Energetic and exergetic analysis of a triple-effect distiller driven by solar energy

Ousmane Sow, Monica Siroux*, Bernard Desmet

*Laboratoire de Mécanique et d'Energétique, Université de Valenciennes et du Hainaut-Cambrésis, Le Mont Houy,
59313 Valenciennes Cedex 9, France*

Tel. +33 (3) 27 51 19 88; Fax: +33 (3) 27 51 19 61; email: Monica.Siroux@univ-valenciennes.fr

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Abstract

This paper relates to the energetic and exergetic analysis of single-, double- and triple-effect distiller driven by solar energy. Energetic analysis makes it possible to define an applicable zone of operation according to the following criteria: water rejection limit to 50%, maximum salinity limit to 5.5%, and minimum energy consumption. This analysis also makes it possible to quantify energies: energy necessary for the vapour condensation and the power consumption per unit mass of pure water. Exergetic analysis makes it possible to show that the most significant exergy losses are condenser losses and water alimentation losses and that the condenser losses decrease with the number of effects. The exergetic efficiencies have also been found. They are located between 19 and 26% for a triple-effect system, between 17 and 20% for a double-effect system, and less than 4% for the single-effect system. Consequently, it seems interesting to implement a double- or triple-effect system.

Keywords: Energy; Exergy; Desalination; Distillation; Triple-effect

1. Introduction

A priority project of the economic and social development policy of Senegal is the Channel of Cayaor project, which satisfies the water requirements for large cities and the small surrounding localities [1]. It is in this context that the researchers of the University of Dakar centred their work on the desalination of brackish water. The

work presented here, which falls under the continuity of the studies undertaken by the researchers of Senegal, has as objective to study a distiller driven by solar energy. Energetic and exergetic analyses were used to study energetic performance of single-effect systems (S1) and multiple-effect systems [double-effect (S2) and triple effect (S3)]. Energy analysis is based on the conservation of mass and energy and makes it possible to seek an applicable zone of operation

*Corresponding author.

for each system. Exergetic analysis identifies the components of the system which are at the origin of the exergy losses and is based on the exergy concept. The exergy concept is related to the energy and the reversible character of a process [2–5]. Indeed, exergy represents the energy supplied in a reversible process. As for the losses due to irreversibilities, there are several kinds: exergy destruction, lost work, friction, irreversible heat. Thus, the exergy analysis includes the First and Second Law of Thermodynamics. This makes it possible to evaluate both quantitatively and qualitatively the degree of degradation of energy, i.e., to calculate with precision the consequences of the various phenomena of thermodynamic irreversibilities, and therefore to quantify correctly the thermodynamic losses of a system. Consequently, only the exergy analysis makes it possible to define the thermodynamic efficiency correctly, expressing the degree of perfection, i.e., the thermodynamic quality of the systems [6].

Exergetic analysis of the traditional processes of desalination in the pertinent literature has been treated by some authors. A typical ideal distillation process was proposed and analyzed with particular attention to the minimum work requirement for individual processes by Cerci [7]. This author showed that the minimum work relation for the distillation process is the same as the minimum work input relation for an incomplete separation of incoming saline water, and depends only on the properties of the incoming saline water and the outgoing pure water and brine. An energy and exergy analysis of a reverse osmosis unit alone and coupled to a membrane distillation unit was presented by Criscuoli and Drioli [8] in order to determine the energy requirements related to the integrated system with respect to the reverse osmosis one. This analysis led to an evaluation of the potentialities of the integrated membrane processes in desalination operations. To evaluate the foundation of the optimal design of most desalination systems, Spiegler and

Fig. 1. Presentation of the triple-effect distiller.

El-Sayed [9] carried out an evaluation of minimum work necessary to produce 1 m³ of fresh water by a process of reversible desalination. This approach allowed then to evaluate the exergy destroyed in the traditional systems of desalination and thus to compare their performances and the costs of operations. They noted a close competition between reverse osmosis and distillation for seawater desalination.

However, the study of a multiple-effect distiller driven by solar energy is nonexistent in the literature. Thus, to study such a system, it is necessary to undertake an energy and exergy analysis.

