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Study of a modified multiple effect distillation (MED) brackish water system for a minimal water footprint

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ABSTRACT

In this paper, a modified multiple effect distillation (MED) system will be studied for a minimal water footprint in the Algerian desert, as to preserve the aquifer and for a sustainable use of this later. In fact, the water footprint is the most important factor to take into consideration in the treatment of the brackish underground water in the Algerian desert to preserve this unique source of water. The modification of MED system consists on the change of the last water condenser of the unit for a hybrid condenser (water and air condenser). For this purpose, a MED system is studied for its high recovery ratio for brackish water treatment, its flexibility with different salt concentrations, its low thermal energy need, and its robustness. The results show that the introduction of a hybrid condenser in the system allows a minimal water footprint, which is expressed by the cooling water ratio running from 4 to 18 times less than a standard water condenser system. This new configuration is applicable for a top brine temperature ranging between 75°C to 100°C. Otherwise, for low-temperature MED, the total heat area of the system would reach twice the total heat area of a standard MED system. Finally, a nine effects standard MED system rejects six times the feed water quantity at a higher temperature than that of the aquifer's from the last condenser and 4%–10% of brine. Whereas, the modified MED system will reject only 4%–10% of the brine at the end of the process and zero cooling water, which is a satisfactory result for a sustainable exploitation of the aquifer.

Keywords: MED process; Desalination; Brackish water; Water footprint; Recovery ratio

1. Introduction

The water scarcity problem is nowadays a huge part of the environmental crisis. Population and economic growth including industry and agriculture, increase water demand on earth, meanwhile, the freshwater sources are limited to 2.5% of available water and just 30% of this last are ground and surface sources [1]. That is why there is a need to provide fresh water from the remaining water sources. For this purpose, desalination technologies have been implemented in different parts of the world, mainly in North Africa and in the Middle East, where there is

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about 50% of the global installed desalination capacity [2,3]. These regions have also the highest rates in the world of depletion of water resources [2].

Generally, desalination plants are situated in the coastal areas to provide the huge freshwater demand of the big cities. However, many other non-coastal regions of the world, desert regions, for instance, face freshwater scarcity problem and need desalination to treat their limited brackish water source. Although desalination is considered as a solution for water scarcity, it could present potential negative impacts on the environment.

To purify the salty water and make it potable a great amount of energy is needed. Using conventional energy sources as fossil fuels to power desalination plants will accentuate the climate change crisis and greenhouse gas emissions. In order to overcome the freshwater scarcity crisis without increasing the energy and climate change crisis, renewable energy sources are a favorable alternative to replace conventional fossil fuel energy sources. But not all desalination processes or energy supply systems from renewable sources or their combinations may be feasible technically and/or economically for all locations [4].

Thus, even if desalination is an appropriate solution to the freshwater shortage crisis, many economic factors, and environmental impacts command the feasibility of this solution. The economic factor is usually the most important parameter to take into account for desalination plant choice, but the water footprint of the desalination plant on the region's water source is also a crucial factor, as well as, the characteristics of the studied region.

In Algeria, desalination has gone through two steps: first, it was only used for the industrial sector, and then it has been used for the population needs of freshwater.

In the 2000s, 13 coastal desalination plants using reverse osmosis technology with a total capacity of 2,260,000 m^3 have been implemented, [5]. The RO technology is the most used process for desalination in Algeria, however, solar thermal desalination technologies are only studied for small scale projects of desalination.

Kehal [6] presents the perspective and evolution of the water resources and desalination in Algeria. The author presents also, the first solar desalination unit in Algeria, which is located in the desert for brackish groundwater desalination.

Saadi and Kehal [7] said that solar desalination would be a suitable combination to provide fresh water without using conventional energies in the Algerian desert. Bouchekima [8] provides an experimental investigation on the distillation performance of the solar stills working with brackish water in the south of Algeria. He concludes that this system can provide an economical and practical solution to satisfy the drinking water demand for remote arid areas. Tigrine et al. [9] worked on the reverse osmosis desalination process in the coastal region powered by photovoltaic solar energy. Abdeslame Dehmas et al. [10] studied the feasibility of wind energy powering reverse osmosis in the coastal area, and Triki et al. [11] studied the feasibility of a standalone wind energy system to power brackish water reverse osmosis desalination unit in the Algerian desert.

Diaf et al. [12] provide outdoor/indoor performance analysis of a new multiple ray solar distillation system and he concludes that solar distillation is a viable and competitive solution to treat brackish water in remote areas.

The studied region concerns the Algerian desert characterized by an arid climate with almost no rain except a few days per year with very low annual precipitations [13–15]. To support the population, agriculture, and industry water demand, this region relies on the only source of water which is the Albian aquifer. However, the Albian aquifer contains brackish water with different levels of salt from one well to another. In 2007 Kedaid [16] published the salinity map of the Albian aquifer (Fig. 1). The salinity level of the aquifer is slightly increasing each year mainly because of the high level of pumping which is more than the aquifer recharge since the 70's [17]. Due to overuse, the salinity increases rapidly since it is estimated to be between 2 and 6 g/L in 2015 [13,14]. On the other hand, the chemical characteristics of this aquifer are higher than the limits of potable drinking water fixed by the World Health Organization. This could lead to several health problems, especially with long term consumption. Furthermore, it is noted in the Sahara and Sahel Observatory studies that a lot of agricultural lands are destroyed because of the saline water used for irrigation. In addition to that, an important decrease in agricultural production, (even for palm trees), is noted [15].

