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Natural vacuum distillation for seawater desalination – A review

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ABSTRACT

The availability of fresh drinking water is one of the biggest concerns today. It is a bigger challenge for arid and semi-arid areas. In these regions, desalination is heavily relied upon for meeting freshwater demands. Many processes for desalination have been introduced in an effort to minimize the use of non-renewable energy sources and cut down on pollution. The purpose of this study was to present a review on one such process, namely the natural vacuum distillation (NVD). NVD uses the barometric height of water column (approximately 10.3 m) to generate a "natural vacuum" in the headspace above the water column. This low-pressure environment makes it possible to carry out the desalination process at low temperatures, which can be easily attained from renewable energy sources or from waste heat sources. Another benefit of such a process is that mechanical pumping is required only for start-up, hence reducing power requirements. This paper presents a review of the work carried out on the NVD process so far, the different systems that have been designed using this principle and the major factors that affect the production of water using this technology. Additionally, it points out the areas that need to be investigated further and underscores the future prospects of the NVD process.

Keywords: Desalination; Natural vacuum distillation; NVD; Renewable energy

1. Introduction

The availability of freshwater is one of the most serious problems faced by the world today. According to estimates, over a billion people today lack access to freshwater and over 2.5 billion people do not have access to basic sanitation [1]. By 2025, the situation may worsen to the extent that two-thirds of the world's population may suffer either from high or moderate water shortages [2]. Many health issues today are a direct consequence of the unavailability of clean drinking water. As such, water desalination is the only promising option to, at least partially, meet the water needs. Obviously, it is a much more viable option than importing or transporting freshwater.

The major types of seawater desalination processes, in use around the world today, are the multi-stage flash (MSF), multi-effect distillation (MED) and the reverse osmosis (RO) process. MSF is the most popular of the desalination processes for large-scale productions. MED is older than MSF but suffered some operational problems and was limited to the maximum size of the units, and hence, it lost its popularity. Recent developments in the process though have seen it competing with the MSF in terms of size and performance. RO is also making rapid

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development and gaining increasing popularity. Different membrane designs and structures are used, and recovery rates up to 70–90% are achievable [3]. The choice between these desalination processes is made on technical, economical and/or political grounds [4].

These processes, however, require a huge amount of energy input for desalination. An average of more than 20 MJ/m^3 of total electricity consumption is estimated for thermal processes, whereas the number drops to 4–6 MJ/m^3 for the RO processes. For thermal desalination processes, energy accounts for up to 60% of the total cost [5]. It is not just a matter of energy cost but there are many environmental concerns attached as well. Greenhouse gases generated from the burning of fuel and noise pollution (from pumps etc.) are two of the major environmental concerns associated with these processes [6]. Another significant impact of the desalination processes is the thermal pollution caused by discharge of the brine, which is at a higher temperature than seawater. In thermal desalination processes, this difference could be as high as 15℃ [7]. Another issue common to all desalinations processes is the brine disposal. The higher salt concentration of the disposed brine is a threat to marine life.

To address the problems of high energy consumption and many of the environmental issues, renewable energy is sought as an alternative to drive the desalination processes. Energy experts believe that by the year 2050, 100% of the world's electricity demands could be met by renewable energy [8,9]. Similarly, for desalination, many potential sources for renewable energy have been identified, including solar, geothermal, wind and tidal energy [10]. However, solar energy remains the most frequently used energy resource [11]. Areas that are most likely to suffer water shortages usually enjoy an abundance of solar energy. For example, studies have shown that the annual mean radiation in Bahrain is 5,200 W hr/m^2 [12]. This is good enough for a medium-sized power generation process. Also, studies have shown that the solar–thermal desalination plants are considered to be the most economical among the renewable energy-driven plants [13,14].

Different techniques have been adopted for using solar energy in desalination by researchers [15]. One way is to convert it to electricity, by use of photovoltaic cells, to drive processes such as RO and electrodialysis (ED). These processes are limited in application due to low efficiency, low yield and batch operation. Another way of utilizing the solar energy is to use it directly to operate MSF or MED processes. A novel technique for causing the phase change required for these processes was introduced in 2003, which makes use of natural vacuum distillation (NVD) [16,17]. NVD is based on the principle of attaining natural vacuum through the barometric head of a water column. Total vacuum is equivalent to a water column with a height of approximately 10.3 m. The experimental studies reported in the literature have claimed to achieve pressures as low as 0.5 kPa using NVD (see Table 1). The low pressure created causes the desalination to take place at low temperatures, which are easily achieved using solar energy.

