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Energy and Exergy Analysis of the Solar Membrane Distillation System for Seawater Desalination

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Abstract

Electricity–water cogeneration power plants are an important tool for advancing sustainable water treatment technologies because they provide a cost-effective and environmentally friendly solution for meeting the energy and water needs of communities. By integrating power and water production, these technologies can reduce carbon emissions and help mitigate the impact of climate change. This work deals with the energy and exergy analysis of a cogeneration plant for electrical power generation and water desalination using real operational data. The power side is a solar energy installation (flat plate collector and Photovoltaic panel), while the desalination side the system of air gap membrane distillation (AGMD). A mathematical model was implemented in MATLAB software and validated through a comparison with previously published research. The exergy analysis was carried out based on the second law of thermodynamics to evaluate the irreversibility of the plant and the subsystems. In this study, the components of the sub-systems were analyzed separately to identify and quantify the component that has a high loss of energy and exergy, and moreover, a parametric study was conducted. According to the energy and exergy analyses, the highest source of irreversibility occurs in the flat plate collector with 50% of the total exergy destruction. However, PV, AGMD, and condensers also contribute to energy loss. Further, the thermodynamic efficiency of the cogeneration plant was obtained as 51.38%, which is more effective than other systems. The obtained results from this study can be employed as a guide to reduce exergy destruction in the whole solar AGMD desalination system

Key Words*:* Solar desalination, Desalination, AGMD, Plant solar collector, Photovoltaic panel, Exergy

Analyse énergétique et exergétique du système de distillation à membrane solaire pour le dessalement de l'eau de mer

Résumé

Les centrales électriques de cogénération électricité-eau sont un outil important pour faire progresser les technologies durables de traitement de l'eau, car elles offrent une solution rentable et respectueuse de l'environnement pour répondre aux besoins en énergie et en eau des communautés. En intégrant la production d'électricité et d'eau, ces technologies peuvent réduire les émissions de carbone et contribuer à atténuer l'impact du changement climatique. Ce travail porte sur l'analyse énergétique et exergétique d'une centrale de cogénération pour la production d'électricité et le dessalement de l'eau à l'aide de données opérationnelles réelles. Le côté alimentation est une installation d'énergie solaire (capteur plan et panneau photovoltaïque), tandis que le côté dessalement est constitué d'un système de distillation par membrane à entrefer (AGMD). Un modèle mathématique a été implémenté dans le logiciel MATLAB et validé par une comparaison avec des recherches précédemment publiées. L'analyse exergétique a été réalisée sur la base de la deuxième loi de la thermodynamique pour évaluer l'irréversibilité de l'installation et des sous-systèmes. Dans cette étude, les composants des sous-systèmes ont été analysés séparément pour identifier et quantifier le composant qui présente une perte d'énergie et d'exergie élevée, et de plus, une étude paramétrique a été menée. D'après les analyses énergétiques et exergiques, la source d'irréversibilité la plus élevée se produit dans le collecteur plan avec 50 % de la destruction totale de l'exergie. Cependant, le photovoltaïque, l'AGMD et les condenseurs contribuent également à la perte d'énergie. De plus, le rendement thermodynamique de la centrale de cogénération a été obtenu à 51,38 %, ce qui est plus efficace que les autres systèmes. Les résultats obtenus de cette étude peuvent être utilisés comme guide pour réduire la destruction exergétique dans l'ensemble du système de dessalement solaire AGMD.

Mots clés : Dessalement solaire, Dessalement, AGMD, Capteur solaire végétal, Panneau photovoltaïque, Exergy.

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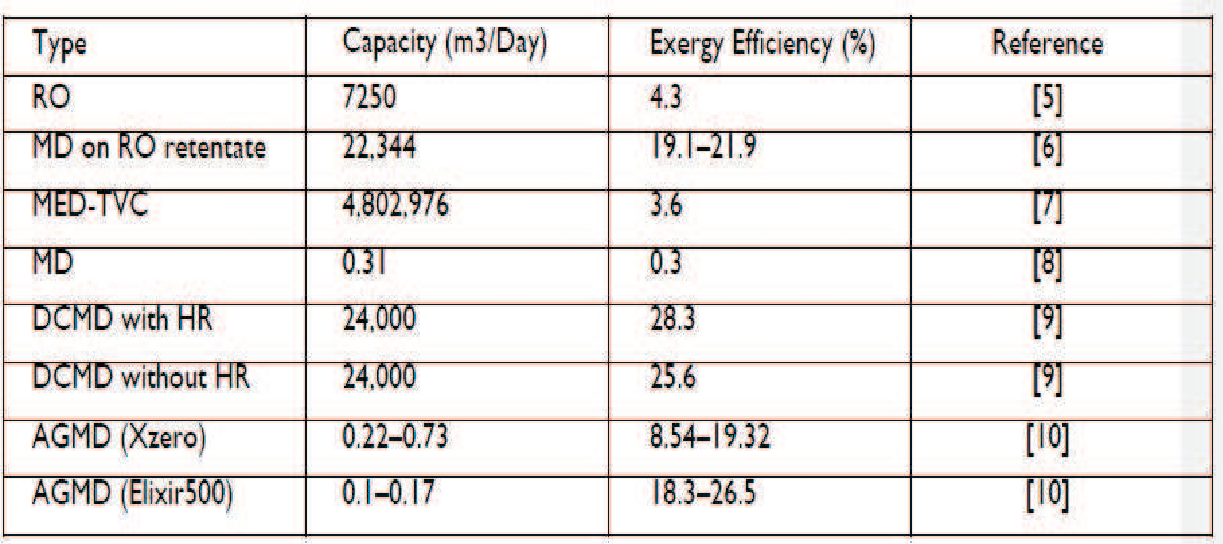
INTRODUCTION