Therefore, the treatment of this brackish water seems to be unavoidable for this region. Not to forget that the salinity level of the aquifer is increasing each year.

This source of water needs to be protected to ensure survival in this region, protected from overexploitation, pollution, and an increase of salinity level. Also, the studied region suffers from a weak electricity network and possesses a high solar potential. That is why the thermal process is more suitable for powering a desalination system.

The studied region lacks in qualified workers, thus it is more suitable to use a desalination process that needs less qualified staff.

So, the objective of this research is to provide a desalination system for brackish water treatment with a minimal water footprint and a minimal impact on the environment to preserve the aquifer while coming up with a solution to water scarcity, for this specific region.

The desalination technology selected for this study takes into account different parameters: the water footprint, the

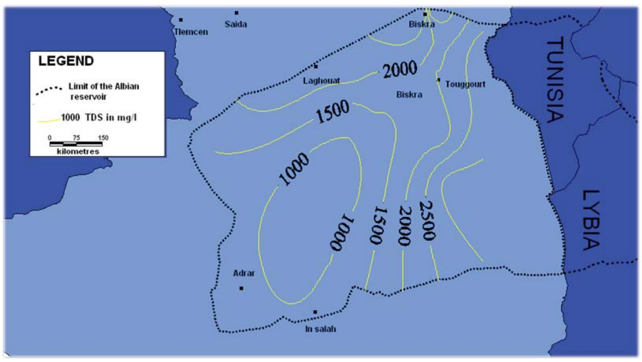

Fig. 1. Distribution of total dissolved solid concentrations (TDS) in well waters from the Albian [16].

water salinity variability, the roughness, and the simplicity of the process the type of energy used by the desalination technology, and the available renewable energy. According to ecological concern, the most important ones are the water footprint and the use of renewable energy.

Thus, we propose to use multiple effect distillation (MED) technology to treat brackish groundwater. This choice has been made for several reasons listed below.

- MED technology is flexible regarding salt concentration variation.
- MED technology has a higher recovery rate which leads to minimal water footprint.
- MED can be directly coupled to solar thermal energy or waste thermal energy.
- MED needs less maintenance and doesn't need high qualifications.

The choice of MED was made for its very high recovery and the availability of solar energy in the studied region (Algerian desert). Its ability to use directly the solar thermal energy, which will minimize dependency on water-intensive power sources [3], especially in this region where the electrical network is weak.

In the studied region, the brackish water has very diverse and variable levels of salinity and components, which makes the use of MED more favorable.

MED process powered by solar energy showed good results treating brackish underground water and agriculture drainage water according to Stuber et al. [3]. More details about MED advantages in treating brackish water are discussed by Stuber et al. [3].

At the end, the robustness and flexibility of MED for treating sources with fluctuating salinity and its application with a directly driven thermal source such as solar thermal energy make MED the ideal candidate for our case study.

Thermal desalination processes, including MED process, share the fact that they generate thermal pollution in the ecosystem, by rejecting a brine at high salinity and temperature, and by rejecting a big amount of heated water from the last condenser.

To overcome this enviromental issue, the desalination process should reach a high recovery rate, which is possible with low salinity feed water, and should reduce or eliminate the rejected heated water from the last condenser.

To keep the desalination system simple and with easy monitoring, we modified the last condenser of a standard MED process to an hybrid (water and air) condenser, where the cooling water amount is reduced to be equal to the feedwater. This amount of water (feedwater) could not condensate all the vapor of the last effect, that's why the remaining vapor from the water condenser will be directed to the air condenser to finish the condensation.

This modification will allow a total elimination of the rejected hot water from the last condenser.

In this paper different parameters were compared for both configuration MED-water condenser and MED-hybrid condenser. to evaluate performances of both systems, we have taken into consideration the number of effects, the impact of the top brine temperature (TBT) on the area of heat exchangers, the cooling water ratio, the Gain output ratio GOR, and the recovery ratio according to the feed water salinity.

2. MED process description

Multi-effect distillation is a process, which relies on a phase change to separate water from salt by evaporation. The salty water is heated in an evaporator with an external heat source, which could be liquid, or steam, taken from a special boiler, a power generation turbine, a thermal solar system, or a waste energy source. The salty water is heated to its boiling point which depends on the level of salt in the water and the pressure inside the evaporator, then a part of it is evaporated and the separation of the water from the salt is done, to get the desalinated water at the end, the generated vapor is condensed in a condenser. To avoid the scaling and tube corrosion problems which lead to a reduction of the heat transfer efficiency and the lifetime of the components, the generated vapor is transported to the condenser through a demister to stop brine droplets mixing with the generated vapor and the final product [18].