This paper presents a review of the work carried out on the NVD process so far and the different systems that have been designed using this principle. It also leads to the equation needed to calculate the evaporation rates and the major factors that affect the production of water using this technology. Additionally, it prompts to the areas that need to be investigated further and the future prospects of the NVD process. In Section 2, a review of the different types of processes based on NVD is presented. Section 3 presents the equation for the evaporation rate, which is essential for mathematical modelling of the process. It also briefly discusses the accommodation factor which is essential to the evaporation rate equation. The factors that affect an NVD process are detailed in Section 4 and the paper end with some recommendations and concluding remarks in Section 5.

2. Natural vacuum distillation

NVD uses the simple idea of using the barometric pressure of a column of water to create a vacuum chamber, which allows for the evaporation of water at relatively lower temperatures. If a column of water, with a sealed top, is allowed to drain into a container of water, then it stops draining after the head of the water column (approximately 10.3 m) equals the atmospheric pressure acting on the water in the container. The space above the water level in the top end will thus have a natural vacuum created. A system based on this principle is capable of creating vacuum without using any evacuation pump. Under such low-pressure conditions, saline water can be easily evaporated at low temperatures, with minimal energy input, and subsequently condensed to obtain freshwater.

Some studies have been carried out to investigate theoretical and experimental aspects of the NVD systems. Table 1 summarizes and compares the findings of the different investigations reported in the literature. Detailed discussion of these systems follows in the subsequent sections.

2.1. Single-stage NVD systems

A desalination system based on the NVD was first studied by Al-Kharabsheh and Goswami [16] in 2003.

Table 1
Summary of the various NVD systems reported in literature

Year	Author(s)	Exp./Th.	Primary heating source	Production rate (kg/d)	Power requirements	Production cost	Evaporator size (m^2)	Operating pressure (kPa abs)
Single-stage processes								
1995	Bemporad [19]	T	Solar	1.7	50 W		0.047	
2003	Al-Kharabsheh and Goswami [18,20]	T	Solar	5.8[a]	150.3 W		0.1	
		E	Solar	6.5[a]	158 W		0.1	3.2–4.7
2003	Midilli and Ayhan [21,22]	T	Solar	235			0.16	
		E	Solar	95	2.6 kWh/kg		0.16	15.13
2004	Reali et al. [23]	T	Solar	1×10^5	2.162 kWh/m^3	\$5/m^3		
2007	Eames et al. [35]	E	Solar	30	4.7 m^2 solar panels			0.5
2008	Gude et al. [24–31]	T	Solar	108	15 m^2 solar collector		0.2	
		T	Solar PV	108	23 m^2 of PV panels		0.2	
		T	Solar/TES	108	15 m^2 panel/1 m^3 TES		0.2	
		T	Waste heat	108	260 W		0.2	
		E	Solar	192	Reflector		0.2	
2008	Moore et al. [38]	T	Electrical	350	1.97 kWh/m^3			
2010	Ayhan and Al-Madani [32]	E	Solar	130	1.6 kW	\$0.7/m^3		14.7
2012	Jitsuno and Hamabe [34]	E	Electrical	10	550 W			
Multistage processes								
2007	Reali [39–41]	T	Solar	1×10^5	1.0 kWh/m^3	\$5/m^3		
2008	Abutayeh and Goswami [42–44]	E	Electrical	40	4.87 kW			12–70
2012	Gude et al. [46]	E		500	8.7 kW	\$3/m^3	1.5	2.0–13.8

[a] Units reported are kg/d m^2.