2. Triple-effect distiller driven by solar energy

Fig. 1 presents the principle of the triple-effect distiller driven by solar energy. Salted water arrives in the installation through the pump (P1) at temperature T_1 (point 1). It goes through the heater (1–2) and then the expansion valve (V_a), before penetrating the evaporator (point 3a) at a temperature close to that of evaporation. It then becomes a liquid–steam mixture (point 5a), due to the solar energy that is all the heat input (exchanger 11–12), and the “vacuum” inside tank A, which corresponds to the saturated vapor pressure (p^*_{sat}) of the raw material. The vapor phase is extracted in 6a, while the brine extracted in the first enclosure (point 4a) is used to feed cell B, in the same way as the vapor produced in the first (A) effect is used to vaporize the salted water of the second (B) effect. Similarly, the brine resulting from the second effect (B) is used to feed the third effect (C), and the vapor produced in B is used to evaporate the water of tank C. The vapor extracted from C will heat the heater. At the last stage, a condenser enables the vapors produced in the third effect to become liquid. The pumps (P3, P4, P5) make it possible to extract produced pure water.

3. Energetic and exergetic analysis

The installation analysis is the result of both an energetic analysis, which makes it possible to determine an applicable zone of operation for each system, and an exergetic study, which makes it possible to locate the components of the installation which are at the origin of the exergy losses.

3.1. Energetic analysis

An applicable zone of operation is to be defined from the energetic analysis, based on the following criteria:

- brine rejections limited to 50% in order to preserve the reserves
- maximum salinity limited to 5.5% in order to avoid salt blocking the components
- minimum energy consumption.

The energetic analysis consists in modelling various systems (S1, S2, S3) in steady operation. This modelling is based on the conservation equations of the mass and energy applied to every component of the installation (evaporators, condenser, heater, various valves, various extraction pumps).

The assumptions of the study are:

- The presence of the air in the manufacturing unit of fresh water is neglected.
- The contributions of the kinetic and potential energy in the balance of total energy are also neglected.
- Tanks A, B, and C are well insulated and thus there are no thermal losses towards outside.
- The vapor is assumed to be without salt.
- There is no source or well of mass in the system.

Based on these assumptions, the conservation equations of the mass and energy are expressed in their general form:

$$\Delta(q_m)_{ec} = 0 \quad (1)$$

$$\Delta(h \cdot q_m)_{ec} = W' + Q' \quad (2)$$

To these equations are added:

- Equations expressing the influence of the presence of salt on the thermodynamic characteristics (density [10], specific enthalpy [11], saturated vapour pressure [12]):

$$\rho^*(s_e, T, p) = \frac{\rho(s_e, T, 0)}{[1 - p/K(s_e, T, p)]} \quad (3)$$

$$h^*(s_e, T) = 4.185 \cdot [D_1(s_e) + A_1(s_e) \cdot T + B_1(s_e) \cdot 10^{-4} \cdot T^2 + C_1(s_e) \cdot 10^{-6} \cdot T^3] \quad (4)$$

$$p_{sat}^*(s_e, T) = p_0(T) \cdot e^{\log(10) \cdot [-1.106 \cdot 10^{-2} I(s_e) + 9.1673 \cdot 10^{-4} I(s_e)^2]} \quad (5)$$

where $K(s_e, T, p)$, $\rho(s_e, T, p)$, $A_1(s_e)$, $B_1(s_e)$, $C_1(s_e)$, $D_1(s_e)$, and $I(s_e)$ are polynomial functions.

- The definition of the efficiencies of the exchangers (evaporators and heater):

$$\varepsilon = \frac{\text{exchanged heat}}{\text{exchangeable heat}} \quad (6)$$

The result is a system from 15 equations to 15 unknown factors for the single-effect system, a system of 22 equations to 22 unknown factors for the double-effect system and a system of 29 equations to 29 unknown factors for the triple-effect system. The method of analysis consists of studying the evolution of the analysis parameters while varying the energy provided by the solar loop, $q_{11/12}$.

