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Evolution of a green mechanical vapor condensation desalination system

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ABSTRACT

Water suitable for human and animal consumption and for agricultural use is declining worldwide. A vast amount of seawater is available for purification, but the major current technologies, reverse osmosis, and mechanical vapor condensation (MVC), have a number of drawbacks, leading to rather costly purified water due to requirements of costly plant construction – based on pressure-resistant stainless steel – and/or high energy costs. An analysis of MVC operations, that are designed for sub-atmospheric pressures, reveals MVC technology can be evolved to a green MVC (GMVC) system that with specific design changes of the heat exchangers, can be operated at ambient atmospheric pressure and in a multi-stage sequence, providing savings from less costly construction materials such as polycarbonate, and improved energy efficiencies. Both very small and very large installations are made possible. In addition, the GMVC design provides for a more compact construction that can be readily transported to remote locations and easily scaled up as water requirements increase.

Keywords: Desalination; Green mechanical vapor condensation; Reverse osmosis

1. Introduction

Water suitable for human and animal consumption and for agricultural use is declining worldwide. Although the world's oceans contain vast quantities of water, the relatively high salt content renders it unfit for the above applications. Several commercial methods for desalination have been operating successfully for many years [1]. At present, the majority of commercial systems utilize reverse osmosis (RO) or one of the conventional thermal processes: multi-stage flash (MSF), multiple-effect distillation (MED), or mechanical vapor compression (MVC).

Although reverse osmosis has become by far the leading technology for desalination of seawater, especially due to its low energy consumption, there are a number of drawbacks centered around the filtration membranes [2,3]. These membranes are rather costly to manufacture, and performance degrades rapidly when fouled, such as by contamination or blockage, by inorganic, organic, and biological contaminants. In order to reduce fouling, the feed water is typically chemically treated with inhibitors to reduce the inorganic scale and with biocides to reduce microbial growth. These treatments add to the operating costs. In addition, the membranes require periodic cleaning, sometimes referred to as shock-flushing, that must be performed off-line. The contaminants removed from the flushing process are often diverted directly to the ocean, posing environmental concerns. RO systems are also typically quite large, constructed mainly of heavy and expensive stainless steel, require a significant capital investment, and are not designed to be relocatable [4].

Due to these challenges in RO technology, alternatives were examined with attention given to energy, investment and depreciation, and maintenance costs. The most promising alternative found was single effect mechanical vapor condensation (MVC) technology. Introduced in the 1980's, the MVC system was motivated by the need to develop a thermal desalination process driven solely by electrical power. In this process, vapor produced from heated source water, such as seawater, is subjected to mechanical compression, thereby producing condensed, purified water.

The latent heat released during condensation is available for heating additional source water to produce new vapors and the cycle is repeated [5].

MVC has several features that make it an attractive competitor to other technologies:

- Little or no pretreatment of the feed water.
- Acceptable energy consumption.
- Very pure condensate is produced.

Although there are a few variations of MVC, they all operate at multiple pressures, thereby requiring pressure equipment. If operation could be performed at ambient pressure so that less costly equipment could be employed, MVC would be an especially attractive technology. Although an extensive literature search found no MVC systems that currently operate at ambient pressure, no compelling reasons were found to refrain from operating at ambient atmospheric pressure.

Despite this technology producing very pure water and requiring few or no pre-treatments of source seawater, the market share is very small, only about 0.1% [6]. Indeed, although in theory vapor compression distillation is a relatively simple technology, putting it into practice economically at a commercial scale is challenging. Trade-offs between energy efficiency and process kinetics typically result in a rather costly operation. The typical operating pressure is sub-atmospheric, resulting in a requirement for pressure-resistant metal structures, vacuum pumps, and a relatively large compressor. Although overall efficiency is improved by operating at sub-atmospheric pressures rather than at atmospheric pressure, this decision results in an increase in the kinematic viscosity of the vapor and in a need for larger volume containers for both evaporation and condensation, with a concurrent reduction in the heat exchange surfaces per unit volume. With these constraints, it is inevitable that energy efficiency is sacrificed for improved kinetics. In addition to the aforementioned concerns, when seawater is used as the water source, the additional expense is incurred due to the need for corrosion-resistant metals for containers and piping that directly contact the seawater.