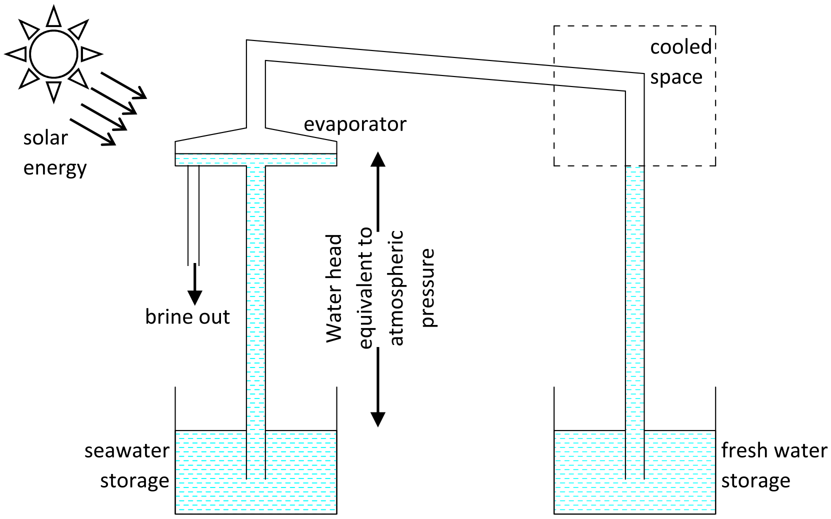

Fig. 1. Schematic representation of desalination system using the NVD process.

The system consists primarily of a saline water column and a freshwater column connected together by a vacuum chamber. A schematic representation of such a system, using NVD, is illustrated in Fig. 1. The vacuum is created by balancing the atmospheric pressure with the water columns on both sides. The saline water is heated using a solar heating system and passed on to an evaporator. The vapour is then condensed, and the freshwater is collected in the freshwater tank.

The system was theoretically modelled [18] using material and energy balances as well as salt concentration analysis. Evaporation rates in the evaporator were modelled according to a model developed by Bemporad [19], which describes the hydrodynamic behaviour of saline water, connected to freshwater through a vacuum chamber. The model was used to find optimum working conditions and parameters for the system. It was found that the process worked best with a water depth of 0.08 m in the evaporator and a brine withdrawal rate of 0.1 kg/h. The output rate was shown to be mainly dependent on the saline water temperature. An increased temperature on the saline water side allows for a higher temperature difference between the two sides (which is the driving force). An output rate of 0.1739 kg/h was predicted by the model for the system. An experimental system was then set up with an evaporator area of 0.2 m^2, heated by an electric heater to simulate the effect of solar panel heating [20]. The experimental production rate was lower than that predicted by the simulated process by about 5–10%. This discrepancy is attributed to two assumptions used in the simulation model, namely that the entire vapour is condensing on the freshwater side and that the heat losses in the pipes and connectors are negligible.

This system is capable of continuous operation. However, the experimental analysis was done on a batch mode with an operating period of just six hours. As expected, the output rate was reported to fall over time.

Another study, almost simultaneous to the first one, was done by Midilli and Ayhan [21]. This was also similar in construction and based on the same working principles. A fan was used to drive the vapour from the evaporator side to the condenser. Thermodynamic analysis was presented for the process under free and forced convection. The process was designed to use renewable energy, without any need for pumping or electrical heating.

An experimental system was set up by Midilli and Ayhan [22] based on the design suggested by the theoretical model. The experiments were carried out with free and forced mass convection. They yielded a product rate lower than that predicted from the model. From the figures presented in the paper, the maximum freshwater production rates corresponding to the theoretical and experimental investigations are 9.79 and 3.96 kg/h, respectively. The energy consumed by the experimental set-up was almost three times higher than that predicted by the theoretical analysis. The authors attributed these disparities to heat and pressure losses in the connections.

Reali et al. [23] presented another system based on NVD, although they chose to call it differently as “solar barometric desalination”. The system took intake from the sea, and the storage tanks were all kept at almost 10 m below the sea level. Five different water storage tanks were used with as many as six pumps. A special venting system was used to remove non-condensable gases. Another important feature of this system was the use of a "demister" to separate the water vapour from the saltwater droplets. A solar collector field using flat plate solar collectors was used to heat the water. Although they did not report the production amount from the system, they did, however, show theoretical calculations based on a production rate of 100 m^3/d assuming an operation time of 10 h per day. Based on a 20-year plant lifetime, they estimated the cost of production to be around 5 $/$m^3$, with 4 $/$m^3$ for capital costs and 1 $/$m^3$ for operation and maintenance costs. The total power consumption was estimated to be 2.162 kWh/m^3.

