OPTIMIZATION OF THE NUMBER OF EFFECTS IN THE DESALINATION PLANTS FOR MULTIPLE EFFECTS

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By a thermodynamic approach, we determined the thermodynamic parameters characterizing the performances of the multiple effects system of desalination plant: ratios of brine and pure water recovery, salinity, energy, exergy, according to the provided necessary energy per unit of treated salt water mass. Thus, the model suggested in this present article allows, not only to arise all the characteristics common to the processes of desalination for multiple effects generally, but also to identify, for one kilogram of introduced salt water, the production in each effect, according to the provided energy, and the number of effects.

Keywords: ecology of water resources, optimization, energy, exergy

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Introduction

An increase in population, a rural migration to cities, an increase in industrial demand, are independent factors of an increase in water requirements. Fresh water natural resources are no long driving sufficient, because more than 98 % of the earth resources have a too high content salt. The desalination of water thus becomes absolutely necessary and cannot be circumvented in order to dispose of sufficient quantities of consumable drinking water or for needs for irrigation or even for industries.

In Senegal in particular, this water deficit is now a critical national problem. Several projects were born in to yield fresh water by the localities far away from the big cities. It was proposed to exploit the brackish water (drilling, well, desalination…). Thus, the Laboratory of Applied Energy (LEA) of the Polytechnic University (ESP) of Dakar centred its research on the desalination of brackish water of the Saloum islands.

Let us note however that the majority of desalination techniques are to be met very high capital costs as well as his high running costs. These constraints push

developing countries into adopting with their economic reach. Consequently the major question which emerges is as follows:
How to manage the adopting of a powerful technique of desalination based on the use of easily accessible energy?
With respect to this problem, solar energy, an inexhaustible source, becomes a real candidate. In spite of the availability of this energy source, it is necessary to reduce the losses of energy in order to increase the output of the solar desalination plants. The increase in the output of these installations contributes to the reduction not only of their size, but also to decrease necessary size of solar collector to ensure the operation of desalination. Our study will be divided into two parts.
In the first part of this article, we will quantify with precision, the losses of energy by a second law analysis of multiple effect installations. Indeed, Spiegler and El Sayed [1], Yunus [2] have come to the obvious conclusion that, if the desalination process were to be fully reversible, the cost would be enormous since a plant of infinite size would be needed; an impossible endeavour. It follows that the only way process is to minimize the losses, thereby requiring a second law approach.
The exergetic analysis makes it possible to evaluate quantitatively and qualitatively the degree of degradation of energy, related to the thermodynamic irreversibilities, i.e. to correctly quantify the losses in the systems. Ali Mr. El Nashar and Atef Al Baghadi [3] presented a system of desalination for 18 effects laid in two parallel series of 9 effects. The exergetic losses in the installation were carefully highlighted. However, the gain output of the multiple effects process, the object of their article, was not approached. In the present work we were particularly interested in the losses generated in the system, when the number of effects and the quantity of provided energy vary. In all the study the results are in term of normalized 1 kg of treated salt water, i.e. all the characteristics are expressed per unit of introduced salt water mass.

The second part of this article presents a quantitative analysis of the production of water of installations for multiple effects, on the basis of the equations of steady state thermodynamics, applied to the various components of the total system. It is possible to consider not only the quantity of water being obtained and the water rejections, but also to have further information on the energy behavior of these processes, when one introduces into the system one kilogram of brackish water. As for the first part of the study, all the analysis was made according to the quantity of provided energy (basic variable of the study) and of the number of effects (principal parameter of the study).

Schematic description of the multi effect desalination

The system is presented Fig. 1.
In this description we consider the following notation: A_i for the effect A_i and $V_{4a_i\text{-}3a_i+1}$ for the valve located between items 4 and 3 of A_i effect.
Brackish water passing throw the P_1 pump, enters the various heaters (r_n, r_2,…r_1) in succession and arrives in the evaporator at a temperature close to that of saturation at the point 3_{a_1}. Because of energy provided by the $Ech_{11\text{-}12}$ exchanger, and of the vacuum which reigns in the tank (A_1), water passes in a state of a liquid-vapour mixture at the point 5_{a_1}. The vapour heat is incoming feed water at the point 6_{a_1} before reaching in the second evaporator by the point 7_{a_1}. This makes it possible to vaporize salt water of the second effect, i.e. the brine of the first outgoing effect of the valve between 4_{a_1} and 3_{a_2}. At the point 9_{a_1} pure water is extracted. The same process continues until the last effect where the vaporized fluid reaches the feed water in component r_n, before entering the condenser. After complete condensation of the vapour, the pure water is extracted by the pump $P_{ep}(n)$ and brackish water is extracted as at point 10 by the P_{sa} pump.