The condenser has two purposes in this process, condensate the generated vapor to produce a desalinated water, and preheats the feedwater of the evaporator. The cooling water in the condenser removes the excess heat of the generated vapor that was added to it in the evaporator by the heat source, the supplied heat to the evaporator is transferred from the heat source to the generated vapor, this transfer degrades its quality, which means that the evaporator does not consume all the supplied heat. From an energy point of view, the biggest losses occur in the condenser, because just a part of the cooling water will be sent to the evaporator as feedwater, and the remaining cooling water is discharged back to its source with the heat removed from the generated vapor [18].

In a single effect evaporation system, the mass of water produced is less than the mass of the heating steam used to operate the system. This rate in the thermal desalination technologies is defined as the performance heat ratio which is less than 1 for this system. Regarding this low heat performance, the single effect evaporator system has no practical use on an industrial scale [19].

In order to improve the heat performance ratio, several effects (evaporators) are connected in series to use the energy supplied to the first effect to generate vapor as many times as possible, this gives a place to a multi-effect distillation plant MED. That means, the higher the number of effects, the higher the heat performance ratio is. But for some technical limitations, the number of effects is limited in real applications. These limitations are due to the temperature difference between the first effect condensing temperature and the condensing temperature at the final condenser. The first effect temperature is limited by calcium sulfate scaling conditions to 120°C as top brine temperature, and the last condenser temperature is limited to the cooling water temperature source (seawater or other sources) [20]. In addition, the typical temperature difference between effects for the MED system is in the range of 1.5°C–2.5°C [18]. Between these two hot and cold temperatures, the number of effects is chosen regarding the design production rate, the required performance ratio, and the economic impact of the capital cost which increases with the number of effects [20].

The MED unit can be configurated in different ways regarding the direction of the feed water and the generated vapor from one effect to the other. In this case, there are three types of possible arrangements, the forward feed arrangement the most used one where the feedwater and the generated vapor flow in the same direction, its advantage is that the least salinity is at the high temperature in the first effect. The parallel feed arrangement and the backward feed arrangement which is rarely used in desalination for the big risk of scaling since the first effect have the highest temperature and salinity. The choice of the best configuration depends on the operation conditions [21].

Also, there are two ways to connect the effects together, in the first one the effects are connected horizontally. This configuration is the most used at a large scale capacity unit because of its stability and simplicity in operation and maintenance. In the second one, the effects are connected vertically [20].

To reach a higher thermal performance ratio, the MED unit can be combined with a mechanical vapor compressor (MVC), to a thermal vapor compressor (TVC), and an absorption and adsorption heat pump (ABHP, ADHP). The most used combination is the MED-TVC for its simplicity and efficiency, even if the MED-ABHP and MED-ADHP show better efficiency than the MED-TVC but it is still at a laboratory scale [12].

In this study, a simple MED multi-effect distillation system is considered instead of the MED-TVC or MED-HP system because the two latter require a high thermodynamic source to operate.

The MED configuration considered is presented in Fig. 2. The system has n number of effects (evaporators) in series, n–1 feed water preheaters, a final condenser, and a vacuum system.

Effects and feedwater preheaters are numbered 1 to n and 1 to n–1, respectively. The supply of water ($\dot{m}_f$) flows from effect 1 to n. In the first effect, an external heat source with ($\dot{m}_s$) mass flow is used to evaporate part of the feed water ($\dot{m}_f$). The generated steam ($\dot{m}_{bv}$) then flows to the next effect acting as a heat source releasing its latent heat during condensation. However, the steam generated raises the temperature of the feed water inside the first preheater by ΔT before moving to the second effect. The remaining supply water ($\dot{m}_{B,1}$) from the first effect flows to the next and will be evaporated by flash ($\dot{m}_{fv}$) due to the low pressure which decreases from one effect to another to reduce the temperature of boiling point and allow boiling at a temperature lower than the previous effect by boiling ($\dot{m}_{bv}$) due to the heat exchanges with the steam generated from the first effect. This operation continues until the final condenser where all the vapor generated by the last effect is condensed. Part of the cooling water ($\dot{m}_c$) will be used as feed water ($\dot{m}_f$) and will flow through the preheaters from n–1 to 1 before injection in the first effect. The remaining cooling water will be rejected ($\dot{m}_c - \dot{m}_f$). The brine is discharged from the last effect ($\dot{m}_B$), and distilled water from all effects ($\dot{m}_D$) is collected and from the condenser except for the first effect.

3. Mathematical modeling of MED unit

The mathematical model used in this study is a simple model developed by Darwish et al. [21]. This model includes the basic thermodynamic laws, heat transfer equations, and thermodynamic relations, and the most important phenomena of the process.