3.2. Exergetic analysis

Introducing the concept of exergy, an exergetic analysis of the single-, double- and triple-effect distillation systems is proposed here in order to identify the components of the system, which are at the origin of the exergetic losses. The assumptions of the exergetic analysis are the same as those of the energy analysis. Under these assumptions, the system exergetic balance in steady operation is written:

$$\Delta(q_m \cdot ex)_{ec} = Ex'_q + Ex'_w + Ex'_{det} \quad (7)$$

where q_m is the mass flow rate ($\text{kg} \cdot \text{s}^{-1}$), $ex = h - T_0 \cdot s$ is the specific exergy ($\text{J} \cdot \text{kg}^{-1}$), Ex'_q is the exergy of thermal power exchanged between the system and its surroundings (W), Ex'_w the exergy of mechanical power exchanged between the system and its surroundings (W), and Ex'_{det} the destroyed exergy flow rate (W).

Fig. 2 highlights the input exergy and the exergy losses for the multiple effect system:

- the input exergy: thermal input exergy on the heating loop (11/12) and mechanical input exergy provided by various pumps: P1, P2, P3, P4, P5;
- the exergy losses in the various components: evaporators A, B, C; heater; condenser; valves Va, Vb, Vc;
- the exergy losses in the water flow: incoming salted water (1) and outgoing pure water (8a, 8b, 9) and brine (10).

Specific exergetic losses are obtained starting from the exergy balance [1]:

- in evaporator A

$$ex_{det,a} = q_{11/12} \left[\frac{T_0}{T_{sat,a}} - \frac{T_0}{\varepsilon_{11/12} (T_{11} - T_{sat,a})} \right] \ln \frac{T_{11}}{T_{12}} \quad (8)$$

- in evaporator B:

Fig. 2. Exergetic balance of the triple-effect distiller. Ex'_q is the thermal input exergy on the solar loop (11/12), Ex'_w is the mechanical input exergy provided by various pumps (P1–P5), and Ex'_{det} are the exergetic losses (components, water flow).

$$ex_{det,b} = x_a (h_{6a} - h_{7a}) \left(\frac{T_0}{T_{sat,b}} - \frac{T_0}{T_{sat,a}} \right) \quad (9)$$

- in evaporator C:

$$ex_{det,c} = x_b (1 - x_a) (h_{6b} - h_{7b}) \left(\frac{T_0}{T_{sat,c}} - \frac{T_0}{T_{sat,b}} \right) \quad (10)$$

- in the heater:

$$ex_{det,h} = T_0 c_p \ln \frac{T_2}{T_1} - \frac{T_0}{T_{sat,c}} x_c (1 - x_b) (1 - x_a) (h_{6c} - h_{7c}) \quad (11)$$

- in the condenser:

$$ex_{det,cd} = q_{ref} \left[-\frac{T_0}{T_{sat,c}} + \frac{T_0}{\epsilon_{ref}(T_{sat,c} - T_{e,ref})} \ln \frac{T_{s,ref}}{T_{e,ref}} \right] \quad (12)$$

- in valve V_a :

$$ex_{det,2-3a} = \frac{T_0}{T_{sat,a}} \frac{p_1 - p_{sat,a}}{\rho} \quad (13)$$

- in valve V_b :

$$ex_{det,4a-3b} = (1 - x_a) T_0 (s_{3b} - s_{4a}) \quad (14)$$

- in valve V_c :

$$ex_{det,74b-3c} = (1 - x_a) (1 - x_b) T_0 (s_{3c} - s_{4b}) \quad (15)$$

- in the incoming salted water:

$$ex_{det,entry1} = (h_1 - h_0) - T_0 (s_1 - s_0) \quad (16)$$

- in the outgoing pure water:

$$ex_{det,exit8a} = x_a [(h_{8a} - h_0) - T_0 (s_{8a} - s_0)] \quad (17)$$

$$ex_{det,exit8b} = x_b (1 - x_a) [(h_{8b} - h_0) - T_0 (s_{8b} - s_0)] \quad (18)$$

$$ex_{det,exit9} = x_c (1 - x_b) (1 - x_a) [(h_9 - h_{10}) - T_0 (s_9 - s_0)] \quad (19)$$

- in the outgoing brine:

$$ex_{det,exit10} = (1 - x_c) (1 - x_b) (1 - x_a) [(h_{10} - h_0) - T_0 (s_{10} - s_0)] \quad (20)$$

Exergetic losses are obtained by considering the following conditions:

- initial temperature of water is 20°C
- initial salinity of water is 1%

- ambient temperature is 28°C
- exchanger efficiency is 0.85
- temperature of saturation in effect 1 is 60°C
- temperature of saturation in effect 2 is 55°C
- temperature of saturation in effect 3 is 50°C
- ambient conditions are taken as reference.