Building on these early ideas, Gude and Nirmalakhandan [24] presented a modified system, which could use low-grade heat sources to produce freshwater. Theoretical models were presented to make use of various renewable energy sources to be used in the system including solar energy, solar photovoltaic, thermal energy storage and geothermal energy as well as waste heat from processes. For experimental analysis, grid power was used to get a production rate of 0.33 kg/h using 3,122 kJ/kg of freshwater. They extended the study to include a thermal storage tank coupled with solar photovoltaic and heat rejected from an absorption refrigeration system (ARS) [24]. Results of this study showed that the heat rejected by an ARS with a 3.25 kW cooling capacity, along with an additional energy input of 208 kJ/kg of freshwater, is adequate to produce desalinated water at an average rate of 4.5 kg/h. The absorption refrigeration system is driven by solar energy during sunlight hours and by an auxiliary electric heater during non-sunlight hours [25].

Gude et al. [26] studied the system theoretically using flat plate solar collectors with a thermal energy storage (TES) tank. The TES was used to drive the process during the night-time when solar energy was not available. They concluded that the system could produce 4.17 kg/h of freshwater with a solar collector area of 15 m^2 with 1 m^3 of TES volume or 18 m^2 with 3 m^3 of TES volume. Such a low-energy input system was found to be very economical, and the payback period was estimated to be two years only. The same set-up was also employed to investigate the possibility of using NVD for wastewater reclamation [27].

From the different studies considered by Gude and his co-workers [24–30], it was found to be the use of a solar collector coupled with photovoltaic battery. The solar energy is used directly for heating during the sunlight hours, and the energy stored in the photovoltaic battery is used when sunlight is not available. A comparison of this arrangement was done with those used in the previous studies [24,28], and it was found that this system was completely based on renewable energy and did not rely on the grid power or fossil fuels for heating or mechanical pumping power requirements. The condenser was just a cooled space kept under the shade. There is no mention of a cooling mechanism employed on the condenser side. This could be feasible in areas where ambient temperatures fall to 10–15˚C. However, for areas with a hot climate, a cooling mechanism needs to be developed. An exergy analysis was also carried out for the different set-ups, which shows that low-grade heat source had the least exergy destruction while solar energy was more suited to thermal processes due to its higher exergy values [31].

Ayhan and Al-Madani [32] presented a feasibility study of using NVD in hot climate regions. They showed some promising results with a production rate of around 5.42 kg/h for 1 m^2 evaporator area. They also estimated the production cost of freshwater in Bahrain environment as 0.7 $/$m^3$. The authors claimed that this is significantly lower than the real production cost corresponding to other desalination means (thermal or RO processes). They later managed to increase the production rate significantly by creating a combined effect of evaporation and cavitation [33]. The temperature difference between the evaporation chamber and the seawater supply was adjusted in a manner to cause cavitation within the chamber and the bubbling resulted in increased evaporation rates.

Recently, Jitsuno and Hamabe [34] have conducted experiments on a system using simulated NVD. The simple experimental system built by the researchers was evacuated using a vacuum pump. However, they asserted that NVD could be used for actual operation in the arid lands of Africa, which was the prime objective of their study. They reported a production rate of 0.42 kg/h per m^2 of evaporator area and claimed a life period of more than 30 years for such a system.

Eames et al. [35–37] developed a set-up that uses natural vacuum to create an evacuated flash chamber. Cold saline water enters the condensation side of the chamber, before being sent to a solar collector for heating and is then sprayed through a nozzle into the flash chamber. The brine settles on one side while the vapour is condensed by the cold feed on the condenser side. By using a barometric chamber in this way, a flash evaporation process can be used to desalinate water at relatively low temperatures, typical of those available from low-cost solar–thermal collectors. The system was able to produce freshwater at rates of 1.25 kg/h using a 4.727 m^2 of solar collector area. Potential application of building a desalination plant