To simplify the analysis and model, the following assumptions were taking into account:

- Steady-state operation
- Same temperature differences between effects and preheaters
- Equal generated vapor by boiling in each effect
- Constant specific heat C for brine and feed water
- Constant latent heat
- Formed vapor are salt-free
- Energy losses to the surrounding are negligible

The model is used to generate the following data:

- Brine and distillate flow rate distribution
- Salt concentration distribution
- Heat transfer area
- Feed water flows rates
- Heat source flows rates
- Cooling water flow rate
- Gain output ratio, the performance ratio, and other characteristics rates of the MED unit.

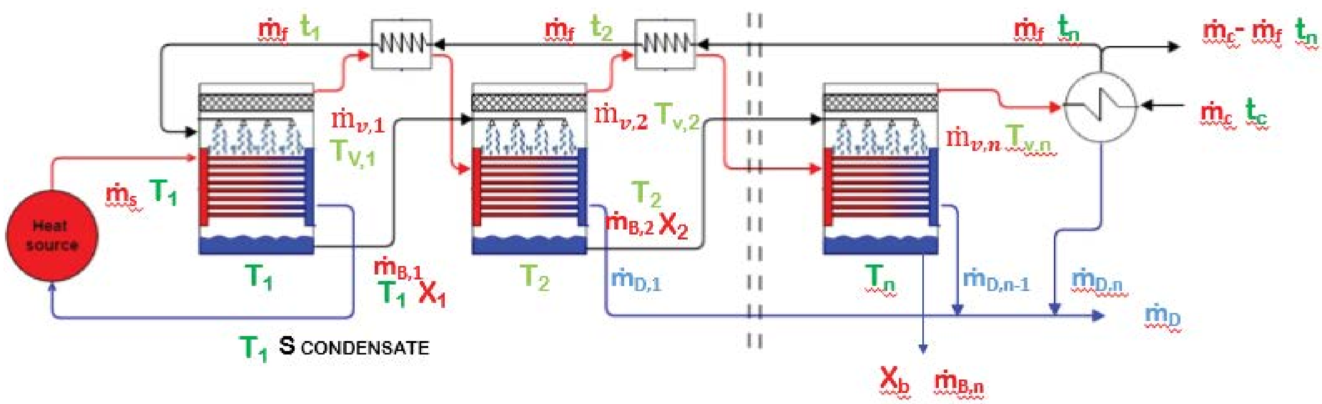

Fig. 2. MED unit scheme.

- Input data to the modeling, such as the salinity of the feed water, the mass flow rate of the produced water, the temperature of the cooling source, and the temperature of the heat source are given in Table 1.

The mass balance for all the MED unit under steady-state assumes that the feedwater flow rate is equal to the sum of the distillate water ($\dot{m}_D$) and the rejected brine ($\dot{m}_B$):

$$\dot{m}_f = \dot{m}_B + \dot{m}_D \tag{1}$$

The salt concentration balance for this equation:

$$X_f \dot{m}_f = X_B \dot{m}_B + X_D \dot{m}_D \tag{2}$$

ith $X_D = 0$ produced water is free of salt.

From Eqs. (1) and (2), the feedwater flow rate needed for a known distillate water capacity is given by:

$$\dot{m}_f = \dot{m}_D \left(\frac{X_B}{X_B - X_f} \right) \tag{3}$$

where X_f is known from the feed water quality data and X_B is limited by the temperature of the last effect in the forward feed configuration according to the solubility diagram of the calcium sulfate [22]. The temperature difference between effects ΔT and pre-heaters $\Delta T'$ are given by:

$$\Delta T = \frac{\text{TBT} - T_n}{n - 1} \tag{4}$$

where TBT is the top brine temperature in the first effect and T_n is the temperature of the last effect.

The temperature distribution inside effects and pre-heaters are calculated respectively by the following equations:

$$T_{i+1} = T_i - \Delta T \tag{5}$$

$$T'_{i+1} = T'_i - \Delta T' \tag{6}$$

3.1. Preheaters equations

In all the preheaters, the same amount of vapor from the previous effect ($\dot{m}_{v,I}$, $T_{v,i}$) is condensed to heat the feed water from T'_{i+1} to T'_i using the released heat by condensation, this fraction is equal to $y\,\dot{m}_f$.

The equations for all preheaters are mathematically similar:

Table 1
Input data

Feedwater salinity	X_f	4 g/L
Produced water mass flow	$\dot{m}_D$	57.8 kg/s
Cooling source temperature	T_c	25°C
Top brine temperature	TBT	from 65°C to 100°C

- Energy balance:

$$y\,\dot{m}_f L = \dot{m}_f C_p \Delta T \tag{7}$$

where y is calculated by:

$$y = C\,\frac{\Delta T}{L} \tag{8}$$

- Heat transfer equation:

$$Q_{\text{ph},i} = A_{\text{ph},i} U\,\text{LMTD}_{\text{ph}} = \dot{m}_f C_p \Delta T \tag{9}$$

where LMTD is the log mean temperature difference method is given by:

$$\text{LMTD}_{\text{ph}} = \frac{\left(T_{v,i} - T'_{i+1}\right) - \left(T_{v,i} - T'_i\right)}{\ln\left(T_{v,i} - T'_{i+1}\right) / \left(T_{v,i} - T'_i\right)} \tag{10}$$

As described before the behavior of the effects is the same except for the first one, that is why the equations used for the first effect are not the same as the others.