Exergetic efficiency is obtained as a function of input exergy and destroyed exergy:

$$\eta_{ex} = 1 - \frac{ex_{det}}{ex_{11,12} + w_{p1} + w_{p2} + w_{p3} + w_{p4} + w_{p5}} \quad (21)$$

where ex_{det} is the destroyed exergy in the components of the system and the water flows ($J.kg^{-1}$), $ex_{11,12}$ is the thermal input exergy on the heating loop ($J.kg^{-1}$), and w_{p1} , w_{p2} , w_{p3} , w_{p4} , w_{p5} is the mechanical input exergy provided by the pumps ($J.kg^{-1}$).

4. Results and discussion

The energetic study enables us to obtain the following results for each system: recovery ratio for the pure water $r_{ep} = q_{m,ep}/q_{m,es}$ and for the brine $r_{sa} = q_{m,sa}/q_{m,es}$, salinity, the power consumption per unit mass of pure water $q_{sp} = Q'_{11/12}/q_{m,ep}$, energy necessary for the vapor condensation $q_{ref} = Q'_{ref}/q_{m,ep}$ and the percentage of water rejects.

Figs. 3–6 show the results obtained for the triple-effect system. Figs. 3 and 4 show obtaining of the applicable zone of operation for the triple-effect distiller. Fig. 3 presents the recovery ratio for the pure water and for the brine (r_{ep} and r_{sa}) as a function of the solar energy per unit mass of distillate product $q_{11/12}$. While choosing to limit the brine rejections to 50%, $q_{11/12}$ must be greater than 680 kJ/kg. Fig. 4 presents the brine salinity as a function of the solar energy per unit mass of distillate product $q_{11/12}$. While choosing a maximum salinity of 5.5%, the solar energy per unit mass of distillate product to provide $q_{11/12}$ must be

Fig. 3. Pure water and brine recovery ratio as a function of the solar energy per unit mass of distillate product for the triple-effect system.

Fig. 4. Salinity of brine extraction as a function of the solar energy per unit mass of distillate product for the triple-effect system.

less than 750 kJ/kg. These two criteria enable us to define an applicable zone of operation between 680 kJ/kg and 750 kJ/kg.

Fig. 5. Power consumption per unit of pure water mass for the triple-effect system.

Fig. 6. Energy of cooling per unit of pure water mass for the triple-effect system.

Fig. 5 presents the power consumption per kg of pure water of the triple-effect system as a function of the solar energy per unit mass of distillate product $q_{11/12}$ for several temperatures of the first effect. It is noticed that for the applicable zone, q_{sp} depends very little on the temperature: q_{sp} is about 900 kJ/kg.

Fig. 6 presents the energy necessary for the vapor condensation of the triple-effect system as

Fig. 7. Incoming salted water exergetic losses for the single S1, double S2 and triple-effect system S3.

a function of the solar energy per unit mass of distillate product $q_{11/12}$. It is noticed that for the previously definite applicable zone q_{ref} varies between 550 and 630 kJ/kg.

Table 1 presents the synthesis of the energy analysis for the three systems. It is noted that energies brought into play in the case of the single effect system (q_{sp} , q_{ref}) are very significant, which have led us to eliminate it and be only interested in multiple effect systems.

The exergetic study makes it possible to determine the exergy losses in the components of the system and the water flows (Tables 2 and 3 and Figs. 7 and 8). It can be seen that among the system components the condenser brings the most energetic losses and that these losses fall in a very significant way with the number of effects (Table 2). Moreover, it can be seen that incoming salted water losses represent the most significant part of the losses in the water flows, but this value depends essentially on the reference conditions and it cannot be improved.