Furthermore, in conventional processing, the evaporation step occurs in a single stage using a single compressor, a circumstance that adds to the energy cost. Also in conventional processing, during spraying and/or boiling of the seawater, droplets of saline also form in the vapor zone, resulting in a need to employ a “de-misting” device to remove the saline droplets from the pure water vapor.

When all of the above factors are considered in plant design, rather large structures of considerable weight are required and these structures are expensive and neither movable nor readily transportable.

Although the above description of MVC technology seems to place it as a poor competitor to RO technology, a new approach is presented that uses ambient pressure operation, polymeric components, modular construction, eliminates pretreatment, and has moderate energy requirements. This is viewed as an evolutionary step from current MVC to green mechanical vapor compression (GMVC) distillation. The aspects and advantages offered by GMVC are discussed in greater detail below.

2. Design considerations

The new GMVC system design includes heat exchangers constructed from polymer materials. Replacing metal with polymer is made possible by operating at ambient pressure. This combination of polymer heat exchangers with ambient pressure operation enables improved efficiencies in heat transfer, energy utilization, non-compressible gas purging, and a modular, portable assembly.

2.1. Basic layout

Fig. 1 displays a schematic of the basic layout of the system. The system comprises four main items: tanks 4 for heating supply water; condensed water collection tank 3; counter-flow heat exchangers 2; and evaporation/condensation (E/C) blocks 1. The E/C blocks are mounted in an enclosing container. The E/C block is displayed in greater detail in Fig. 2.

The E/C block comprises alternating evaporation cavities 5 and condensation chambers 6. Duct work is provided for supplying compressed steam 7 and for collection of condensed water 8. Also included is a purge duct for the release of steam that has a high concentration of atmospheric gases. Each block also includes a collection area for percolated water.

Fig. 3 displays a section of an E/C block in more detail. The steam condenses into water 13 in condensation chambers 6 and collects in the bottom of the chamber. The spaces between condensation chambers are the evaporation cavities 5 that are blocked at the top with plugs 10. The condensation chambers 6 have sidewalls 11 of plastic film or extruded profiles. The other surface, exposed to the evaporation cavities, is covered with a thin, hydrophilic fabric 12. The fabric directs percolating saline solution into a collection tank. When the condensation chambers are of thin films that may be deformed under pressure fluctuations, the fabric aids in stabilizing the film.

2.2. Heat exchanger

In any MVC application, an important factor in the overall volume of working assemblies is the heat exchange

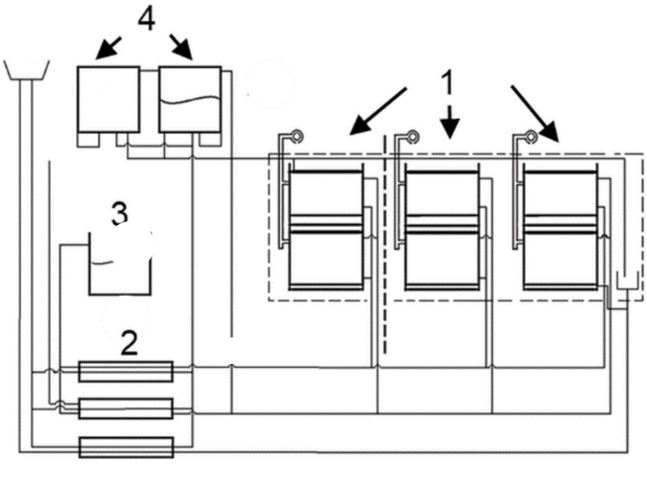

Fig. 1. Major items in a purification assembly.

