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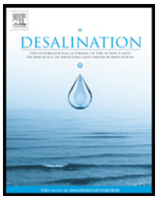

Simulation of solar vacuum membrane distillation unit

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HIGHLIGHTS

- The coupling of the solar energy with the hollow fibres module.
- Modeling of heat and mass transfer in vacuum membrane desalination coupled with solar energy.
- The determination of daily and yearly desalination unit production.

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ABSTRACT

The present research work is interested in modelling and simulating a plant of vacuum membrane distillation (VMD) for seawater desalination coupled with solar energy. Its aim is not only to develop a mathematical model describing the functioning of VMD hollow fibre module coupled with a flat solar collector, but also to determine the daily productivity of this unit. The mathematical model shows that the daily production can reach 38 kg/day. The integration of the solar energy allows the improvement of the desalination plant productivity.

1. Introduction

The desalination of seawater is considered as the most important source of potable water for arid and semiarid zones [1]. Although its technologies are operational for many years, their cost often limits their use only to the rich countries. The possibility of designing innovative processes based on the coupling of this technology with the solar energy is becoming an attractive way to reduce the production costs and to increase the process performance [2]. For solar-powered desalination units, two different layouts are developed: compact system and two-loop system, in which seawater is heated directly inside collectors or by means of an intermediate heat exchanger, respectively [3].

Membrane distillation (MD) is a relatively new process that is investigated worldwide as a conventional separation process [4], such as distillation and reverse osmosis. Actually, it is a thermal membrane separation process that involves the transport of vapour through micro-porous hydrophobic membranes and operates on the principle of vapour–liquid equilibrium as a basis for molecular separation [5–8]. MD systems can be classified into four different configurations: direct contact MD (DCMD), air-gap MD (AGMD), sweeping gas MD (SGMD) and vacuum MD (VMD). The DCMD, AGMD and VMD are the best suited for desalination applications [6,9,10]. An experimental study carried out by Huayan et al. [11] to compare the efficiency of DCMD, SGMD and VMD, using a salt solution feed. They showed that the VMD presented the highest flux among the three MD configurations. Therefore, the VMD is chosen for the MD configuration adopted in this work.

The VMD process is based on the evaporation of solvents through hydrophobic porous membranes improved by applying vacuum or low pressure on the permeate side [12]. Permeate condensation takes place outside the module, inside a condenser or a trap containing liquid nitrogen [7].

The analysis of the operating conditions shows that the parameters key is a relatively low temperature and pressure. Moreover, the process coupling VMD with a source of energy (solar or geothermal) could compete with reverse osmosis [3,7,14,15].

Being capable of directly using solar thermal energy, the solar membrane distillation desalination system has evolved as a promising green technology for alleviating the water resource problem [15,17]. R. B. Saffarini et al. [16] showed that solar heater costs accounted for over 70% of the total cost for all systems, suggesting the desirability of using alternative sources of thermal energy, such as solar energy.

Since the majority of research studies concern the coupling of solar collectors with the other configurations of the DM such as DCMD [17,18] and AGMD [19–21], Wang et al.[22] were among the first to

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Nomenclature

C_p	seawater heat storage capacity
$\dot{D}$	mass flow of the distillate
J_v	molar water flow
K_m	Knudson permeability
L	module length
$\dot{m}_\mathrm{oxy}$	auxiliary mass flow
$\dot{m}_e$	mass flow of the entry of the module
$\dot{m}_{ret}$	mass flow of retentate
$\dot{m}_s$	mass flow at the exit
P_vacuum	vacuum pressure
R	radius
T	temperature
T_i	Intefacial temperature
T_a	ambient temperature
T_r	tank temperature
T_ret	retentate temperature
V	tank volume
v_m	mean velocity

Subscripts

CC	central compartment
CE	external compartment
CM	compartment in the medium
Int	interior
Ext	external

Greek symbols

ω	recycling ratio
λ	water conductivity
ρ	water density

couple VMD with solar energy. Their study shed the light on a designed and tested solar-heated hollow-fibre-based VMD system. The largest permeate flux obtained is 32.19 L m^{-2} h^{-1} of membrane area with an 8-m^2 solar energy collector. Therefore, Mericq et al. [10] studied the possibility of submerging the plate DMV membrane in the salinity gradient solar ponds and the solar collector. The use of solar collector does not only seem to be the most interesting solution but also allows a maximum permeate flux of 142 L m^{-2} h^{-1} to be reached with permeable membrane.