The exergetic efficiency is obtained from Eq. (21). Taking into account the applicable zones of operation identified by the energy analysis, the exergetic efficiencies are between 19%

Table 1
Synthesis of the energy analysis for the three systems (1, 2, 3 effects)

	Applicable zone of operation ($q_{11/12}$), kJ.kg ⁻¹	q_{sp} , kJ.kg ⁻¹	q_{ref} , kJ.kg ⁻¹	Rejects, %
1 effect	[1200; 1950]	2350	[2000; 2350]	[20; 50]
2 effects	[900; 1100]	1300	[750; 900]	[18; 32]
3 effects	[680; 750]	900	[550; 630]	[18; 28]

Table 2
Percentage of the exergy losses in the system components

	Evaporator A	Evaporator B	Evaporator C	Heater	Condenser	Valve V _a	Valve V _b	Valve V _c
1 effect	13.24	—	—	4.41	52.98	0.034	—	—
2 effects	10.12	6.54	—	4.46	30.9	0.46	6.54	1.48
3 effects	7.35	5.35	5.35	4	18.7	0.05	9.36	5

Fig. 8. Exergetic losses in the valves and the condenser for the triple-effect system.

Table 3
Percentage of the exergy losses in the water flows

	Entry 1	Exit 8a	Exit 8b	Exit 9	Exit 10
1 effect	25.16	3.31	—	—	0.88
2 effects	33.9	2.38	2.38	—	1.19
3 effects	38.10	2	1.67	1.53	0.65

Fig. 9. Exergetic efficiencies for the single (S1), double (S2) and triple-effect (S3) system.

and 26% for a triple-effect system, between 17% and 20% for a double-effect system, and less than 4% for the single-effect system (Fig. 9).

5. Conclusions

This work presents energetic and exergetic analysis of single-, double- and triple-effect distiller driven by solar energy. Energy analysis made it possible to define for each system an applicable zone of operation according to the following criteria: limit the brine rejection to 50%, limit maximum salinity to 5.5%, minimize energies. This analysis also made it possible to quantify energy necessary for the vapor condensation and the power consumption per unit mass

of pure water. Exergetic analysis made it possible to show that the most significant exergetic losses are the condenser losses and the incoming salted water losses and that the condenser losses fall with the number of effects. The exergetic efficiencies have also been found. They are located between 19% and 26% for the triple-effect system, between 17% and 20% for the double-effect system, and less than 4% for the single-effect system.

These results show that:

- energies brought into play in the single-effect system are very significant
- the profit is important for the double-effect system and less important for the triple-effect system.

This means that, in spite of its simple design, the single-effect system generates a high operating cost. This led us to eliminate the single-effect system and to be only interested in the double- or triple-effect systems.

In addition, the regulation of the flow rate of the input water was considered, which would limit, *a priori*, the losses of energy as well as the brackish discharges [13].

6. Symbols

c	—	Velocity, m.s^{-1}
c_p	—	Specific heat at constant pressure, $\text{J.K}^{-1}.\text{kg}^{-1}$
Ex	—	Exergy, J
Ex'	—	Exergy power, W
ex	—	Specific exergy, J.kg^{-1}

h	—	Specific enthalpy, J.kg^{-1}
p	—	Pressure, Pa
r	—	Recovery ratio
q_m	—	Mass Flow rate, kg.s^{-1}
Q'	—	Thermal power, W
S	—	Entropy, J.K^{-1}
s	—	Specific entropy, $\text{J.K}^{-1}.\text{kg}^{-1}$
s_e	—	Salinity of brine, %
T	—	Temperature, K
t	—	Time, s
W'	—	Mechanical power, W
w	—	Specific mechanical exergy, J.kg^{-1}
x	—	Degree of humidity

Greek

ε	—	First law efficiency, %
η	—	Exergetic efficiency, %
ρ	—	Density, kg.m^{-3}

Subscripts and superscripts

a	—	Relating to cell A
b	—	Relating to cell B
c	—	Relating to cell C
det	—	Destroyed
ec	—	Flow
ep	—	Pure water
es	—	Salted water
ex	—	Exergy
irr	—	Irreversible
p	—	Pump
ref	—	Cooling
q	—	Relating to heat
sa	—	Brackish
sat	—	Saturation
sp	—	Specific

w	—	Relating to work
0	—	Relating to the environment
$*$	—	Relating to a brackish solution

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