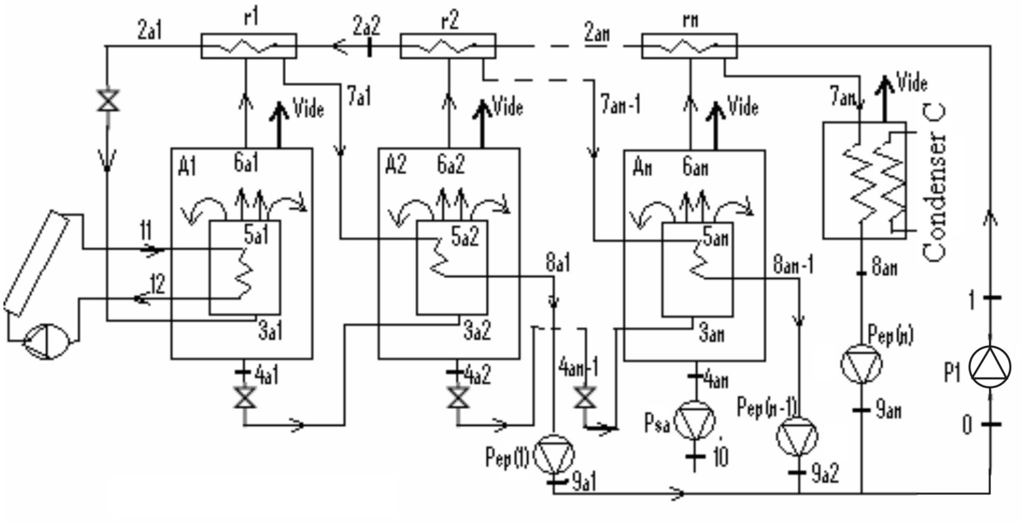

Fig. 1. *Presentation of a system of desalination to multiple effects*

Exergy analysis

Hypotheses

Leading causes of creation of entropy [4, 5] at the origin of the exergetic losses of importance in this work are:

a. The generation of entropy due to heat transfer between the various fluids of the system (evaporators, heaters, condenser, flows of water);

b. The generation of entropy in an isenthalpic relaxation due to the passage through the valves;

c. The generation of entropy due to viscous dissipation (neglected);

d. The generation of entropy due to thermal losses by conductivity (neglected);

e. Variations of kinetic and potential energy (neglected).

Mathematical model

Taking into account the assumptions quoted above (3.1), the exergy mass [6, 7] expresses itself as follows:

$$ex = h - T_0 s \tag{1}$$

The exergetic balance in steady state [7], in its general formulation is expressed as:

$$\Delta[q_m ex]_{ec} = W' - Ex'_q - Ex'_{\det} \tag{2}$$

With W' – mechanical power provided to the system, expressed in *W*, Ex'_q – exergetic flow provided to the system, expressed in *W*.

The enthalpy of the various points was calculated with the influence of the presence of salt [8, 9]. Equations (1) and (2) applied to all the components of the installation give the results of Table 1.

Table 1

Loss of exergy in the various components and flows of water

Expression of the exergetic losses due to the heat transfers		
Evaporator of effect 1 ($Ex_{\det a_1}$)	$Ex_{\det a_1} = \left(\dfrac{T_0}{T_{sat\,a_1}} - \dfrac{T_0}{\varepsilon_{11/12}\left(T_{11} - T_{sat\,a_1}\right)} \ln\left(\dfrac{T_{11}}{T_{12}}\right) \right) q_{11/12}$	(3)
Evaporator of an effect *i* ($Ex_{\det a_i}$ $2 : i : n$)	$Ex_{\det a_i} = \left[\dfrac{T_0}{T_{sat\,a_i}} - \dfrac{T_0}{T_{sat\,a_{i-1}}} \right] \left(h_{6a_{i-1}} - h_{7a_{i-1}}\right) \prod_{i=2}^{n} x_{a_i}\left(1 - x_{a_{i-1}}\right)$ (avec pour $i = n$ alors $T_{2an+1} = T_1$)	(4)
Heater r_i ($Ex_{\det r_i}$)	$Ex_{\det r_i} = T_0 Cp \ln\left(\dfrac{T_{2a_i}}{T_{2a_{i+1}}}\right) - \left(\dfrac{T_0}{T_{sat\,a_i}}\right)\left(h_{7a_i} - h_{6a_i}\right) \prod_{i=1}^{n} x_{a_i}\left(1 - x_{a_{i-1}}\right)$	(5)
Condenser *C* ($Ex_{\det C}$)	$Ex_{\det C} = \left[-\dfrac{T_0}{T_{sat\,a_i}} + \dfrac{T_0}{\varepsilon_{ref}\left(T_{sat\,a_i} - T_{e\,ref}\right)} \ln\left(\dfrac{T_{s\,ref}}{T_{e\,ref}}\right) \right] q_{ref}$	(6)
The expression of the exergetic losses in the flows of water		
Feed water ($Ex_{\det 1}$)	$Ex_{\det 1} = \left[\left(h_1 - h_0\right) - T_0\left(s_1 - s_0\right) \right]$	(7)
Pure water ($Ex_{\det 9a_i}$)	$Ex_{\det 9a_i} = \prod_{i=1}^{n} x_{a_i}\left(1 - x_{a_{i-1}}\right) \prod_{i=1}^{n} \left(h_{9a_i} - h_0\right) - T_0\left(s_{9a_i} - s_0\right)$	(8)
Brackish water ($Ex_{\det 9sa}$)	$Ex_{\det sa} = \prod_{i=1}^{n} \left(1 - x_{a_i}\right) \left[\left(h_{10} - h_0\right) - T_0\left(s_{10} - s_0\right) \right]$	(9)
The expression of the exergetic losses in the valves		
Valve $V_{2a_1/3a_1}$ ($Ex_{\det(V2a_1/3a_1)}$)	$Ex_{\det(V_{2a_1/3a_1})} = \dfrac{T_0}{T_{sat\,a_1}} \left(\dfrac{p_1 - p_{sat\,a_1}}{\rho} \right)$	(10)
Valve $V_{4a_i/3a_i+1}$ ($Ex_{\det V_{4a_i}}$)	$Ex_{\det V_{4a_i}} = \left[T_0\left(s_{3a_{i+1}} - s_{4a_i}\right) \right] \prod_{i=1}^{n-1} \left(1 - x_i\right)$	(11)

Energy loss results

Conditions of simulation

The equations presented in Table 1, were solved by matrix inversion with the Matlab software. As explained above, all the results are expressed per unit mass of salt.