Exergy refers to the amount of energy that is available for use within a system from a thermodynamic perspective. It represents the useful and usable portion of energy. The exergy analysis takes into consideration the quality and quantity of the energy exchange processes with the environment. This analysis helps to uncover the underlying reasons for any energy system malfunctions. Energy analysis is based on the first law of thermodynamics and is only concerned with energy conversion. It does not show how and where irreversibility or losses occur in the system. Exergy analysis goes beyond this by pointing to the association of extreme irreversibility or destruction with processes and helps identify pathways to sustainability. Unlike energy, external energy is destroyed and can only be conserved when all processes that occur in the system and its surrounding environment are reversible. Therefore, exergy is a useful tool for determining the location, type, and true magnitude of energy loss, which manifests as waste energy destruction or emission [1–2].

Table1 summarizes the values of the exergy efficiencies obtained in the most common desalination technologies. To confirm the choice of AGMD, a comparison of desalinated water production costs is presented. The energy consumption and final water production cost of desalination systems depend on the nature of the processes, the type of energy used and their drinking water production capacity. The specific energy consumption by RO isbetween 2 and 3 kWh.m−3 [3], while that of MED varies from 5 to 10.33 kWh.m−3 and14.56 kWh.m−3 for the MSF [4]. The energy consumption and water cost of DM systems vary respectively from 1 to 9000 kWh.m−3 and from 0.3 to 130 $/m3 depending on the configurations used [5]. Guillén-Burrieza et al. [6] carried out the technical and economic analysis of a 100 m3/day project for a desalination unit based on membrane distillation technology associated with a field of solar collectors. During their in-depth economic assessment, the cost of water was estimated at between 10.6 and 12 $.m−3.

Table 1. Summary of exergy efficiency for different MD configurations from the literature.



Type	Capacity (m3/Day)	Exergy Efficiency (%)	Reference
RO	7250	4.3	[5]
MD on RO retentate	22,344	19.1–21.9	[6]
MED-TVC	4,802,976	3.6	[7]
MD	0.31	0.3	[8]
DCMD with HR	24,000	28.3	[9]
DCMD without HR	24,000	25.6	[9]
AGMD (Xzero)	0.22–0.73	8.54–19.32	[10]
AGMD (Elixir500)	0.1–0.17	18.3–26.5	[10]

Accurately assessing the performance of separation systems that employ solar energy and MD relies heavily on the evaluation of exergy. The major goal of this research is to undertake a thermodynamic analysis of a desalination system using solar energy and AGMD, with an emphasis on performance parameters. The solar AGMD desalination system was modeled using MATLAB software 2013b, and a series of mathematical calculations were carried out based on previously described design parameters to assess the system's performance under varying operating conditions. The proposed system consists of an AGMD desalination unit and a solar thermal collector, and the analysis of the system is performed by examining variations in energy efficiency and exergy efficiency.

