}_{18}(h_{19}-h_{18})$ $=\dot{m}_{26}(h_{27}-h_{26})$	$\dot{Ex}_{15}+\dot{Ex}_{18}+\dot{Ex}_{26}$ $=\dot{Ex}_{16}+\dot{Ex}_{19}+\dot{Ex}_{27}$ $+\dot{Ex}_{GHX}^{D}$
Evaporator	$\dot{m}_{16}+\dot{m}_{27}=\dot{m}_{17}$	$\dot{Q}_{evap}=\dot{m}_{17}h_{17}-\dot{m}_{16}h_{16}-\dot{m}_{27}h_{27}$	$\dot{Ex}_{16}+\dot{Ex}_{27}=\dot{Ex}_{17}+\dot{Ex}_{evap}^{D}$
Compressor	$\dot{m}_{17}=\dot{m}_{18}$	$\dot{W}_{Comp}=\dot{m}_{17}(h_{18}-h_{17})$	$\dot{Ex}_{18}=\dot{Ex}_{17}+\dot{Ex}_{Comp}^{D}$
Ejector	$\dot{m}_{19}+\dot{m}_{25}=\dot{m}_{20}$	$\dot{Q}_{Eject}=\dot{m}_{19}h_{19}+\dot{m}_{25}h_{25}-\dot{m}_{20}h_{20}$	$\dot{Ex}_{19}+\dot{Ex}_{25}=\dot{Ex}_{20}+\dot{Ex}_{Eject}^{D}$
Absorber	$\dot{m}_{20}=\dot{m}_{26}+\dot{m}_{21}$	$\dot{Q}_{abs}=\dot{m}_{20}h_{20}-\dot{m}_{26}h_{26}-\dot{m}_{21}h_{21}$	$\dot{Ex}_{20}=\dot{Ex}_{26}+\dot{Ex}_{21}+\dot{Ex}_{abs}^{D}$
SHX Exchanger	$\dot{m}_{22}+\dot{m}_{24}=\dot{m}_{23}+\dot{m}_{25}$	$\dot{Q}_{SHX}=\dot{m}_{22}h_{22}+\dot{m}_{24}h_{24}-\dot{m}_{23}h_{23}-\dot{m}_{25}h_{25}$	$\dot{Ex}_{22}+\dot{Ex}_{24}=\dot{Ex}_{23}+\dot{Ex}_{25}+\dot{Ex}_{SHX}^{D}$
Pump	$\dot{m}_{21}=\dot{m}_{22}$	$\dot{W}_{Pump}=\dot{m}_{21}(h_{22}-h_{21})$	$\dot{Ex}_{22}=\dot{Ex}_{21}+\dot{Ex}_{Pump}^{D}$

Table 3 – Performance parameters of multigeneration system.

Components	Performance Parameters
DAR-EC SYSTEM	
COP	$COP = \frac{\dot{Q}_{evap}}{\dot{Q}_{gen} + \dot{W}_{comp} + \dot{W}_{pump}}$
Net cooling capacity	$\dot{Q}_{evap} = \dot{m}_{17}h_{17} - \dot{m}_{16}h_{16} - \dot{m}_{27}h_{27}$
Net work of the compressor	$\dot{W}_{comp} = \dot{m}_{17}\frac{h_{18s} - h_{17}}{\eta_{s\_comp}}$
Net work of the pump	$\dot{W}_{pump} = \dot{m}_{21}\frac{h_{22s} - h_{21}}{\eta_{s\_pump}}$
Isentropic efficiency of the compressor	$\eta_{s\_comp} = \frac{h_{18} - h_{17}}{h_{18s} - h_{17}}$

h_{18s} is the isentropic outlet enthalpy of compressor

Figure 2 shows the constituent elements of the ejector, namely the nozzle section, the mixing chamber and the diffusion chamber. For synthesis reasons, the characteristic equations, as well as the assumptions used for modeling the ejector, are not presented here.

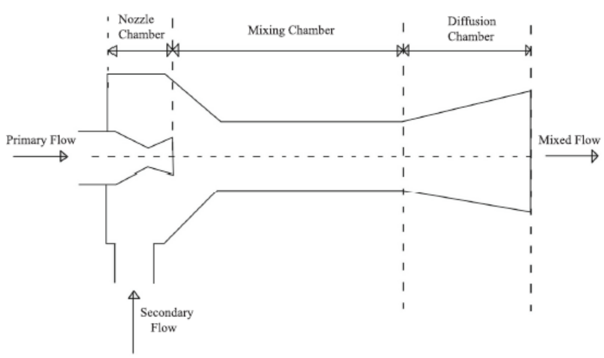

Figure 2 – Schematic diagram of the ejector [13].

IV. RESULTS AND DISCUSSIONS

A. *Thermodynamic Performance*

The thermodynamic performance of the DAR-EC cycle is primarily grounded in the two laws of thermodynamics, which articulate the quantitative conservation of energy and the qualitative degradation of energy, respectively. An energy analysis of a system involves tracking the energy supplied and released by the system. The concept of exergy balance is rooted in both the laws of thermodynamics. This article's energy performance considerations encompass the cycle performance coefficient, evaporation temperature, and cooling capacity. Other heat exchanges can also be scrutinized to assess the performance of a diffusion–absorption refrigeration, equipped with an ejector and a compressor (DAR-EC). The exergy analysis employed in this study seeks to ascertain the exergy destructions in each component of DAR-EC and identify the elements that have a significant share in the overall destroyed exergy. Utilizing the heat flux of 7368.20 kW (at 109.5 °C) rejected by the previous system (refer to Table 1) facilitated the derivation of the following results. The distribution of the different heat exchanges of the DAR-EC components is shown in Figure 3. The absorber evacuates the majority (36%), followed by the generator (31%) and the evaporator (16%). The remainder is distributed between the condenser and the rectifier.