In order to avoid the problems of building up salt on the components of the installation resulting from the highly salinities at high temperatures [10-12] processes of desalination is carried out at low pressure and low temperature. In any case the provision of energy at high temperature from solar prediction is expensive so this also drives us to use low temperatures and pressures. Thus the conditions of simulation are the following ones:

– Initial temperature of water (T_1) is 20 °C;

– Initial salinity of water (s_1) is of 1 %;

– Ambient temperature (T_0) 28 °C, s_0 entropy of the air with 28 °C, atmospheric pressure, h_0 is the corresponding enthalpy;

– Effectiveness of the heaters is 0.85;

– Temperatures of saturation of the various effects are: 75, 70, 65, 60, 55, 50, 45, 40, 35 °C.

The number of effects is an input to the program as is the heat input from the solar collector.

The variable of entry is the quantity of heat provided per unit of treated salt water mass ($q_{11/12}$).

Presentation of the results

Legend of the first part of the study:

	effect 1		effect 6
	effect 2		effect 7
	effect 3		effect 8
	effect 4		effect 9
	effect 5		

The results of this study relate to various systems, energy of the simple effect (1 effect) to a system comprising 9 effects.

Fig. 2 presents the exergetic losses in the evaporators of the various effects according to the provided energy per unit of treated salt water mass ($q_{11/12}$).

With the first effect, the exergetic losses are due to the transfer of heat between the coolant of the heating circuit and salt water. For the other effects, these losses are due to the transfer of heat between the steams resulting from the effect (A_{i-1}) and salt water of the effect (A_i) also coming from the effect (A_{i-1}).

We note that these losses are proportional to the quantity of exchanged energy. What results not only in an increasing linearity of the curves representing these exergetic losses according to introduced energy, but also in the change of pace starting from the maximum values. It is explained by the progressive reduction of the quantity of salt water introduced into the various cells caused by the increase in the production of vapor.

The maximum exergy destroyed between the first and the last effect ranges between 35 and 5 kJ/kg of treated salt water.

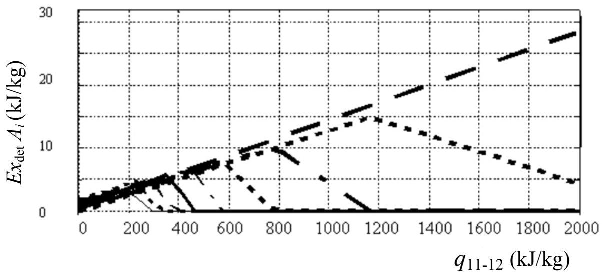

Fig. 2. *Exergy destroyed in the evaporators of the various effects*

Fig. 3 represents the exergy destroyed at the time of the passage through the valves of brine extraction, according to the provided energy per unit of treated salt water mass ($q_{11/12}$). The exergy destroyed in the valves of extraction has a maximum value at the beginning of the process because of the flows introduced into these components (quantity of brine) which start from a maximum value and decrease gradually with the increase in concerned energy. We also note that the speed of waning of these losses increases with the number of effects.

The maximum exergy destroyed between the first and the last effect ranges between 18.5 and 13 kJ/kg of treated salt water.

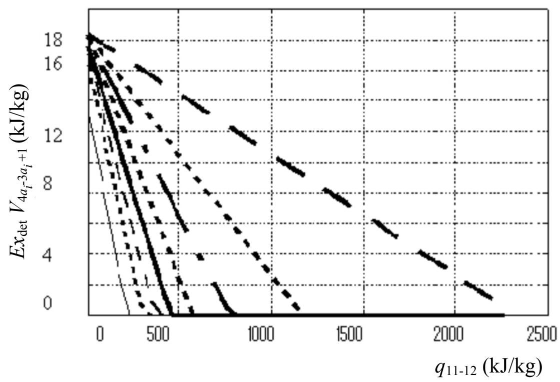

Fig. 3. *Exergy destroyed through the valves of brine extraction*

Fig. 4 makes it possible to evaluate the exergetic losses in the pure water flow by taking as reference the ambient conditions, according to the provided energy per unit of treated salt water mass ($q_{11/12}$).

These losses fall generally with the number of effects i.e. when the variation of temperature with the external medium decreases.

This figure also presents maximum values corresponding to vapor titles equal to 1 in the various effects. Consequently, the quantity of water (brine) introduced into the various effects, in connection with the quantity of produced vapor, decreases continuously when this one increases, until reaching a zero value.

The maximum values between the first and the last effect are between 60 and less than 4 kJ/kg of treated salt water.