First effect:

- Mass balance:

$$\dot{m}_f = \dot{m}_{B,1} + \dot{m}_{\text{bv},1} \tag{11}$$

- Salt balance:

$$X_f \dot{m}_f = X_{B,1} \dot{m}_{B,1} \tag{12}$$

- Energy balance:

$$\dot{m}_{\text{bv},1} L = \dot{m}_s L - \dot{m}_f C_p \left(T_1 - T'_1\right) \tag{13}$$

- Heat transfer equation:

$$Q_s = A_{\text{eff},1} U \left(\Delta T - \text{BPE}\right) = \dot{m}_s L \tag{14}$$

In the first effect, distilled water is not produced and vapor is generated just by boiling because the feedwater temperature is below the saturation temperature of the effect.

Effects from 2 to n:

- Mass balance:

$$\dot{m}_{f,i} = \dot{m}_{B,i} + \dot{m}_{v,i} \tag{15}$$

Where $\dot{m}_{f,i} = \dot{m}_{B,i-1}$ and $\dot{m}_{v,i} = \dot{m}_{\text{bv},i} + \dot{m}_{\text{fv},i}$

And $\dot{m}_{\text{fv},i} = y\,\dot{m}_{B,i-1}$

- Salt balance:

$$X_{B,i} \dot{m}_{B,i} = X_{B,i-1} \dot{m}_{B,i-1} \tag{16}$$

- Heat transfer equation:

$$Q_{\text{eff}} = A_{\text{eff}} U\left(\Delta T - \text{BPE}\right) = \dot{m}_{\text{bv}} L \tag{17}$$

where $\dot{m}_{\text{bv}}$ is the vapor generated by boiling and it is the same for all the effects.

$$\dot{m}_{\text{bv}} = \beta \dot{m}_D \quad \text{and} \quad \beta = \left(\frac{1}{1-\left(1-y\right)^n} - \frac{\dot{m}_f}{\dot{m}_D}\right) y \tag{18}$$

The demonstration is given in Darwish et al. [21] paper.

3.2. Condensers

To condense the vapor generated by the last effect, a final condenser is used. The latter is a water condenser which we replaced by a hybrid composed of a water condenser connected in series with an air condenser (Fig. 3). The simulated results for the two cases were compared and discussed.

3.2.1. Water condenser

For the case where the water condenser is used, the following equations were used for energy balance and heat transfer.

$$\dot{m}_{v,n} L = \dot{m}_c C_p \left(T'_n - T'_c\right) \tag{19}$$

$$Q_c = A_c U \,\text{LMTD}_c = \dot{m}_c C_p \left(T'_n - T'_c\right) \tag{20}$$

Where LMTD_c is the log mean temperature difference of the condenser:

$$\text{LMTD}_c = \frac{\left(T_{v,n} - T'_c\right) - \left(T_{v,n} - T'_n\right)}{\ln\left(T_{v,n} - T'_c\right) / \left(T_{v,n} - T'_n\right)} \tag{21}$$

3.2.2. Hybrid condenser

For the hybrid condenser, the generated vapor from the last effect $\dot{m}_{v,n}$ passes through the water condenser in order to raise the cooling water temperature from t_c to $t_{n'}$, which is equal to the feedwater mass flow and the remaining vapor is condensed in the air condenser, hybrid condenser consists on water condenser, and air condenser. The same equations are used for the hybrid condenser except for some changes (Fig. 3).

In the water condenser, the mass flow of cooling water is equal to the mass flow of the feed water of the unit, and the outlet temperature from the condenser t_n is higher than the normal condenser, due to the fact that this temperature is fixed according to the air condenser temperature, thus, the difference of temperature between inlet and outlet water temperature of the water condenser is bigger.

In the air condenser the specific heat capacity, C_p, and the cooling temperature (ambient air temperature) are changed.

4. Results and discussion

Performance and unit characteristics of both MED-water condenser and MED-Hybrid condenser configurations are analyzed within the same operating conditions. The number of effects was fixed according to the lowest input top brine temperature which is 65°C as it is shown in Fig. 3. The parametric study will reveal the variation of many parameters according to the top brine temperature. This will include the following unit parameters:

- Specific heat transfers area of effects, preheaters, and condenser
- Specific cooling water flows rate of the condenser
- Specific steam heat source flows rate
- Cooling water ratio
- Gain output ratio (GOR)
- Recovery ratio.

4.1. Optimization of the effect number

Fig. 4 shows the limitation of the number of effects for the two configurations according to the temperature difference between two consecutive effects which is considered as 2°C.