System description

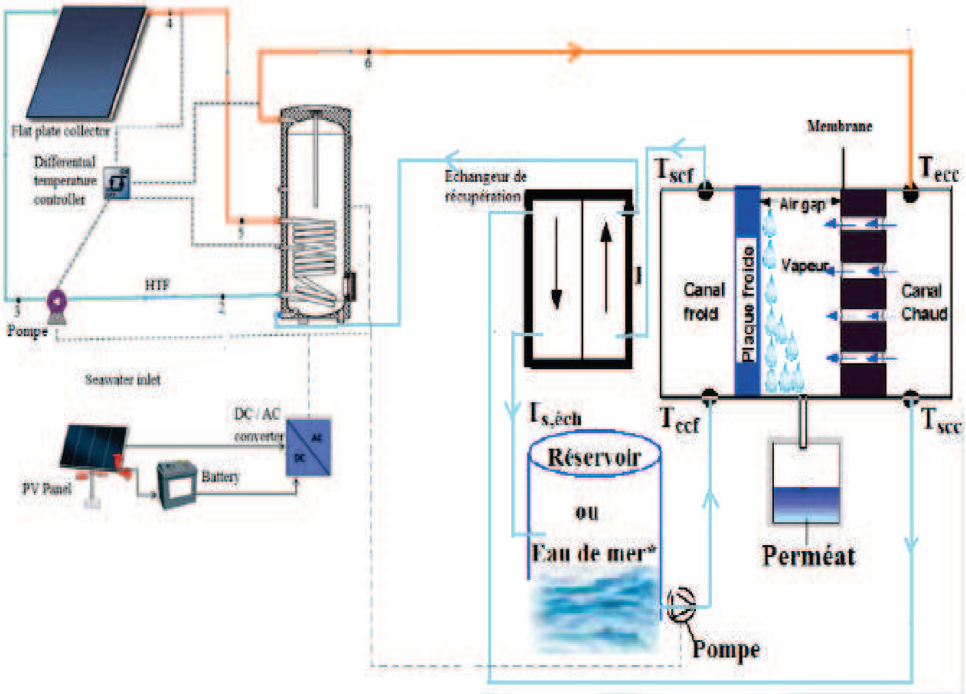


Figure 1. Schematic diagram of a SFPC-AGMD system

Figure 1 is a schematic diagram showing a process aimed at producing high-quality distilled water while conserving energy. The system is made upof a solar flat plate collector paired with an AGMDunit. The brine's heat is recovered by preheating the feed solution, and the feed temperature is maintained by a pump that circulates the solution through the AGMD unit's cold and hot channels.The combination of the flat plate collector provides the system with self-sufficiency. The solar collector utilizes sunlight to extract heat, and the absorber inside the collector converts the sun's radiation into heat. This type of installation, combining these advanced technologies, can have practical applications in sectors such as the navy, emergency medical aid, or enhancing the living conditions in remote areas.