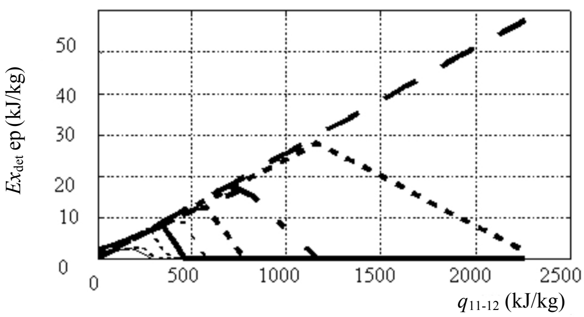

Fig. 4. *Exergetic losses during the flow of pure water*

Fig. 5 shows the exergetic losses in the brine rejections, according to the provided energy per unit of treated salt water mass ($q_{11/12}$). Like for the valves of brine extraction (Fig. 3), this Fig. 5 presents maximum values at the beginning of the operation which decrease in a linear way until reaching a zero value.
The maximum values between the first and the last effect range between 14 and 58 kJ/kg of treated salt water.

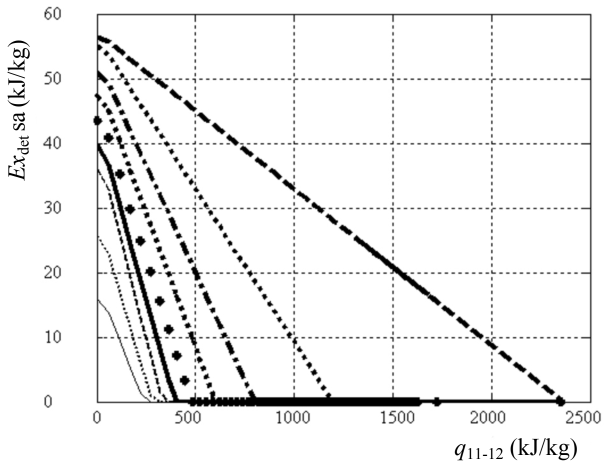

Fig. 5. *Exergetic losses of the rejections of the brine*

Fig. 6 presents the exergetic losses of the condenser according to the provided energy per unit of treated salt water mass ($q_{11/12}$).

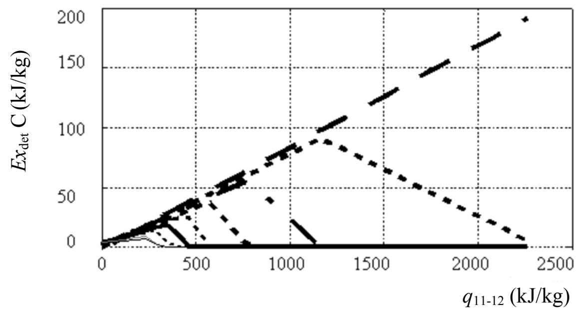

Fig. 6. *Exergetic losses in the condenser*

It gives an idea of these losses caused by heat exchange between the vapor resulting from the last effect and the coolant circuit of the condenser. These losses thus depend primarily on the quantity of the produced vapor. Thus, they increase with this one until reaching a maximum value corresponding to a title of value equal to 1, before starting to decrease. The shape of the curves of Fig. 3, 5, and 7 presents a similarity. In effect, these last all are in connection with the produced vapor. Between the first and the last effect, the maximum exergetic losses range between 200 and 12 kJ/kg of treated salt water.
Fig. 7 makes it possible to evaluate the exergy destroyed in the heaters (r_i, according to the provided energy per unit of treated salt water mass ($q_{11/12}$). The observations made on the preceding figures are checked on the level of the heaters. The exergetic losses in these components range between 35 (effect 1) and 17 kJ/kg of treated salt water (effect 9).

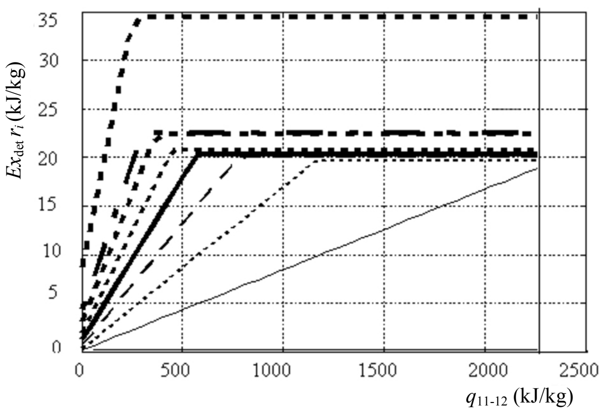

Fig. 7. *Exergy destroyed in the heater*

All in all, knowing that during a heat transfer between two fluids, the creation of entropy takes place when the heat transfer is carried out with a variation of temperature, then on the assumption of a condensation without under cooling and evaporation without overheating, one can admit that the creation of entropy is negligible. Under these conditions, and taking into account the assumptions of the study, the exergy destroyed in the cells where there is no sensible heat (of 2 to n), becomes also negligible. This would explain partly why the dominating losses of exergy are at the level of the condenser, in the heaters, the flows of water, and in effect 1. The localization of these losses makes it possible to realize, that a system for simple effect is not very possible in practice because would inevitably lead to a bad output exergetic (less than 4 % [13]).