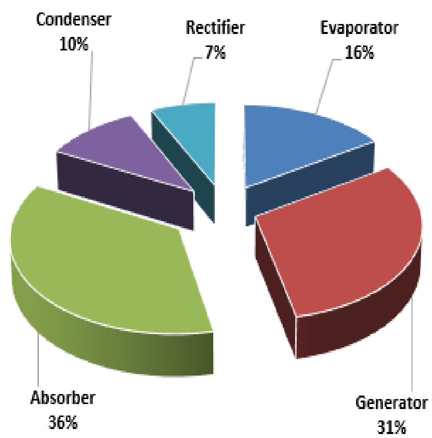

Figure 3 – Distribution of heat exchanges of DAR-EC cycle.

B. *Comparison between DAR and DAR-EC*

Table 4 compares the DAR cycle with the DAR-EC cycle. There was significantly more heat transfer at the evaporator level in the DAR-EC cycle. The COP of the DAR-EC cycle is significantly higher than that of the DAR cycle.

Table 4 – Performance parameters

Operating Parameters	DAR	DAR-EC
Heat transfer from Evaporator [kW]	6,766	12,949
Heat transfer from Condenser [kW]	8,464	8,428
Heat transfer from Absorber [kW]	26,322	29,484
Heat transfer from Generator [kW]	25,226	25,117
Heat transfer from Rectifier [kW]	5,743	5,718
Coefficient of Performance [-]	0.27	0.49

C. *Sensitivity of the DAR-EC System*

The sensitivity to pressure variations in the DAR-EC cycle system is illustrated in Figure 4 and Figure 5. The evolution of the COP with pressure variations is illustrated in Figure 4. The COP increases with pressure, between 2 and 15 Bar. Then, the specific performance decreases with increasing pressure up to 28 Bar. A peak in the COP value is observed at the pressure of 15 Bar, where the COP reaches the value of 0.556.

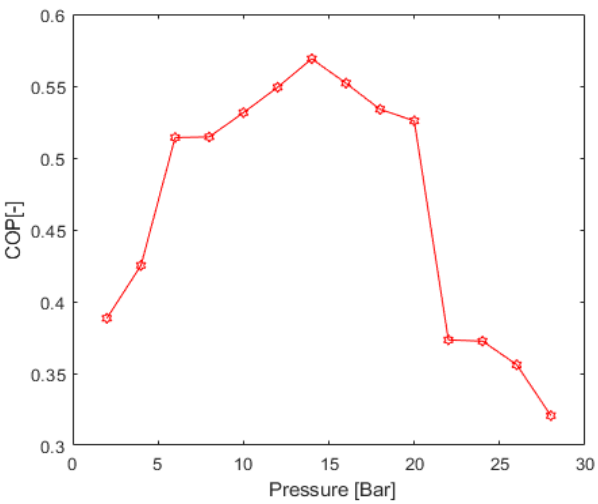

Figure 4 – Effect of pressure variation on the coefficient of performance.

In Figure 5, the cooling capacity (Qevap) increases slightly from the beginning of the pressure variation. As soon as the pressure reaches the value of approximately 4.5 bar, the Qevap increases considerably, with a peak at the pressure of 19 bar. After this point, the Qevap begins to decrease with increasing pressure.

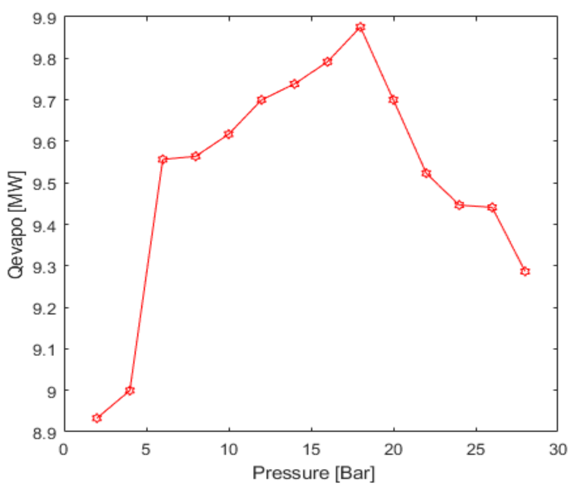

Figure 5 – Effect of pressure variation on colling capacity.

The results of this paper were compared with similar works in the literature [14,15], in order to validate the DAR cycle model. The comparison focuses on the performance and operating parameters of the installation (input and output). The results of the comparison allow the validation of this model.

V. Conclusions

In this study, the thermal performance and energy and exergy conservation in DAR-EC cycle systems using H_2O+NH_3+H_2 as working fluids, are investigated.

The compressor and ejector were added to the DAR cycle to improve its performance. These last ones are located at the evaporator outlet and the other at the absorber inlet. This led to an increase in pressure at points 18 and 19. The components of the cycle were also affected by these two added components, particularly the SHX heat exchanger. Although the DAR-EC system is located downstream of the Kalina cycle (dedicated to cogeneration), in the same heat recovery circuit, and is powered by a low-temperature heat flow, the cycle yielded very satisfactory results. The results show that the DAR-EC cycle is significantly more efficient than the DAR cycle, with a $COP_{DAR\text{-}EC}$ of 0.49. Future work will involve further enhancing the performance of the DAR-EC cycle by adjusting certain parameters.

VI. References

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