2. Mathematical modelling

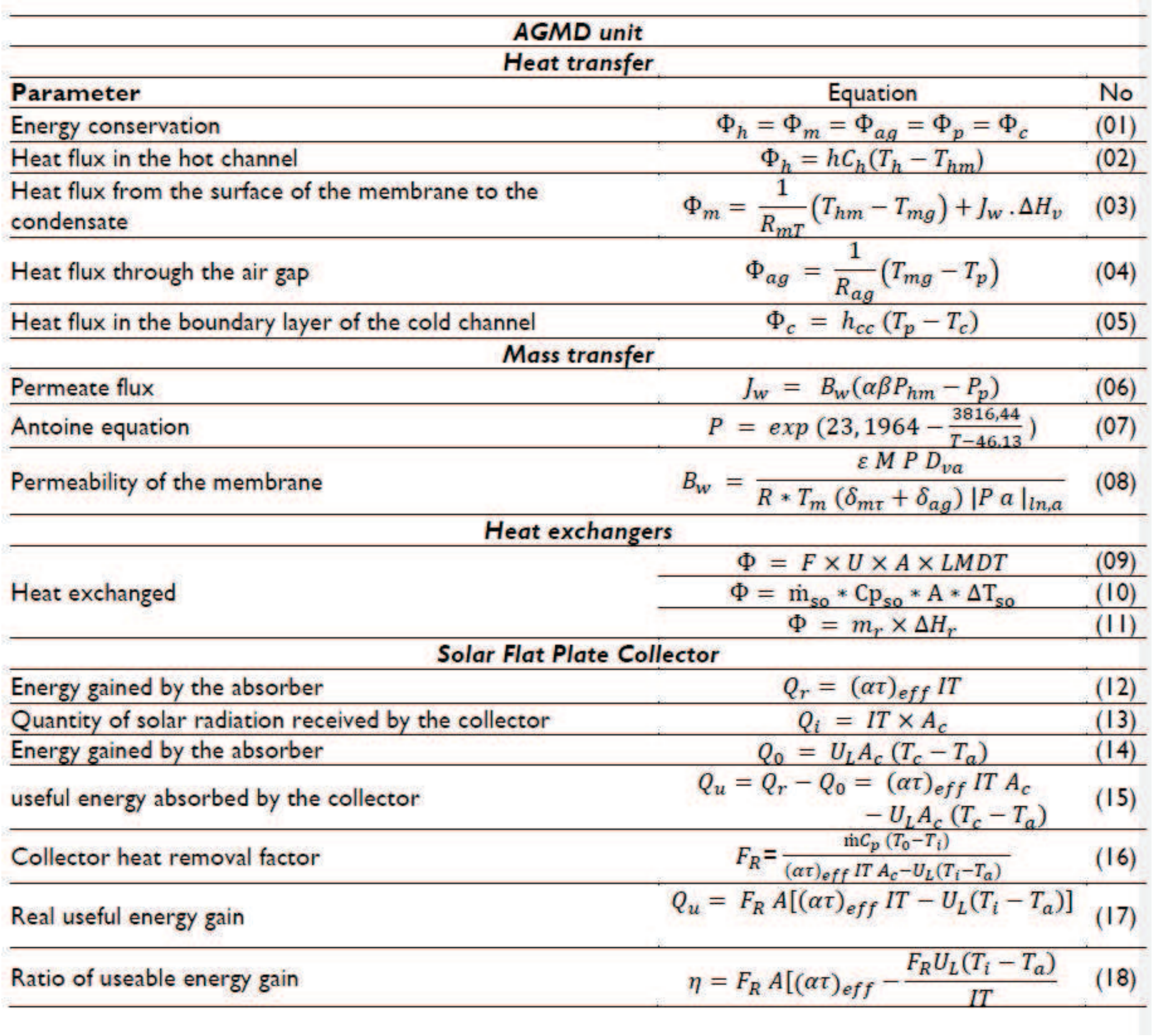
2.1. Thermodynamic Analysis

A mathematical representation of the AGMD desalination system combined with solar energy has been established utilizing the principles of the first and second laws of thermodynamics. The model incorporates equations for determining the physical characteristics of seawater and brine as well as heat transfer coefficients (Table 2).

To simplify the developed model, the following assumptions and hypotheses were considered:

- The system runs at a dynamic state throughout;
- Thermal losses have been studied;
- Kinetic and potential exergies are ignored;
- An average pump efficiency of 75% is estimated;
- Dead state properties for fluids are evaluated at T0= 25 °C and the dead state salinity X0= 35 g.kg−1.

Table2.Mathematical model equations



AGMD unit		
Heat transfer		
Parameter	Equation	No
Energy conservation	$\Phi_h = \Phi_m = \Phi_{ag} = \Phi_p = \Phi_c$	(01)
Heat flux in the hot channel	$\Phi_h = hC_h(T_h - T_{hm})$	(02)
Heat flux from the surface of the membrane to the condensate	$\Phi_m = \frac{1}{R_{mT}}(T_{hm} - T_{mg}) + J_w . \Delta H_v$	(03)
Heat flux through the air gap	$\Phi_{ag} = \frac{1}{R_{ag}}(T_{mg} - T_p)$	(04)
Heat flux in the boundary layer of the cold channel	$\Phi_c = h_{cc}(T_p - T_c)$	(05)
Mass transfer		
Permeate flux	$J_w = B_w(\alpha\beta P_{hm} - P_p)$	(06)
Antoine equation	$P = exp\,(23,1964 - \frac{3816,44}{T-46,13})$	(07)
Permeability of the membrane	$B_w = \frac{\varepsilon\, M\, P\, D_{va}}{R * T_m\,(\delta_{m\tau} + \delta_{ag})\,\lvert P\, a\,\rvert_{ln,a}}$	(08)
Heat exchangers		
Heat exchanged	$\Phi = F \times U \times A \times LMDT$	(09)
	$\Phi = \dot{m}_{so} * Cp_{so} * A * \Delta T_{so}$	(10)
	$\Phi = m_r \times \Delta H_r$	(11)
Solar Flat Plate Collector		
Energy gained by the absorber	$Q_r = (\alpha\tau)_{eff}\, IT$	(12)
Quantity of solar radiation received by the collector	$Q_i = IT \times A_c$	(13)
Energy gained by the absorber	$Q_0 = U_L A_c\,(T_c - T_a)$	(14)
useful energy absorbed by the collector	$Q_u = Q_r - Q_0 = (\alpha\tau)_{eff}\, IT\, A_c - U_L A_c\,(T_c - T_a)$	(15)
Collector heat removal factor	$F_R = \frac{\dot{m}C_p\,(T_0 - T_i)}{(\alpha\tau)_{eff}\, IT\, A_c - U_L(T_i - T_a)}$	(16)
Real useful energy gain	$Q_u = F_R\, A[(\alpha\tau)_{eff}\, IT - U_L(T_i - T_a)]$	(17)
Ratio of useable energy gain	$\eta = F_R\, A[(\alpha\tau)_{eff} - \frac{F_R U_L(T_i - T_a)}{IT}$	(18)

GOR can be mathematically represented by equation 19. For a desalination system, the Performance Ratio (PR) is defined as the ratio of distillate mass to energy input. It can be expressed by Equation 20.

$$GOR = \frac{\dot{m}_p \times \Delta h_v}{\dot{m}_{sw} \times C_{p,sw} \times (T_{h,in} - T_{h,out})} \qquad (19)$$

$$PR = \frac{\dot{m}_p}{Q_h} \qquad (20)$$

3.2. Exergy Analysis

There are four main parts to the overall energy rate: physical (Eph), chemical (Ech),kinetic (Eke), and potential (Epe). The general energy balance can be obtained by thefollowing equation:

$$\dot{E}x = \dot{E}_{ph} + \dot{E}_{ch} + \dot{E}_{ke} + \dot{E}_{pe} \qquad (21)$$