Conclusion of the first study

This study made it possible to appreciate quantitatively the exergetic losses in a system for multiple effects. Thus, the results show that the highest losses are caused not only by the exchange between the coolants and salt water, but also by the condensation of the vapors produced in the last effect and the flows of water. The weakest losses are at the level of the valves of brine extractions. Generally these losses decrease when the number of effect increases. Consequently, this analysis recommends increasing the number of effect ad infinitum.

This conclusion raises another problem: which number of maximum effect does one have to implement to optimize the multiple effect desalination plant? We shall for that purpose, study the influence of the increase of the number of effect on the production of water.

Production analysis

Working hypotheses (same assumption as previously)

a) The presence of air in the production unit of fresh water is neglected.
b) The variations of kinetic and potential energy are neglected.
c) The thermal losses towards outside are negligible in the various tanks.
d) The extracted steam is free from salt.

Equations

– Conservation equation of the mass

$$\Delta[q_m]_{ec} = 0 \qquad (12)$$

– Conservation equation of the energy

$$\Delta[hq_m]_{ec} = W'_E + Q' \qquad (13)$$

The development of the equations (12) and (13) applied to all the components of the installation (evaporators, the condenser, heaters, and various extraction valves) leads to a series of coupled equations, given in Table 2.

Table 2

Results of the thermodynamic study

Enthalpy of the liquid mixture vapor of the first effect at the point $5_{a_1}(h_{5a_1})$	$h_{5a_1} - h_{3a_1} = q_{11/12}$	(14)
Enthalpy of the liquid mixture vapor in an effect *i* at the point $5_{a_i}(h_{5a_i})$	$h_{5a_i} = \frac{x_{a_{i-1}}}{1-x_{a_{i-1}}}\left(h_{7a_{i-1}} - h_{8a_{i-1}}\right) + h_{3a_i}$	(15)
Titrate vapor of an unspecified effect $A_i(x_{a_i})$	$x_{a_i} = \frac{h_{5a_i} - h_{4a_i}}{h_{6a_i} - h_{4a_i}}$	(16)
Report/ratio of pure water recovery of an effect $A_i(r_{ep\,a_i})$	$r_{ep\,a_i} = \frac{q_{mep\,a_i}}{q_{mes\,a_1}} = \frac{q_{mep\,a_i}}{q_{mes\,a_i}}\frac{q_{mes\,a_i}}{q_{mes\,a_1}} = \prod_{i=1}^{n} x_{a_i}\left(1 - x_{a_{i-1}}\right)$	(17)
Report/ratio of brine recovery of an effect $A_i(r_{sa\,a_i})$	$r_{sa\,a_i} = \frac{q_{msa\,a_i}}{q_{mes\,a_1}} = \frac{q_{msa\,a_i}}{q_{mes\,a_i}}\frac{q_{mes\,a_i}}{q_{mes\,a_1}} = \prod_{i=1}^{n}\left(1 - x_{a_i}\right)$	(18)
Total production of water in number of effect $(prod_{a_i})$	$prod_{a_i} = \sum_{i=1}^{n}\prod_{i=1}^{n} x_{a_i}\left(1 - x_{a_{i-1}}\right)$	(19)
Salinity of the brine extracted from an effect $A_i(s_{4a_i})$	$S_{4a_i} = \frac{S_{3a_i}}{(1 - x_{a_i})}$	(20)
Enthalpy of the fluid at the entry of effect 1 i.e. at the exit of the heater r_1: h_{2a_1}	$h_{2a_1} = h_{3a_1}$	(21)
Enthalpy of salt water at the exit of the various effects (h_{4a_i})	$h_{4a_{i-1}} = h_{3a_i}$	(22)
Enthalpy on the outlet side of the heaters (h_{7a_i})	$h_{7a_i} = h_{6a_i} - \frac{h_{2a_i} - h_{2a_{i+1}}}{\prod_{i=1}^{n} x_{a_i}\left(1 - x_{a_{i-1}}\right)}$	(23)
Energy of cooling per unit of introduced salt water mass $(q_{ref/es})$	$q_{ref/es} = \frac{Q'_{ref}}{q_{mes\,a_1}} = \prod_{i=1}^{n} x_{a_i}\left(1 - x_{a_{i-1}}\right)\left(h_{7a_n} - h_{8a_n}\right)$	(24)
Energy of cooling per unit of produced pure water mass $(q_{ref/ep})$	$q_{ref/ep} = \frac{\prod_{i=1}^{n} x_{a_i}\left(1 - x_{a_{i-1}}\right)\left(h_{7a_n} - h_{8a_n}\right)}{\sum_{i=1}^{n}\prod_{i=1}^{n} x_{a_i}\left(1 - x_{a_{i-1}}\right)}$	(25)
Specific energy in the various effects $(q_{sp\,a_n})$	$q_{sp\,a_n} = \frac{q_{11/12}}{\sum_{i=1}^{n}\prod_{i=1}^{n} x_{a_i}\left(1 - x_{a_{i-1}}\right)}$	(26)

With these equations are added those giving the influence of the presence of salt on the characteristics of the mixture water-salt [8, 14, 15].

Results of the second study

Conditions of simulation

The conditions of simulation are the same ones as those presented in paragraph *Energy loss results*.

Thus, the parameter of simulation is always the number of effect, and the basic variable always remains the quantity of heat provided per unit of treated salt water mass ($q_{11/12}$).