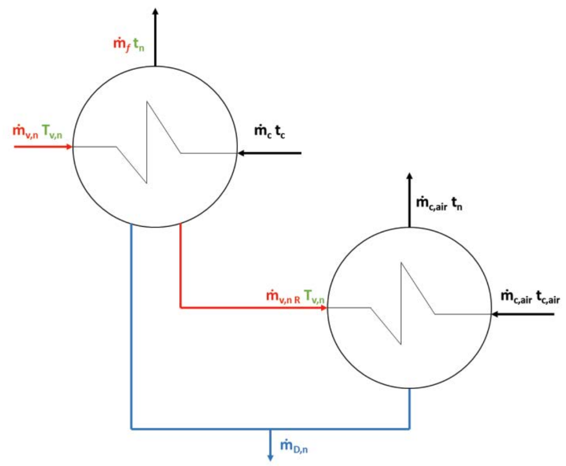

Fig. 3. Hybrid condenser.

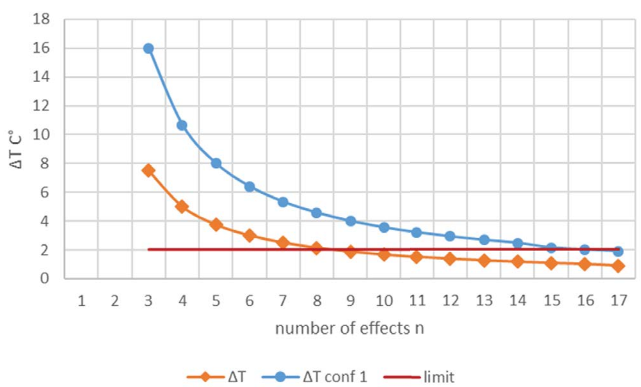

Fig. 4. Limit of the effects number on the MED water condenser configuration and the MED-hybrid condenser.

As it appears in the Fig. 4, the MED-hybrid condenser is more limited than the MED-water condenser in terms of effect extension, where the configuration with the hybrid condenser is limited to nine effects instead of 17 effects for the water condenser configuration. This is due to the temperature difference between the heat source and the last effect which is limited regarding the cooling fluid temperature and the type of the last condenser.

In this case, the limitation of the number of effects is due to:

- Temperature of the last effect, higher for the hybrid condenser (air + water), than for the standard condenser (water)
- Ambient air temperature which is higher than the temperature of the cooling water
- Type of condenser because the temperature difference between the inlet and the outlet of the air condenser must be at least 20°C instead of 10°C in a water condenser

Therefore, the parametric study will be applied for nine effects for both configurations.

4.2. Effect of the top brine temperature on the MED unit

In this part, we will check the influence of the top brine temperature on the different parameters of the MED units for both standard water condenser and hybrid condenser.

Fig. 5 represents the variation of the total heat exchange area according to the top brine temperature. We notice that the more the top brine temperature increases the more the size of the MED unit decrease for both configurations. Also, a really important result of this variation is that the difference in the size unit between the two configurations decreases drastically with the enhancement of the top brine temperature. This means that for a hybrid condenser configuration, the top brine temperature must be as high as possible to reduce the heat area difference and make this configuration practicable. We notice that from 75°C the total heat transfer area of the hybrid MED system equals the total heat transfer area of the standard MED system almost at 65°C. By reaching 100°C this one is 50% smaller than the standard MED at 65°C. The variation of the heat exchange area in the last condenser is presented in Fig. 6.

As we can see the size of the last condenser in the hybrid configuration is smaller than the standard configuration, which was unexpected, regarding the heat capacity of the air. But the fact that in the hybrid configuration we have a water condenser with an important Δt temperature difference, this one will condense a bigger part of the vapor and the rest of the vapor will be condensed in the air condenser which explains this result.

Fig. 7 displays the aim of the transformation made in the last condenser. It presents the difference in the cooling water mass flow for the two configurations.

As we can see in the hybrid condenser, the cooling water mass flow represents the feed water of the unit, instead of in the standard configuration, where an important part of this cooling water at a higher temperature will be rejected from the unit to the aquifer. This graph shows the importance of a hybrid condenser for the arid non-costal area. We notice that for the same amount of clean water produced we need 10 times less cooling water mass flow in the last condenser of the hybrid system, with zero rejection of water from this last condenser, compared to the standard MED system.

The two next figures will show the impact of the top brine temperature and the hybrid configuration from an energetic point of view.

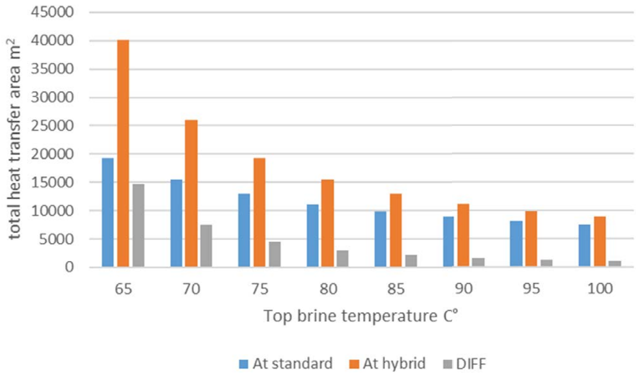

Fig. 5. Variation of total heat transfer area regarding the top brine temperature for both configurations.