The values for both physical and chemical exergy are calculated as follows:

$$\dot{E}_{ph} = \dot{m}e_{ph} = \dot{m}[(h_s - h_0) - T_0(s_s - s_0)] \qquad (22)$$

$$\dot{E}_{ch,w} = \dot{m}e_{ch} = \dot{m}\sum\omega_k(\mu_k^s - \mu_{ok}^o) \qquad (23)$$

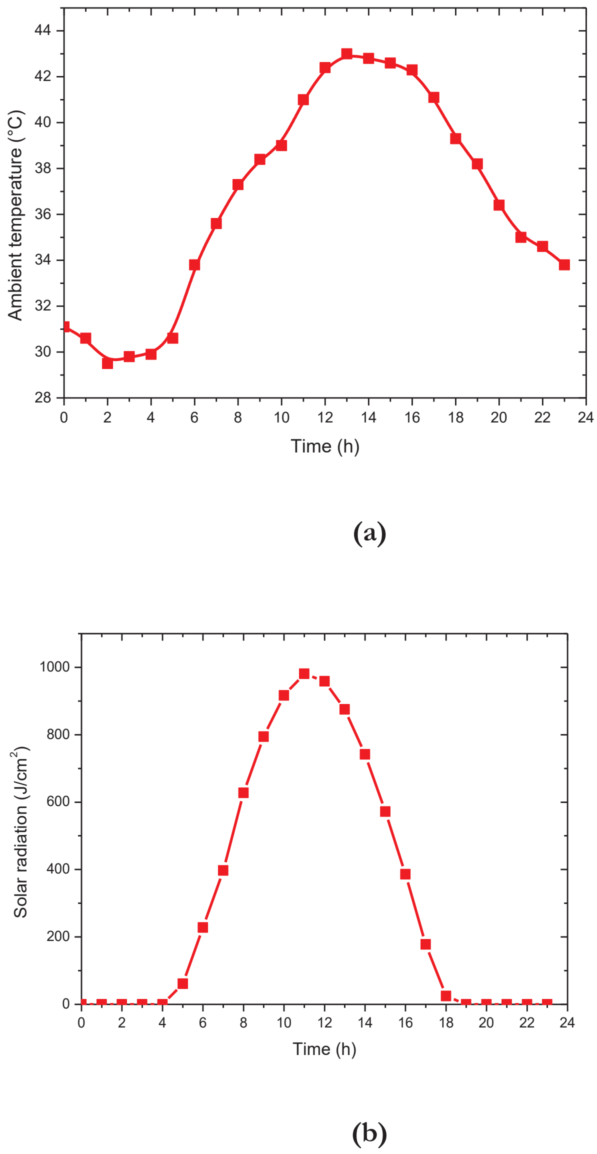
A system's exergy efficiency is the ratio between the minimum separation work and the fuel energy:

$$\eta_{ex} = \frac{\dot{W}_{min}}{\dot{E}_f} \qquad (24)$$

Minimum work to separate (W_{min}) is the energy of the product in the desalinationprocess, while fuel energy (E_f) is the thermal energy provided to the system.

3. RESULTS AND DISCUSSION

The solar radiation data utilized in this study wereobtained with high accuracy from a radiometric station located on the roof of the applied research unit for renewable energies (URAER) building in Ghardaia. Figure 2 shows the global solar irradiation evolution with daytime for the month of July. The irradiation has a bell-shaped profile that is consistent with the prediction of well-known semi-empirical models from the literature. It is also noted that the highest temperature and solar radiation values are recorded on July 21, which is the most appropriate day to be considered in the present work.



(a)

(b)

Figure 2. Environmental conditions on 21July(Ghardaïa site).

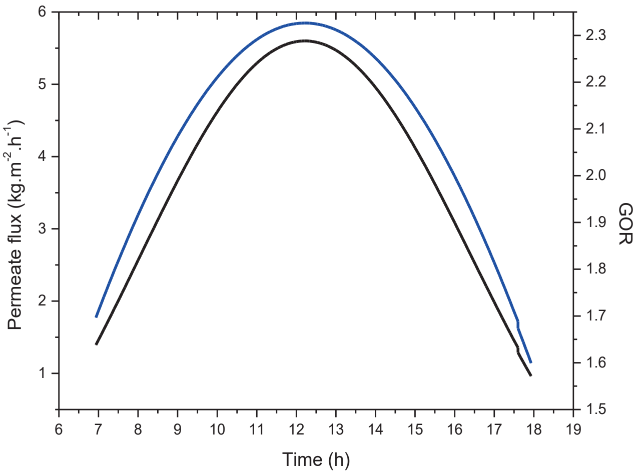


Figure3. Variation of permeate flux and GOR over the local time.