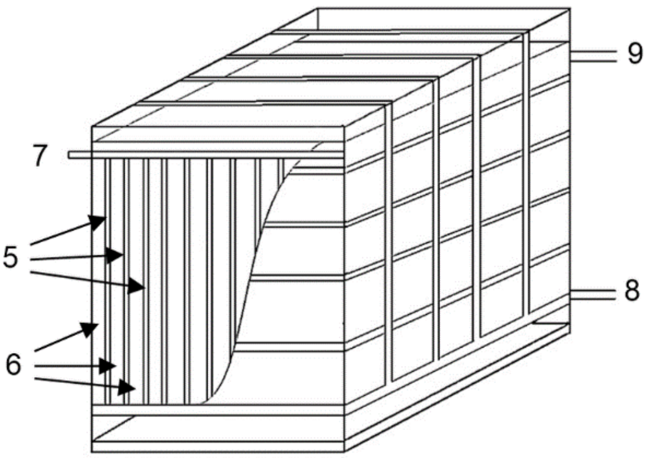

Fig. 2. Components of an evaporation/condensation block.

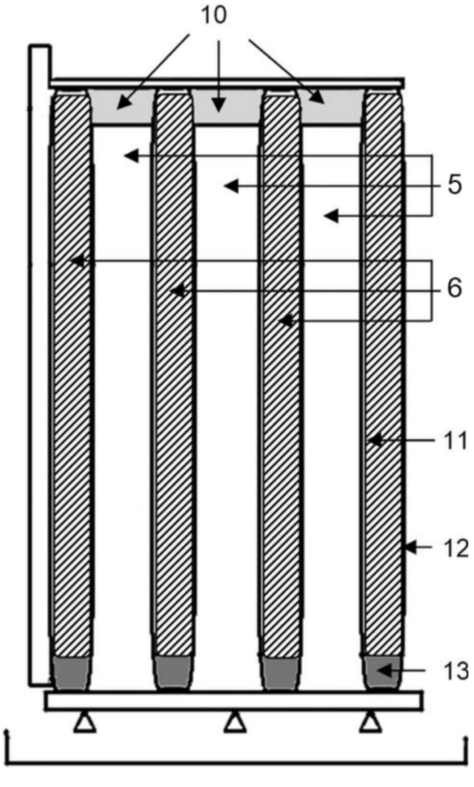

Fig. 3. Details of an evaporation/condensation block.

surface area per unit volume. By operating at normal atmospheric pressure, the bulk of the metal heat exchange material can be replaced with commercially available polymeric material with a significant increase in heat exchange surface per unit volume, resulting in a reduction of the thermal and pressure differentials required between the condensation area and evaporation area. The polymeric assembly can be housed in a robust metal cage to allow centralization of the feeding and purge means and to contain the thrusts of the compressed steam.

The combination of the structure of the polymeric evaporation surfaces with the reduction in thermal differential enables a seawater feed to evaporate without boiling. In addition, the evaporation can occur in a single, simple container that is not in contact with salt water, in multiple steps of progressive concentration, taking advantage of the lower energy required for the initial evaporation steps. This design also provides a simple, energy-efficient means for purging non-compressible atmospheric gases.

2.3. Heat transfer

The main component of the new green mechanical vapor compression (GMVC) design responsible for providing cost savings compared to existing technology is the heat transfer equipment. Current technology operating at sub-atmospheric pressure requires pressure and corrosion-resistant materials that are typically made from passivated stainless steel. This equipment tends to be costly, to have a rather large weight per volume, and is not readily moved or transportable after installation. In addition, vacuum pumps are required to produce the sub-atmospheric pressure.

Because the GMVC design is operated at ambient pressure, the heat transfer equipment can be constructed from light-weight, inexpensive materials such as polycarbonate. In addition, the walls of the heat exchanger can be much thinner and the evaporation and condensation chambers reduced in volume, providing a surface area per volume that is substantially greater than is possible with the conventional metal heat exchange unit. Operating at ambient pressure provides a very low kinematic viscosity coefficient of steam, resulting in very low resistance to vapor flow in the system. This low resistance enables the condensation chambers to be designed with thin walls and narrow evaporation interspaces, resulting in a very large heat exchange surface per unit volume. Polycarbonate plastic film or extruded alveolar polycarbonate are examples of materials that are suitable for this application. This heat exchanger design is a plate form, providing a number of advantages compared to the pipe form used in conventional heat exchanger design [7].