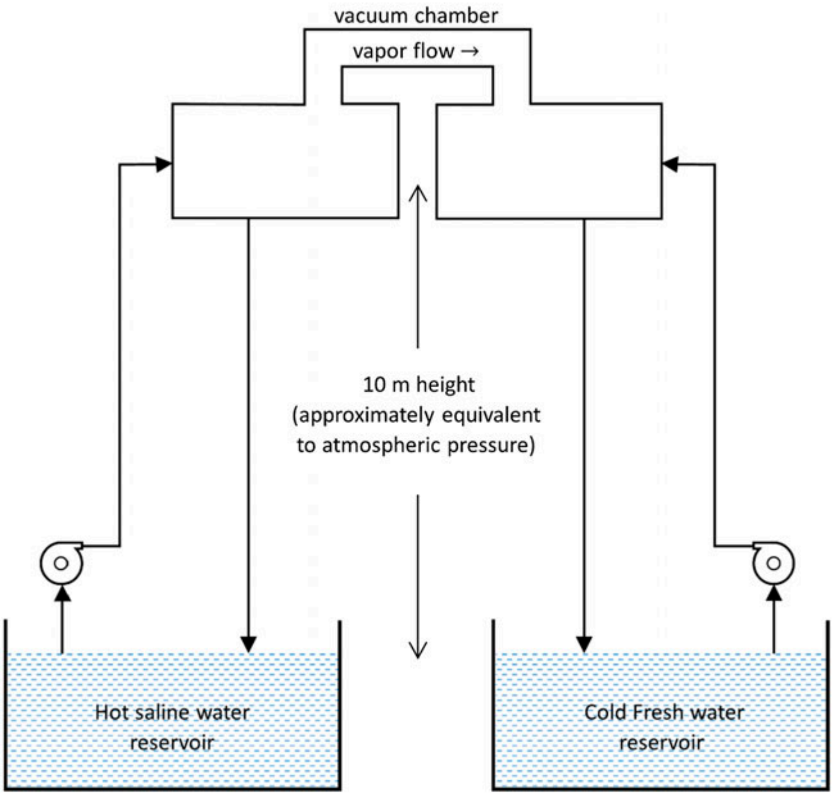

Fig. 2. Schematic representation of NVD system adapted from Moore et al. [38].

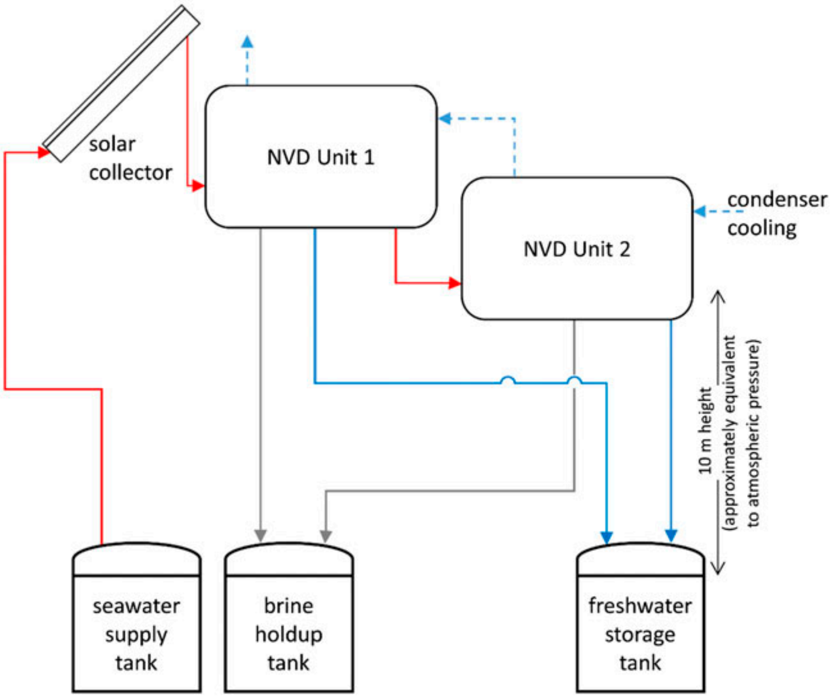

Fig. 3. Schematic representation of a multistage NVD system.

on this idea using waste heat from a power plant in Cyprus has also been investigated [36,37].