Figure 3 shows the permeate flux and GOR as a function of the local time. It can be seen that the permeate flux increases at the beginning of the day to reach about5.6 kg.m−2.h−1 at a feed temperature of 62 ◦C and a flow rate of 0.01 kg.s−1 as the maximum value is obtained at 12:00 h. The obtained results show a good agreement with the results provided in the literature. The main performance parameters for thermal desalination system evaluation are gained output ratio (GOR). The larger GOR is, the higher the thermal energy utilized efficiency is [8]. Figure 4 shows that the PR increases as the inlet temperature of the hot fluid increases in the same way as for the GOR and reaches its maximum PR = 0.98 at around 12:00 h. A high PR means that a high flow rate of distillate is obtained for a given thermal energy input. Usually, high PR can be achieved by using well-designed system components with high energy efficiency and good insulation material.

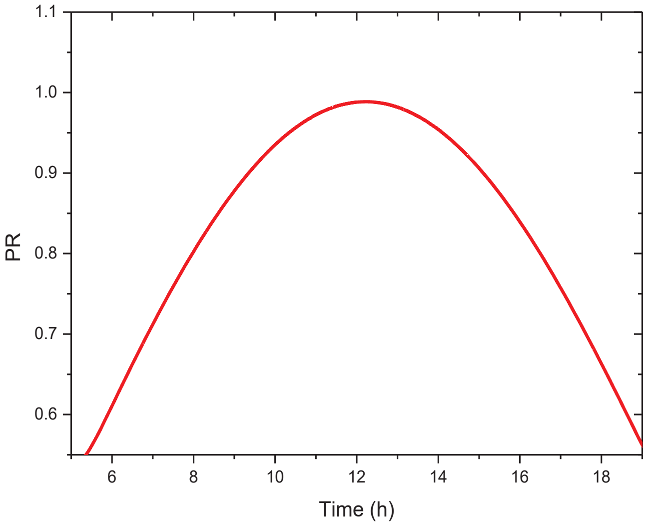


Figure 4. Variation of performance ratio over the localt ime.

To assess irreversibility in a system, the exergy analysis was conducted using the sec-ond law of thermodynamics. This later refers to the equivalent amount of mechanical work that can be produced from other forms of energy. The exergetic analysis was conducted using data from July 21, which corresponds to the day when the collector field received the. highest solar flux density. The minimum work of separation Wmin represents the productexergy in the desalination process. Figure 5 shows the minimum work of separation and.exergy efficiency of AGMDaccording to local time. The maximum value of Wmin is 0.17 kW and is recorded at 12:00 h for a feed temperature of 62 ◦C and flow rate of 2 L.min−1. Hence, low-temperature vapor could be employed to improve minimum work. The obtained values are comparable to those obtained by Miladi et al. [8], where it is revealed that the highest values for exergetic efficiency were recorded at 0.116%. Additionally, it is evident that the overall exergy efficiency calculated for the AGMD system has a maximum value of 56.3% at 12:00 h at a cold channel inlet temperature of 29.5 ◦C. However, the obtained value is similar to that reported in the literature for other AGMD, ranging between 52.1% and 55.4% for a cold channel inlet temperature Tc,in varies from 33.8 ◦C to 36.2 ◦C and for a flow rate of 2 L.min−1 [9].

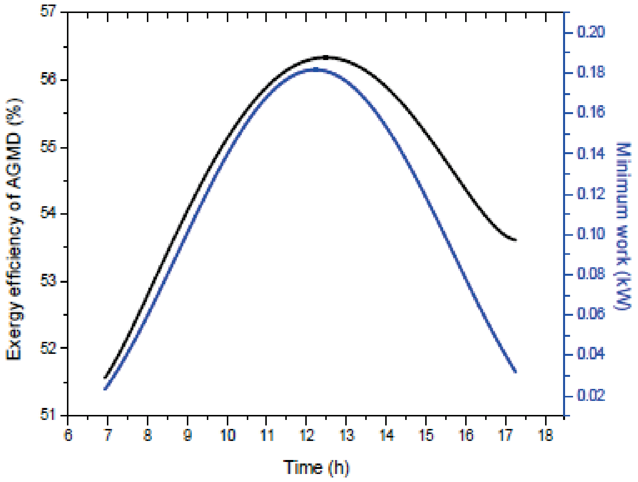


Figure 5. Variation of exergy efficiency of AGMD andthe minimum separation work with time.

Figures 6 and 7 illustrate the performance curves of the solar collectors that were tested during the study. It is important to note that the exergetic efficiency recorded was notably lower than the energy efficiency, with the highest energy yield recorded at 52% and the maximum exergy efficiency at 4.45%. Energy efficiency solely measures the quantity and does not provide a thorough evaluation of the various losses that may occur in solar collectors. The results obtained in this study are similar to those found by Banat and Jwaied [9] and Miladi et al. [10], who recorded maximum exergetic efficiency values of 6.5% and 5.03%, respectively, and maximum energetic efficiency values of 55% and 48.12%, respectively. The energy forms indicated that the solar collector field is effective from an energy perspective but not from an exergy perspective. According to the energy profile, the solar collector field is efficient from an energy viewpoint and inefficient from an exergy viewpoint. Hence, performing an exergetic analysis of other solar field elements would provide the opportunity to make decisions that are more efficient and prevent membrane degradation.