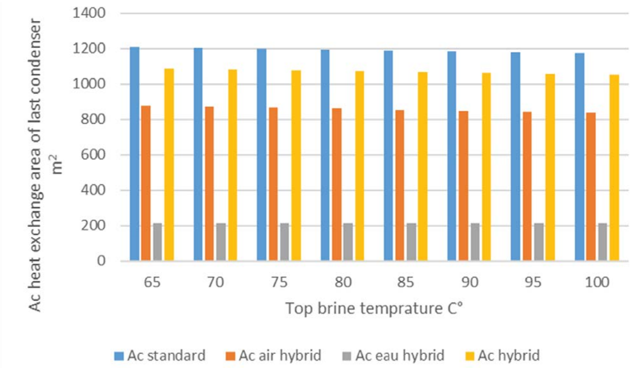

Fig. 6. Variation of the heat exchange area of the last condenser for both configurations.

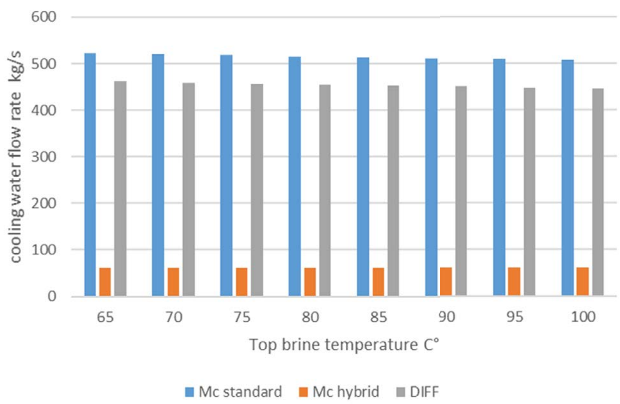

Fig. 7. Variation of the cooling water mass flow for both configurations.

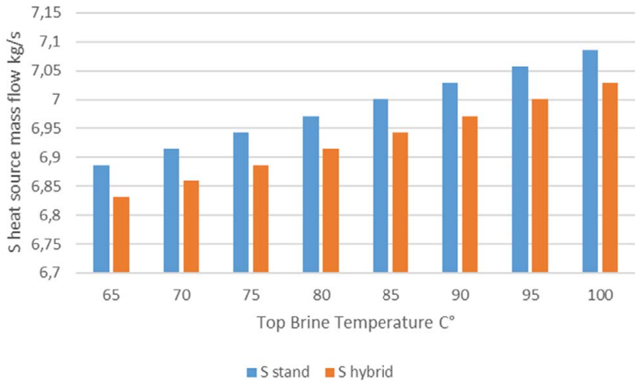

Fig. 8. Heat source mass flow variation regarding the top brine temperature for both configurations.

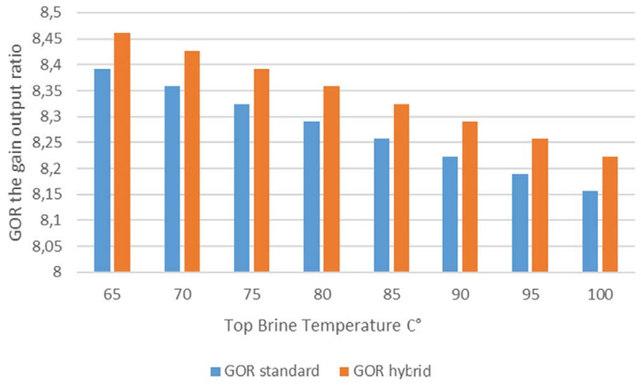

Fig. 9. Gain output ratio variation regarding the top brine temperature for both configurations.

In Fig. 8, we notice the rise of the heat source mass flow with the top brine temperature, which is logical, but the heat source mass flow for the hybrid condenser is lower than for the standard condenser. However, this augmentation of heat source mass flow remains small (from 6.9 to 7.1 kg/s).

Fig. 9 is about the gain output ratio of the unit, obviously. The GOR will decrease with the top brine temperature enhancement because of the increase of the heat source mass flow while the feedwater mass flow stays constant, and the GOR is the ratio of these two. Here again, the decrease of the GOR remains small (from 8.4 to 8.15).

To show clearly the water footprint of the type of final condenser Fig. 10 presents the ratio of the cooling water to the produced water by the unit. This ratio for the MED-hybrid condenser is constant and equal to 1.043, the water footprint for this configuration is the lowest. However, for the MED-water condenser, this ratio could reach more than 18 times for a desalination unit of three effects, which means that the cooling water mass flow is 18 times higher than the produced water. Indeed, the increase in the number of effects in the desalination unit leads to a reduction in the ratio. But even at a high number of effects, the ratio is still important, as it reaches 4–14 effects. This means that at least four times more water should be pumped in each location to treat the actual water consumption, and this will have an important environmental, energetic, and economic impact. Also, the water rejected from the last condenser of the last effect in the standard MED system into the aquifer at a higher temperature will have an important negative impact on this latter.