2.4. Water production

There are three main factors that affect the quantity of condensed water produced per unit volume and time in an MVC system: the heat exchange surface; the global heat transfer coefficient; and the ΔT for heat transfer in the evaporator above the boiling point temperature (BPT) of the water. However, providing the energy for operating at high ΔT is very costly, especially at lower pressures. Therefore, the system must run at the lowest possible ΔT. The new heat exchanger design that incorporates a high heat exchange surface per unit volume and acceptable heat transfer coefficient makes it possible to operate with a very small ΔT. In fact, ΔT is sufficiently low that evaporation occurs without boiling, enabling the evaporative surfaces to be positioned vertically with the saline water percolating against their walls. This also results in the steam that is free of contaminating saline water droplets and the elimination of demisters.

Furthermore, additional efficiencies can be realized when operated in a multi-step condensation mode in contrast to the typical single-step mode for conventional systems. The heat exchange panels can be packaged into a single housing, resulting in evaporation occurring at differential pressures as the saline becomes progressively concentrated as it passes through successive cages. In addition, this multi-step progressive concentration design enables efficient purging of the non-compressible gases.

It is estimated that the heat exchanger will provide 200 m^2 of surface area per cubic meter. When combined with an estimated heat exchange coefficient of 400 W/(m^2·°C), then each cubic meter of a cage assembly would produce about 127 L/h for each 1°C ΔT above BPT provided in each step. Further improvement of the heat exchange coefficient to 1,000 W/(m^2·°C) has been obtained with modest changes by feeding source water in intermittent mode, thereby creating a significantly thinner layer of saline solution, yielding great improvement with reference to the resistance to heat transmission. Appendix 2 shows some examples of possible production of distillate and relative consumption of electrical compression energy for desalination from 35 ppt to 70 ppt as a function of some parameters relating to ΔT for heat transfer, compression, and efficiencies.

2.5 Energy and pressure

In an ideal GMVC process the compression energy needed to obtain a ton of condensed water would be about 1.7 kWh when operating at 100°C (Appendix 1). Moreover, in order to have kinetics, it is necessary to apply a ΔT for heat transfer which similarly has an energy cost of about 1.7 kWh/t/°C operating in ideal terms at 100°C. Literature studies of commercial MVC operations report far higher energy requirements, indicating that significant energy cost reductions can be realized through changes in the operating parameters.

By vaporizing without boiling, the evaporation and condensation chambers can be designed with very thin interspaces, which translates to a high surface area to volume ratio. The thinner the interspaces, the smaller that ΔT for heat transfer can be to yield the same amount of product. A smaller ΔT translates to a smaller compression ΔP, enabling even thinner walls. However, the practical limits of the interspace size and wall thickness for both the manufacture and operation of a heat exchanger are yet to be determined.

2.6. Heat balance

The main thermal losses are due to purging of non-compressible gases, losses through insulation, and above all losses due to heat necessary to compensate for the ΔT manifested in the heat exchanger (HX) that in counter-flow technology, heats the source water and cools the desalinator discharge. Thermal losses through insulation are a function of installation size, production volume, and amount and type of insulation applied. Gas purging must be conducted in order to maintain operating efficiencies. As the water passes through the evaporation process, non-compressible gases accumulate that must be purged. This purging operation results in thermal losses that would be significant in conventional MVC designs. However, the GMVC design enables processing in multiple evaporation-compression cycles, enabling multiple purges that produce only modest thermal losses. Because the thermal losses due to purging of non-compressible gases are low and because the heat of purging is almost completely recovered in the counter-flow HX, these heat losses do not assume any significant importance. The most significant thermal losses are those occurring in the HX in counter-flow with the amount of thermal loss varying according to the ratio of the concentration of source water achieved and to the efficiency of the HX. In order to avoid very expensive and high energy-consuming metal HX, a new solution, made of extruded alveolar polycarbonate material that enables to have costless very large sections and fluids to move in laminar motion, was studied. This solution should be able to provide a 2°C ΔT between counter-flows. Our initial calculation estimate the heat exchange coefficient could exceed 500 kWh/m^3°C; so for the production of 1,000 t/d the volume of counter-flow HX device would not exceed 8.5 m^3; energy to pump would be quite low: for a counter-flow HX having a section of 1 m^2 and 100 m^3 of fluid supply/h, 0.02 kWh/t would be needed for each meter length (i.e., 0.08 kWh/m per ton of distilled water produced in a 35–70 ppt desalination; the preferred length is about 2 m).