Moore et al. [38] came up with another system based on NVD which allows water desalination to be carried out at low temperatures and using a much lower energy than the traditional techniques, Fig. 2. The authors claimed that this system is almost 40% more efficient than RO for a similar production rate. It consists of two water columns, with a height of 10 m each. One column contains cold freshwater, which acts as the condenser and the other contains heated saline water. The hot and cold vapours meet in the vacuum chamber. A thermal equilibrium will eventually be achieved. To overcome this issue, large amounts of water needs to be pumped continuously on both sides. The calculations show that if 100 kg/h is pumped on either side, a product rate of 1 kg/h is achieved which causes the saline output to be cooled by 5.4℃ and the freshwater to be heated by 5.4℃. Huge amounts of storage need to be maintained on both sides to ensure that the streams flowing back to the tanks do not change the system conditions.

2.2. Multi-stage NVD systems

In order to increase the efficiency of the NVD system, many researchers have proposed the use of a multi-stage process. A simple representation of a multi-stage configuration is shown in Fig. 3. Similar to any conventional multi-effect evaporator, the concentrated liquid (brine) moves from one stage to the other. This will result in an increased production rate.

A two-stage NVD process was proposed by Reali [39–41]. This was based on a single-stage design presented in an earlier work [23]. In his analysis, he found that the power consumption for two-stage system was 2.1 kW/m^3, which is much lower than that corresponding to the single-stage system, 1 kWh/m^3.

A MSF desalination system based on NVD was presented by Abutayeh and Goswami [42–44]. This was based on earlier recommendations suggested by Al-Kharabsheh and Goswami [16]. The system is similar to an MSF process. The saline water is heated using a solar heater and then passed on to the NVD flash chamber. Using a multi-stage system allows the vapour produced in one stage to be used to evaporate part of the water in the next stage. This promotes better energy utilization. Product rates of almost 1.66 kg/h were achieved using saline water feed temperature of 80℃. In a later study by Abutayeh et al. [45], theoretical and experimental investigation of the same system showed production rates of a maximum of 42.66 kg/h for a 3-hour period system run with initial pressures of 16 kPa.

A similar approach of using multi-stage system to enhance the product rate and performance was also presented by Gude et al. [46]. Building on their earlier works, they proposed a new two-stage low-temperature phase-change desalination process. The system consists of two evaporation chambers, two horizontal tube condensers (inside tube vapour condensation), one heat exchanger and three barometric columns for each stage. These three columns are the saline water, the brine withdrawal and the freshwater columns, each with its own holding tank maintained under atmospheric pressure. The three columns for each stage are at a height of about 10 m above the ground level to create vacuum pressures naturally in the spaces above the water columns. This configuration allows the desalination process to work without any mechanical pumping. Saline water is heated using a low-grade heat source, and the vapour generated from the first stage is used to heat the feed water in the next stage. The final stage condenser uses cold seawater for condensing the incoming vapour from the second stage. A combined production rate of almost 21 kg/h was achieved from the two stages with an energy consumption of 1,500 kJ/kg of freshwater.

An NVD desalination system using renewable energy will need some sort of energy storage to ensure uninterrupted operation of the process. Depending on the type of renewable energy used with the desalination process, different storage methodologies have been outlined by Gude [47]. As is mentioned earlier, thermal solar energy is considered the most suitable renewable energy source option for driving desalination processes. For such cases, thermal energy storage is required. A detailed calculation of optimum TES for a desalination plant driven by waste heat is given by Gadhamshetty et al. [48].

3. Evaporation rate calculation

The mathematical modelling of the NVD system requires simultaneous solution of equations for mass, energy and salt balances. These equations are the continuity equation, momentum equation, thermal energy equation and the species conservation equations. They can easily be obtained from many references for different coordinate systems [49]. These are partial differential equations, and their solution will require an expression for the evaporation rate.

Many equations have been reported in the literature for determining evaporation rates of pure water. They were all based on the equation derived by the Nobel Award-winning physicist Irving Langmuir [50]. One of the early modifications was presented by Knudsen [51], who introduced the “mass accommodation factor" to account for the difference between the theoretical and experimental evaporation rates:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \alpha(p_{\mathrm{v}} - p_p)\sqrt{\frac{M}{2\pi RT}} \tag{1}$$

where $\mathrm{d}m/\mathrm{d}t$ = mass evaporation rate per unit area ($\mathrm{kg/m^2\,s}$); p_{v} = vapour pressure of the liquid at the given temperature (Pa); p_p = partial pressure of the vapour in the ambient (Pa); M = molar mass; R = universal gas constant ($\mathrm{m^3\,Pa/mol\,K}$); T = absolute temperature (K); α = mass accommodation factor with values from 0 to 1.