Presentation of the results

Legend of the second part of the study:

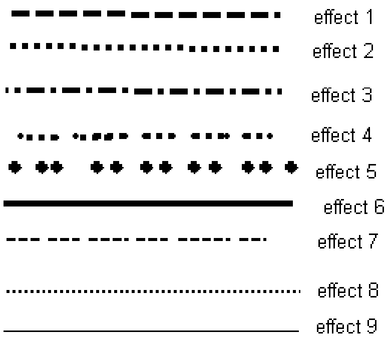

Fig. 8-11 respectively show the evolution of the ratios of recovery of pure water and brine rejection, the vapor title, the enthalpy of the liquid-steamer mixture and the production of pure water according to the variable $q_{11/12}$.

*Note:*An effect of superposition of the curves of Fig. 8 made up of two series of curves makes the reading difficult. This is why it is necessary to give following indications to guide the reader. The curves (*rep*) mark according to $q_{11/12}$ have the same pace as the curves of (*qref*) given to Fig. 13. Whereas the curves (rej) according to $q_{11/12}$ have the same pace as the curves of (ex_{det} $V_{4a_r\text{-}3a_i+1}$) given to has Fig. 3. These two series of curves (*rep* mark and *rej*) joined together in same Fig. 8 give points of intersection whose interpretations are rather interesting.

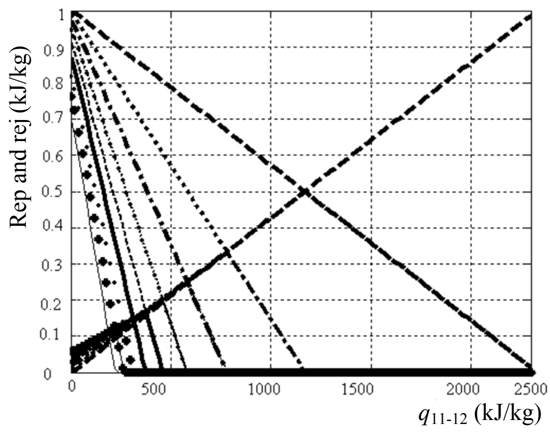

Fig. 8. *Report/ratio of recovery of pure water (rep) and brine rejection (rej) according to the energy provided per unit of salt water mass*

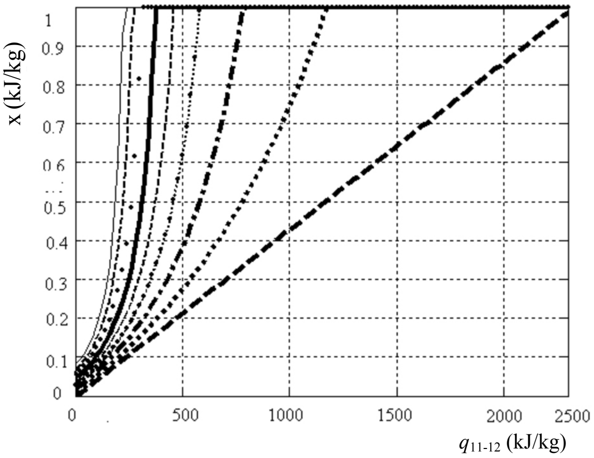

Fig. 9. *Titrate vapor according to the energy provided per unit of salt water mass*

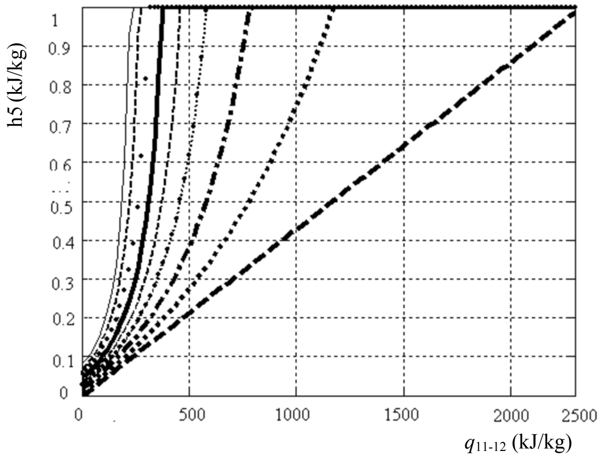

Fig. 10. *Enthalpy of the liquid-steamer mixture according to the energy provided per unit of salt water mass*

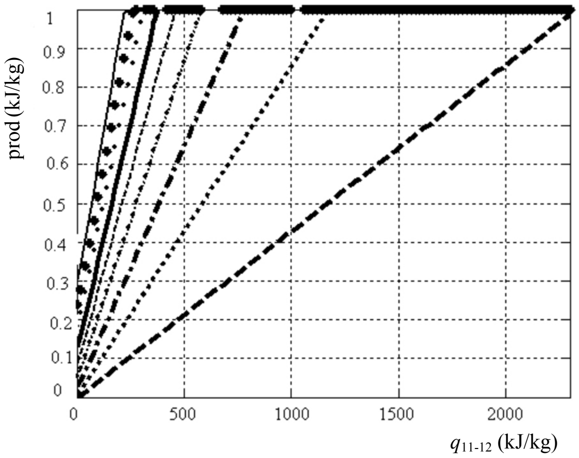

Fig. 11. *Production of one kg pure water per kg of salt water according to the energy provided per unit of salt water mass*