Operating with a counter-flow HX that can assure a 2°C of ΔT between flows when performing at its highest contemplate of production volume at a given concentration, in the presence of good insulation it allows not to need an additional supply of thermal energy. Operating the same device at lower ΔT for heat transfer, since the lower flow of fluids in the HX would result in a lower ΔT between flows and so a lower request of thermal energy for integration, will not require an additional supply of thermal energy either, till thermal losses through insulation play a too important part. On the contrary, operating at lower concentrations with the same HX would possibly lead to requests for thermal contributions.

In conclusion: if the HX is correctly sized, no particular contributions of thermal energy are necessary with the exception of the start of operations.

2.7. $CaSO_4$ and $CaCO_3$ scaling

Over the range of normal operating concentrations and temperatures, no $CaSO_4$ scaling should occur.

To solve the problem of $CaCO_3$ scaling, the literature proposes numerous solutions: chemical treatments, resorting to the nano-flitration of a fraction of the source water... A possibility refers to what is reported by Dreiser et al. [8]. The solution shown refers to the possibility to occasionally increase/decrease the compression pressure of vapor and so – thanks to the deformability of the plastic film – to cause the detachment of the fragile incrustations of $CaCO_3$. This solution would be possible also in our case if the plastic film is hydrophilic (a plasma treatment for example makes plastics films hydrophilic, but it must be tested for how long it keeps that feature) since the adhesive forces of mineral scale deposit are very low on plastic films; hydrophilic plastic films would allow homogeneous percolation of the saline solution making the thin fabric useless.

However, the particular configuration of the GMVC device and the one of the plastic counter-HX in laminar motion under study allow a very preferred solution, that of using just the same distilled water produced to remove the $CaCO_3$ crystals, possibly without additives, or with minimal quantities of acid, considering the greater effectiveness acids have in distilled water:

- for the evaporation device, the fact of having a great multiplicity of packs would allow to feed in one or more packs in turn, without removing them from the insulated container, the distilled water produced in other packs instead of the saltwater and recover it as good water. So $CaCO_3$ scaling would be removed without interrupting the production cycle;
- for our plastic counter-flow HX solution, similarly, it is possible to periodically invert the feed flows between source/distilled water.

2.8. Modularity

A particular benefit realized from using lighter materials with modular structures is the option to design smaller scale desalination units that are easily transported and assembled in smaller communities and more remote locations. The modular design enables easy scaling up of the output as the community water requirements increase. This more compact design also enables the creation of medium or large-capacity desalination plants based on positioning in-line a series of readily available containers. A singe 40-foot container operating at 4°C ΔT could produce about 400 tons of freshwater per day or about 900 tons with intermittent feeding of source water.

3. Summary

Potable water can be produced by several desalination technologies. MVC was selected as the best option to investigate for process improvements. It has been determined that the MVC technology can be evolved to a green mechanical vapor condensation (GMVC) system by operating at ambient pressure with small ΔT, and replacing metal, pipe-based heat exchangers with high surface area per unit volume polymer heat exchangers. The GMVC system provides advantages over current technologies including light weight, lower capital costs, modular construction, no or limited pretreatment of feed water, and moderate energy requirements.