Different values of α have been reported in the literature. They were obtained from experimental analysis based on water evaporating into its own vapour. A review of these studies is presented by Davidovits et al. [52]. They reported a range of values between 0.001 and 1 for the mass accommodation factor. Recent studies claim the mass accommodation factor to be a function of temperature [53,54].

Another water evaporation rate equation that has been widely used for studying NVD systems is the one proposed by Bemporad [19]:

$$\dot{m}_{\mathrm{ev}} = A \times \alpha_m \times \left(f(C)\frac{p_{\mathrm{v}}(T_{\mathrm{s}})}{\sqrt{T_{\mathrm{s}}+273}} - \frac{p_{\mathrm{v}}(T_f)}{\sqrt{T_f+273}}\right) \tag{2}$$

where $\dot{m}_{\mathrm{ev}}$ is the evaporation rate, A is the cross-sectional area of the evaporator, α_m is a modified mass accommodation factor, T_{s} is the temperature of the surface, T_f is the temperature in the freshwater chamber, p_{v} is the vapour pressure of the water and $f(C)$ is a correction factor to account for the presence of a salt concentration C.

The correction factor $f(C)$ is given by the following equation [19]:

$$f(C) = 1 - 0.0054\,C \tag{3}$$

The required thermophysical properties of seawater, such as the vapour pressure, density, specific heat, can be obtained from correlations compiled by Sharqawy et al. [55].

The mass accommodation factor for evaporation, α_m, is an experimental factor reported by Bemporad [19] to be in the range of 10^{-7}–10^{-6}. Other researchers who studied NVD systems using Bemporad's equation for water evaporation have referred to the same range without any mention of the exact number used or the method employed to determine it.

The range reported by Bemporad [19] appears to vary significantly from the numbers reported by other researchers. It is better to investigate the matter experimentally to get a more precise result.

4. Factors affecting the production rate

Several factors affect the production rate of freshwater. They include the seawater inlet temperature, condenser side temperature, evaporator surface area, brine withdrawal rate, water salinity and depth of water in the evaporator. Discussion of each of these factors is presented in the succeeding subsections.

4.1. Sea water inlet temperature

This is perhaps the most important factor that affects the production rate. As can obviously be concluded from Eq. (2), higher T_{s} will give a higher production rate. The production rate increases in an inverse exponential growth with the increase in temperature. This is also established in the studies by Al-Kharabsheh and Goswami [18] and Gude et al. [56].

Although the production rates have been reported differently by different studies based on their working conditions, the general trend is of an increase in the yield with the rise in evaporation temperature. A drop in the thermal efficiency of the process is reported by increasing the inlet temperature [29]. Hence, it is advised to study the cost of raising the temperature and see whether the increase is indeed needed or not.

4.2. Condenser side water temperature

Just like the inlet seawater temperature, the temperature of the cooled desalinated water chamber, or the condenser, is also an important factor. As can be seen from Eq. (2), the evaporation amount is a function of the pressure difference between the vapours above the evaporation chamber and the condenser side water. Higher temperatures on the condenser side result in higher vapour pressures, and this will in turn reduce the driving force for the evaporation process. Hence, it is desirable to have the T_f as low as possible. Since most of the researchers have relied on using ambient temperatures and "cool shaded areas" for condensing, the effect of this temperature has not been reported. However, one can quite easily deduce that a low temperature on the condenser side is highly desirable. Moore et al. [38] have in a way reported this by studying the effect of the temperature difference between the evaporator and condenser side. The production rate was predicted to increase exponentially with the temperature difference.

4.3. Evaporator surface area

The evaporator area plays a major role in the production amount. Obviously, a larger area will result in more evaporation. Again, this effect was not studied by any researcher. Most of the researchers either had conducted only theoretical studies or the pilot plants were of fixed dimensions, and hence, the evaporator area was not varied to study the effect. A scaling of the theoretical model by Al-Kharabsheh and Goswami [18] shows the relationship to be somewhat non-linear.