These four figures characterize perfectly the principle of the systems for multiple effects. Indeed, we note that, when the production reaches a maximum value in a given effect A_i (Fig. 8), that corresponds a minimal value (zero value) to the level of the following effect (A_{i+1}). Beyond this maximum value, the report/ratio of pure water recovery in effect i (Fig. 8) is rigorously identical to that of the brine of the effect (A_{i-1}). Indeed, all the salt water introduced into effect (A_i), starting from the effect (A_{i-1}) vaporizes spontaneously, as soon as the vapor title reaches value 1 (Fig. 9). What implies a null production (Fig. 8) for all the effects located beyond cell A_i, i.e. the A_{i+1} cells, A_{i+2},….A_n. Fig. 10 and 11 give respectively the enthalpy of the liquid-steamer mixture and the production of pure water, according to provided energy but also according to the number of effects used. These four figures (8, 9, 10, 11) also inform about the quantity of energy necessary to reach the maximum production with the last effect, when (n) varies. What makes it possible to judiciously choose the number of effect constituting our system, according to the quantity of energy available. Table 3 below recapitulates energy $q_{max}(n)$ leading to a vapor title equal to the unit to the n_{th} effect (A_n), and the corresponding ratio (*rep*), according to the number of effect (n).

Table 3

Values of q_{max} (n) and *rep* according to the number of effects

(n)	1	2	3	4	5	6	7	8	9
$q_{max}(n)$	2308	1180	780	580	460	360	300	260	220
rep	1	0.5	0.33	0.25	0.2	0.165	0.13	0.1184	0.1
x	1	1	1	1	1	1	1	1	1

Remarks

R_1: The report of $q_{max}(n)$ on the ratio (*rep*) of pure water tends towards a constant. This constant represents the latent heat of phase shift of entering salt water.

This remark gives us a relation specific to the system for multiple effects:

$$\frac{q_{max}(n)}{n} = \text{const} \tag{27}$$

R_2: It is clear that a vapor title equal to one cannot be reached in the cells of the systems for multiple effects, because that would lead to the crystallization of salt on the components. The values of (n) thus constitute a maximum threshold not being able to be reached. What makes it possible to delimit the zones of operation (Fig. 14).

A practical example validating this assertion is based on the study undertaken by El Nashar [3] which lays out two series of 9 effects to make 18 of them. In this precise case, where the rate of feed is worth 17.7 m^3/h in each series and the energy of provided heating of 176 kJ, the distillate flow rate is worth 3.1 m^3/h, and the provided energy per unit of salt water mass is of 35.5 kJ/kg, quite lower than 220 kJ/kg (Table 3). But while analyzing these experimental results of meadows, we realize that this value corresponds to a vapor title equal to 0.17 (i.e. 3.1/17.7). This is perfectly in phase with our results, because our calculations give 0.16 (i.e. 35.5/220); and we are well in the zone of operation (wet vapor) of Fig. 14.

In addition to these remarks, we generally note, a clear improvement of the production. Indeed, when the number of effect increases the aggregate output increases too. However, beyond 6_{th} and 7_{th} effects, this improvement of the system related to the increase in the quantity of recovered pure water, becomes increasingly weak, what is materialized in the present study, by the convergence of the curves towards n^{th} effect.

Fig. 12, 13 and 14 give further information on salinity, the energy of cooling, and specific energy.

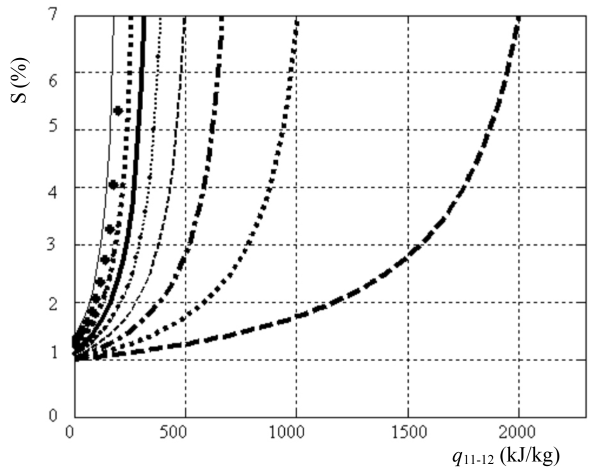

Fig. 12. *Salinity of the brine according to the energy provided per unit of salt water mass*

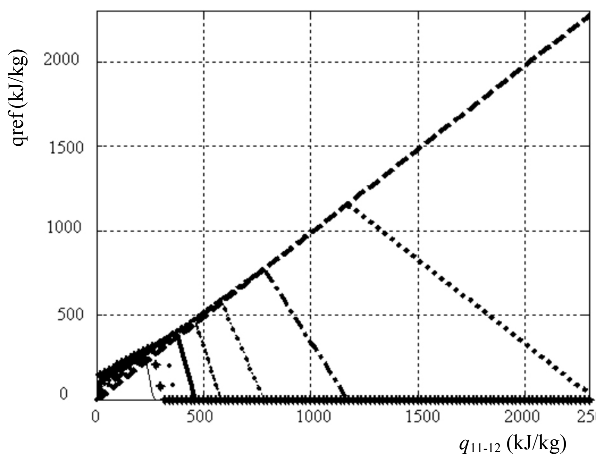

Fig. 13. *Energy of cooling per unit of salt water mass according to the energy provided per unit of salt water mass*

Fig. 12 gives salinity according to provided necessary energy, per unit of salt water mass ($q_{11/12}$). This figure also makes it possible to delimit the maximum value of the size $q_{11/12}$ being likely to create the build up of salt on the components like the exchangers. Indeed, for the strong salt concentrations (beyond a salinity of 5.5 %) [15, 16] there is risk of salt build up.