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Appendix 1: Compression work calculated with theoretical efficiency of compressor and process of 100%

Initial ppt in step	Final ppt in step	Residual fraction of saline solution	Condensed water	Progressive quantity of condensed water	Compression work necessary for condensation in the fraction	Compression energy consumption in the step	Progressive energy consumption	Progressive units of compression work required: kWh/t of H_2O condensed	Progressive % of condensed water/ source water supplied
ppt	ppt	kg/t	kg/t	g/kg	kWh/ton	kWh (*10^3)	kWh (*10^3)	kWh/t	%
35	40	875	125	125	1.2268	153.35	153.35	1.227	12.5%
40	45	777.8	97.2	222.2	1.3673	132.93	286.28	1.288	22.2%
45	50	700.0	77.8	300.0	1.5131	117.69	403.97	1.347	30.0%
50	55	636.4	63.6	363.6	1.6605	105.67	509.63	1.401	36.4%
55	60	583.3	53.0	416.7	1.8119	96.09	605.72	1.454	41.7%
60	65	538.5	44.9	461.5	1.9655	88.19	693.91	1.503	46.2%
65	70	500.0	38.5	500.0	2.1175	81.44	775.36	1.551	50.0%
70	75	466.7	33.3	533.3	2.2873	76.24	851.60	1.597	53.3%
75	80	437.5	29.2	562.5	2.4520	71.52	923.12	1.641	56.3%
80	85	411.8	25.7	588.2	2.6233	67.51	990.63	1.684	58.8%
85	90	388.9	22.9	611.1	2.7953	63.95	1,054.57	1.726	61.1%
90	95	368.4	20.5	631.6	2.9745	60.88	1,115.46	1.766	63.2%
95	100	350.0	18.4	650.0	3.1534	58.09	1,173.55	1.805	65.0%

Appendix 2: Calculated production of distillate and relative consumption of electrical compression energy operating with intermittent feeding as a function of some parameters for desalination from 35 to 70 ppt

Heat exchange: average thermal conductivity of water in the temperature range 20°C–100°C = 0.63 W/m°C; thermal conductivity polycarbonate: 0.63 W/m°C; the thermal conductivity of the external salty aqueous layer (the presence of fabric in the external thickness causes a reduction in the thermal conductivity): 0.55 W/m°C; thickness of the outer layer of percolating condensed saline water in intermittent mode as tested: 0.12 mm; internal layer thickness of percolating condensed water: 0.25 mm; polycarbonate layer thickness: 0.08 mm.

Resulting thermal conductivity (in the absence of intermittent feeding, calculated thermal conductivity is about 400 W/m^2°C)	W/m^2 °C	985
Heat exchange surface/m^3 of the exchanger	m^2/m^3	200
Heat capacity/m^3 with a heat exchange surface of 200 m^2/m^3	kWh/m^3	197
Hourly production of distilled H_2O/m^3 of exchanger for a ΔT for heat transfer of 1°C (the latent heat of evaporation = 627 W/L)	L/h/m^3	314

Distillate production/m^3 of heat exchanger/°C of ΔT over boiling temperature for heat transfer and example of daily production according to the ΔT with a 40′ container with inner volume 50% filled with heat exchanger (i.e., 32 m^3)

ΔT for heat transfer over boiling point temperature	ΔT: °C	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Daily production of distilled H_2O/m^3 of exchanger	m^3 distilled H_2O/m^3/d	7.5	11.3	15.1	18.9	22.6	26.4	30.2
m^3 distillate produced in a 40′ container/d	m^3 distilled H_2O/container/d	239	359	479	599	718	838	958

Compression energy consumption for compression (compression energy to get to the BPT for a desalination from 35 to 70 ppt = 1.55 kWh/t + additional compression energy expended for heat transfer = 1.67 kWh/t/°C); efficiency coefficient 0.783 (compressor 0.85 × electric 0.95 × non-condensable gases and loss of pressure in the ducts 0.97)

Total compression energy (ideal compressor)	kWh/t	3.221	4.056	4.891	5.726	6.561	7.396	8.231
Effective compression energy needed	kWh/t	4.1	5.2	6.2	7.3	8.4	9.4	10.5

Thickness of percolated film that evaporates/h and seconds necessary for a 10% increase in salt concentration (intermittent time lapse; thickness of aqueous film + fabric after stopping the brine supply = 0.12 mm as tested)

Percolated water thickness that evaporates in 1 h	mm/h	1.57	2.36	3.14	3.93	4.71	5.50	6.29
Seconds needed to reach a 10% increase in salt concentration	S	18.5	12.4	9.3	7.4	6.2	5.3	4.6