In this research work, a study of the effect of coupling solar energy with the VMD module on the permeate stream is realized. This study is carried out in step three:

- A modeling of functioning of a plane solar collector,
- A modeling of the heat and mass transfer within the hollow fibre module,
- Finally, a coupling of two models by performing a balance sheet on the whole installation.

Such a global model allows the determination of the instantaneous variation of the distillate flow as well as the daily productivity.

2. Modelling of the functioning of the vacuum desalination membrane coupled with the solar collector

Vacuum membrane distillation is a complicated physical process in which both heat and mass transfers are involved. Indeed, the coupling of the heat and mass transfer equations in each part of the unit; the module, the collector and the tank, lead to the establishment of a model describing the functioning of the desalination unit. The variations of the temperature and distillate quantity during the day were determined.

The model is developed to calculate the effect of the solar energy on the permeate flux.

Fig. 1 shows the plan for the installation. In fact, the hollow fibre module was coupled with a solar flat plate collector to improve its productivity and received a water flow not only to be treated from the tank, but also to provide an elevation of water temperature function of the solar radiation received by the collector. The tank was fed with fresh sea water and retentate flow.

2.1. Solar collector

The coupled collector chosen for this installation is a flat plate collector with a slope of 30°. It was made up of 30 tubes having the length of 2 m and the diameter of 8 mm. The collector exit temperature was determined using a model developed by Frikha et al. [23]. This model allows calculating daily exit temperature variation according to the solar radiation. The latter is calculated using EUFRAT model that determines the different types of radiation as a function of climatic parameters [24,25].

Fig. 2 represents the instantaneous variation of the collector exit temperature for the four typical days of the year which represent the equinox and solstices. With the equinox was the date when day and night are of approximately equal length marking the beginning of spring and autumn. The solstices were both the longest day of the year (in summer) and the shortest day of the year (in winter). This temperature gradually increased for the first few hours of the day and then steadily decreased at the end of the day. So the temperature level depends on the insulation. For the four typical days, the temperature does not exceed the 80 °C which is the membrane temperature permissible. The temperature reached its maximum value, about 80 °C in June. What is worthy to be noted is that these maximum values range from 12 to 13 h, which is the time interval during which the collector received the maximum insulation.

This first part gives us the collector exit temperature variation as a function of the collector feed temperature and solar radiation which it subsequently used.

2.2. Hollow fibre module

Firstly, we have developed a model describing the heat and mass trasfer in the hollow fobre module. This module allows to determine the module exit temperature and permate flow variation as a function the module feed temperature wich the collector exit température in this case [5,12,26].

The hollow fibre module configuration is external–internal. Indeed, the feed fluid circulates outside the fibre and the depression is applied inside the fibre. Hence, the direction of permeate flow is from outside towards the inside [27].

The heat transfered inside the module is coupled with a mass transfer through the membrane, which is due to the difference in pressure on both sides of the membrane. The establishment of a rigorous model describing the heat and mass transfer inside the hollow fibre module is very complex. Some assumptions are followed to mitigate and deal with the problem as shown in Fig. 3.

In fact, the angular distance between fibres is little compared to the radial one. We supposed that the fibres are placed the ones with the dimensions of the others according to the angular distance by forming an assembly of coaxial cylinders. Thus, we consider that the internal fibre diameter represents the vacuum thickness compartment. The fibre thickness represents the membrane thickness and the distance between fibres represents the water thickness compartment. The module consists of a whole coaxial cylinders with alternate compartments water membrane–vacuum membrane where a mass transfer through the membrane happens under the gradient pressure effect.