Fig. 11 shows the recovery ratio variation with the salinity level of the feed water. The recovery ratio of the desalination unit is a very important parameter. It gives the amount of brine rejected from the feed water used. The rejected brine from the desalination units has a big environmental impact, and its treatment needs additional financial charges and leads to a higher water cost. To reduce the impact of the rejected brine the recovery ratio should be as high as possible.

The recovery ratio of the desalination unit depends only on the salinity balance of the unit, which means from the feedwater salinity, which is set from the water characteristics, and from the rejected brine salinity, which is fixed from the thermodynamic solubility graph and depends on temperature. It is clear that the recovery ratio decreases with the increase of the water salinity, where more than 95% is reached at 3 g/L of feedwater salinity, with a limited rejected brine salinity of 70 g/L. The MED unit recovery ratio is 80% with a feedwater salinity of 14 g/L, which gives the possibility to treat the subsurface agricultural drainage water that has a variable salinity level during the year. The treatment of this water is very important to reduce the impact of water pumping on the aquifer by reducing the agricultural

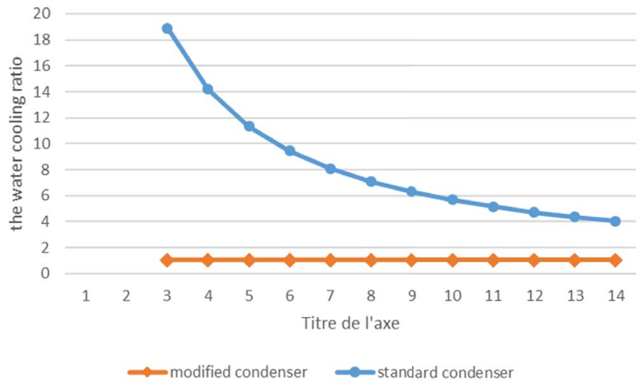

Fig. 10. Variation cooling water ratio with the number of effects.

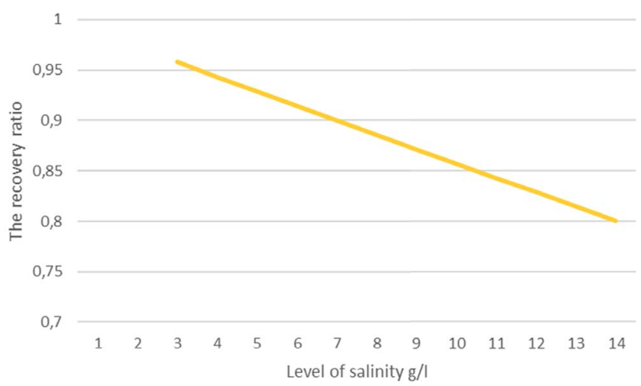

Fig. 11. Recovery ratio variation regarding the level of water salinity.

water consumption which is around 70% of the total water consumption of the region.

5. Conclusion

In this study, we propose a multi-effect distillation system for brackish underground water in the Algerian desert with a minimum water footprint, to preserve the aquifer.

This process was selected according to its qualities regarding its resistance to salinity variation its high recovery rate its ability to be directly coupled to solar energy and its easy maintenance. But to reach a minimal water footprint with this process, the rejected water from the last condenser had to be reduced.

Therefore, we have introduced a modification in the last condenser that eliminates totally the rejected water. This modification consists on the introduction of a hybrid condenser instead of the water condenser.

After the different parametric analyses, it comes out as a first result, that with the hybrid condenser the problem of water footprint has been eliminated as we have no rejected water. Nevertheless, to make this modification operational in terms of size effects, the temperature has to be higher than 75°C. However, this temperature can easily be reached through solar energy system in the Algerian desert.

Besides, the MED system can reach a very high recovery ratio for low salinity brackish water, where it is estimated at 95% for a feedwater of 3 g/L, and 80% for a feedwater of 14 g/L.

Also for the same amount of clean water produced we need 10 times less cooling water mass flow in the last condenser of the hybrid system, with zero rejection of water from this last condenser, compared to the standard MED system. These results show that the modification of the MED system can bring a solution to the water salinity with a minimum water footprint, which has an important impact on the sustainability of the aquifer and thus preserve the region ecosystem.

Symbols

A	—	Area, m^2
C_p	—	Specific heat capacity, kJ/kg K
L	—	Latent heat, kJ/kg
TBT	—	Top brine temperature in the first effect, °C
T_i	—	Temperature of the *i* effect, °C
T_n	—	Temperature of the last effect, °C
U	—	Heta exchange coefficient, kW/m^2 K
$\dot{m}_B$	—	Flow rate of distillate water, kg/s
$\dot{m}_D$	—	Flow rate of rejected brine, kg/s
$\dot{m}_f$	—	Feedwater flow rate, kg/s
X_B	—	Salt concentration of distillate water, ppm
X_D	—	Salt concentration of rejected brine, ppm
X_f	—	Salt concentration of feed water, ppm

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