4.4. Brine withdrawal rate

Not all configurations of the NVD have a provision for brine withdrawal. Some set-ups come with only two legs, feed seawater inlet line and a fresh desalinated water outlet line. Hence, this factor is only for the set-ups that have a brine withdrawal line. Brine withdrawal rate does not appear in the evaporation equation directly so its effect is somewhat subdued. A study by Al-Kharabsheh and Goswami [20] using three different withdrawal rates shows a negligible effect of withdrawal rate on the production. However, the studied range was very small and higher withdrawal rates will mean an unnecessary loss of energy that has gone in to heating the inlet seawater. Lower withdrawal rates will cause scaling of the evaporator surface, which will gradually lead to damage of the equipment and will add to maintenance cost. A stand-off then is seen between these two factors. A quantitative assessment of each factor should lead to an optimal withdrawal rate which is neither too high to cause loss of heating energy nor too low to cause scaling or allow salt deposits in the evaporation chamber. A study done by Gude and Nirmalakhandan [57] also shows that an increase in the brine withdrawal rate results in a drop in the efficiency of the system.

4.5. Water salinity

As is apparent from Eq. (2), the concentration of salt in the water will have an effect on the evaporation rates. However, none of the researchers has investigated this effect experimentally in the NVD system. An increase in the concentration will mean a decrease in the correction factor $f(C)$ of Eq. (3), which will lower the pressure difference between the evaporator and the condenser sides. Similar results for the effect of salt concentration on evaporation rates of water have been reported by El-Dessouky et al. [58].

4.6. Water depth in evaporator

The effect of variation in the depth of the body of water in the evaporation chamber was reported by Al-Kharabsheh and Goswami [20]. He showed that the accumulated output increased slightly as the water depth was increased. As the depth of water increases, the volume of water that needs to be heated also increases. The evaporation rate depends on the surface temperature, and as such, the extra volume of water beneath the surface is an added load for the heating mechanism. However, the evaporation at the surface will result in lowering of the temperature, and hence, the volume of warm water will act as thermal energy storage to render the effect of this temperature drop insignificant. Ibrahim and Elshamarka [59] showed that both the production rate and the efficiency dropped with an increase in the water depth. The system is evacuated using a vacuum pump and not working on the natural vacuum. However, since the operation is under conditions similar to the NVD, one would expect similar trends.

5. Concluding remarks

A review of the various systems operated by the NVD has been presented. The NVD process works under low pressures achieved by gravity. Evaporation is carried out at low temperatures, which means less energy input for heating. This energy can be provided from a waste heat source or from renewable energy sources such as solar energy and geothermal energy. Desalination systems based on NVD are also environmentally friendly because they are either wholly or mostly dependent on renewable energy.

Since the process runs under vacuum, careful design considerations are needed to ensure that the system can run properly. In addition, it is important to ensure that pressure (or vacuum) and heat are not lost in connections throughout the system. The system requires that there be a water column of at least 10 m. So, if there is no existing structure with such provision, a separate tower must be constructed. A recent study done by Ma et al. [60] presents a modification for the NVD system to overcome the problem of the barometric height of water. Another common problem is the accumulation of the non-condensable gases in the system, which need to be vented out to ensure vacuum conditions.

As shown earlier, a number of studies have been done in the area of NVD. They have all been on very small-scale plants with evaporator areas of 0.1 m^2 or 0.2 m^2. Larger plants need to be built and operated to get data that are more realistic in order to obtain a better feasibility study.

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Symbols

$\mathrm{d}m/\mathrm{d}t$ — mass evaporation rate per unit area (kg/m^2 s)
p_v — vapour pressure of the liquid at the given temperature (Pa)
p_p — partial pressure of the vapour in the ambient (Pa)
M — molar mass
R — universal gas constant (m^3 Pa/mol K)
T — absolute temperature (K)
α — mass accommodation factor with values from 0 to 1
$\dot{m}_\mathrm{ev}$ — evaporation rate (kg/s)
A — cross-sectional area of the evaporator (m^2)
α_m — modified mass accommodation factor (kg m^{-2} Pa^{-1} s^{-1} K$^{0.5}$)
T_s — temperature of the surface of seawater (℃)
T_f — temperature in the freshwater chamber (℃)
$f\,(C)$ — correction factor to account for the presence of a salt
C — salt concentration (kg/kg)

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