Fig. 13 gives the energy of cooling, i.e. energy necessary to ensure the complete condensation of the vapors in the last effect, by the only condenser of the system for multiple effects. We naturally note that the maximum value of q_{ref} is equal q_{max}(n).

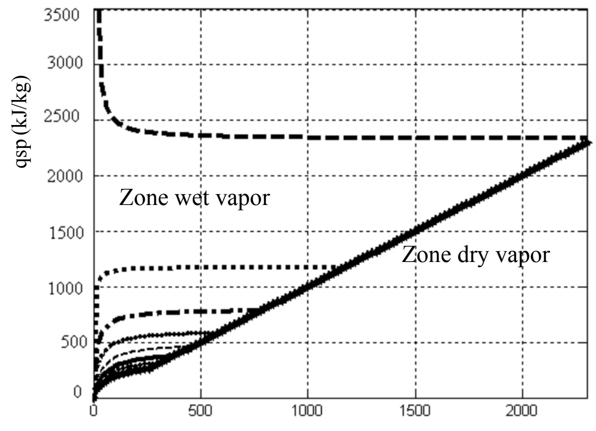

Fig. 14. *Energy provided to produce one kg of pure water according to the provided energy per unit of salt water mass*

Fig. 14 presents energy necessary to produce one kg of pure water (q_{sp}) according to the provided energy reported to the unit of salt water mass. We note a convergence of the various curves towards the value (*n*). All these values are on a linear line which is a "pivot" characteristic of the systems for multiple effects. This line is very useful not only to graphically determine (*n*) according to $q_{11/12}$, but also to delimit the zone of operation optimizing the contribution of energy (zone wet vapor). Indeed, beyond this zone, it is not useful any more to increase the number of effects or energy.

Conclusion of the second study

This second part of the study describes and generally gives the characteristics of the systems for multiple effects, while specifying their performances with respect to the number of effects used and provided energy. She thus gives an idea on the performances of desalination with multiples effects. Indeed, we can say at the conclusion of this study that for 1 kg of introduced salt water, the number of effect could be limited to 9. Indeed, the convergence of the curves towards the last effects shows that beyond 6_{th} and 7_{th} effects, the report/ratio of recovery becomes relatively weak and converges towards 0.1 kg_{ep}/kg_{es}: 0.16, 0.13, 0.12, 0.1 kg_{ep}/kg_{es} (see Table 1 and Fig. 8); this conclusion makes it possible to delimit the capital costs i.e. to limit the number of effects, the supply of energy, the entering salt water flow, and the quantity of pure water provided to the last effect.

General conclusion

The mathematical model presented here, constitutes a coherent analysis as a whole helping to come to a conclusion about the profitability of the installations for multiple effects.

Indeed, the first study, bearing on the exergetic analysis made it possible to show that the exergetic losses fall in a considerable way with the number of effects. Analysis of the production of water, object of the second study, shows that the production also increases with the number of effect, but this increase in production becomes increasingly weak when (*n*) increases. Thus, in our case of study the optimal situation would be to limit the number of effects to 9, and the quantity of energy required per unit of treated salt water mass less than 220 kJ/kg of treated salt water. Table 3 recapitulates the other cases of figure.

The study specifies energy thus leading to a vapor title equal to one according to the number of effects used, i.e. the operational limits of the systems for multiple effects according to the provided energy brought back to the unit of treated salt water mass, and of the number of effect.

Generally, this work gives interesting information on the process multiple effects, in particular on the energy cost of the production of water which could be definitely reduced by the optimization of the number of effects. The continuation of the study could give an alternative for developing countries.

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Symbols

c_p – specific heat at constant pressure, kJ·K^{-1} ·kg^{-1}
Ex′ – exergy power, W
ex – specific exergy, kJ/kg
h – specific enthalpy, kJ/kg
m – mass, kg
p – pressure, Pa
prod – production of water, kg·kg^{-1}
q – specific heat exchanged, kJ/kg
Q' – thermal power, W
q_m – mass flow rate, kg·s^{-1}
rep – report/ratio of pure water recovery, kg·kg^{-1}
rej – brine rejection, kg·kg^{-1}
s – specific entropy, kJ·K^{-1}·kg^{-1}
S – salinity (%)
T – temperature, K
v – specific volume, m^3·kg^{-1}
x – titrate vapor, kg·kg^{-1}
ε – first low efficiency, %

Component symbols

r – heater
V – Valve
Ech *i*/*j* – Exchanging located between items *i* and *j*
P – pump

Subscripts and superscripts

′– Relative to a flow
* – Relative to a saline solution
0 – Relating to the ambient conditions
det – Destroyed
es –Salted water
ep – Pure water
ec – Flow
a_i – Relating to effect A_i
(*i-j*) – component located between *i* and *j*
(*i*/*j*) – Component located between *i* and *j*
ref – Cooling
sa – Brine
sat – Relating to saturation
sp – Specific

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