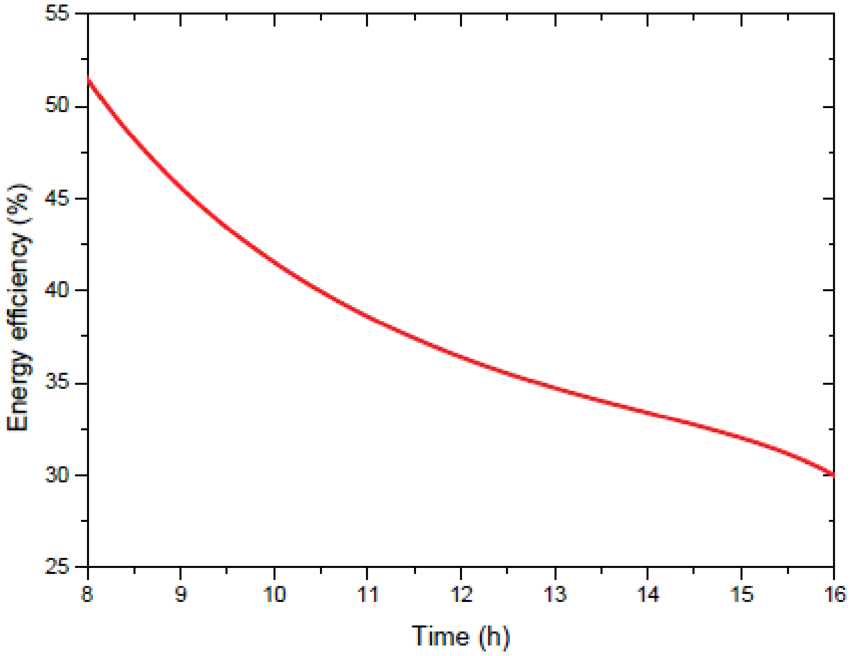


Figure 6. Variation of the collector energy efficiency variation with a solar with time.

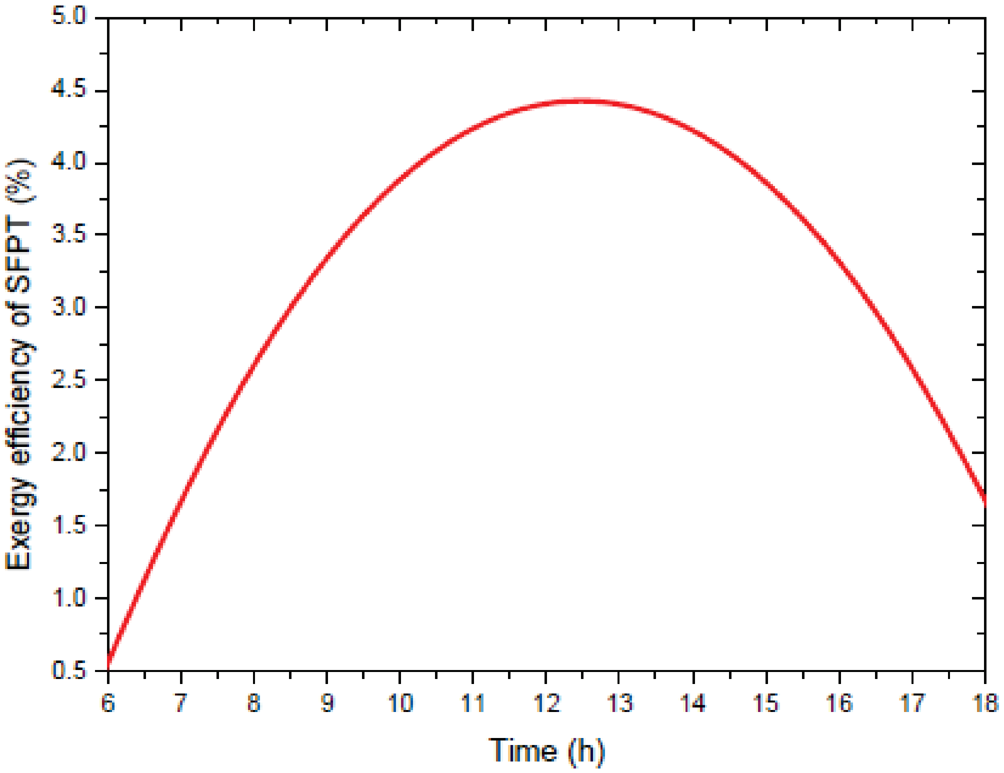


Figure 7. Variation of the collector exergy efficiency variation with a solar with time

Figure 13 displays the distribution of exergy destruction in the AGMD, heat exchanger pumps, and flat plate collector. It can be observed that the majority of the total exergy loss, 95%, takes place in the solar collectors. However, the heat exchanger is the next significant source of exergy destruction, accounting for 2.55% of the total exergy loss, while the AGMD contributes to only 1.44% ofthe total energy loss. This disparity is primarily due to the different temperature values between the flat plate collector, heat exchanger, AGMD, and pumps.

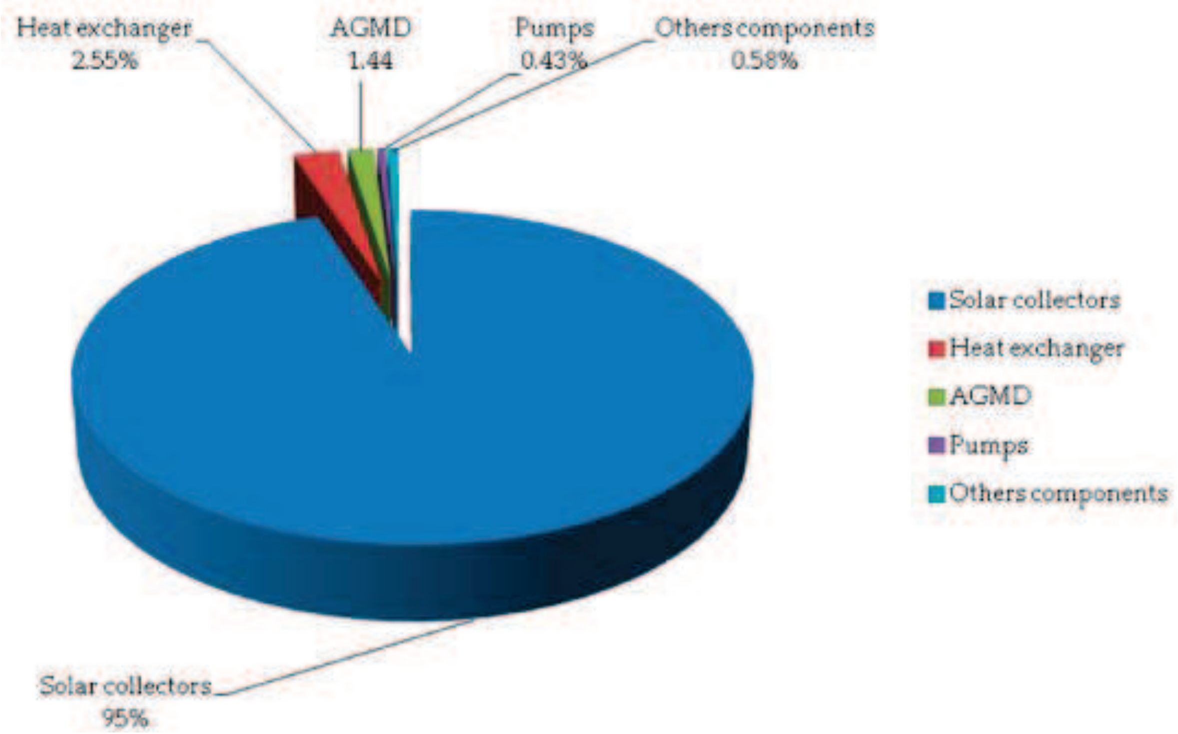


Figure 13. Rates of exergy destruction in the solar AGMD system components.

CONCLUSION

In this study, detailed energy and exergy analysis of a solar-powered AGMD sys- tem for saline water desalination in the Gherdaïa region, Algeria, was conducted. A one-dimensional dynamic model was developed to analyze the heat and mass transfer processes in the AGMD system combined with a flat plate collector in order to predict water production and flux. The model was validated using previously reported flux data and used to examine the impact of various parameters on the efficiency of the solar AGMD desalination system. In addition, both energy and exergy analyses were conducted to evaluate the overall thermodynamic behavior of the solar AGMD desalination system. The main conclusions are summarized as follows:

- The exergy efficiency for the AGMD system is found to be 56.3%, which indicates that the AGMD module of the current design is moderately efficient, and large amounts of energy can be saved. It is important to highlight that all desalination processes have very low energy efficiencies. However, what distinguishes AGMD is that it operates at a lower temperature compared to other thermal distillation processes. This facilitates its coupling with solar energy;
- The maximum exergy destruction occurs in the solar collector (95%) because of the large temperature difference between solar heat and the coolant fluid in the collector field, which results in high irreversibilities. Hence, effort should be made to reduce this exergy loss. Potential improvement of the solar collector field might be achieved by maximizing the collector's optical efficiency as well as minimizing the overall heat losses of the collector area;
- The two main sources of exergy destruction are the solar thermal collector and the desalination unit 95% of the total exergy loss is destroyed in the collector, while 2.55% of the loss of total exergy is destroyed in the heat exchanger and only 1.44% of the total exergy loss is destroyed in the desalination system;

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