MECHANICAL VAPOR COMPRESSION AND RENEWABLE ENERGY SOURCE INTEGRATION INTO DESALINATION PROCESS
LIFE-Desirows Case Example

by

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This paper shows the adequacy of the parameters for correct modelling of a mechanical vapor compression desalination plant, explores the influences of parameters considering an energy efficiency vision of the model, indicating which components affect the most to its final performance and energy consumption. The present work also offers the preliminary results extracted from a real experimental facility powered by RES. The case study, in Cartagena, Spain, as part of the LIFE-Desirows project, aims to address brine disposal, salt crystallization, nitrate elimination, water resource recovery, and carbon neutrality. After providing an overview of the current state of desalination, the focus shifts to brine removal technologies, with a specific emphasis on mechanical vapor compression. The technical aspects of coupling such technologies for enhanced energy efficiency in desalination processes are discussed, along with associated challenges and limitations, as well as the inputs and outputs considered for the analysis. The paper reinforces the importance of improving energy efficiency in thermal desalination processes with its results, fostering a discussion on potential avenues for further research and development in concentrate valorization, as well as its positive effects on the environment and economy.

Key words: *seawater, brine removal, desalination, energy efficiency, sustainability*

Introduction

Water scarcity is considered by the United Nations as a worldwide problem [1], affecting some areas more severely than neighboring regions [2] with clear examples in Europe such as the South-East of Spain [3]. This problem can be monitored not only with the amount of rainfalls registered in an specific area [4], but also testing the water quality of its aquifers, severely damaged in a lot of cases by the presence of pollutants from human-related activities [5], inappropriate disposal of residual brines due to lack of legislation [6], or simply having low capacity due to over-exploitation [7]. One of the solutions to this problem is creating new sources of freshwater from nearby elements where two main strategies can be identified: regeneration [8] and desalination technologies [9]. The regeneration strategy focuses on recy-

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cling wastewater to be reused, but the water quality does not necessarily match human-consumption standards [10]. The obtained water can be safely used for gardening or industrial purposes, supporting strategic economic activities [11]. The desalination strategy, on the other hand, is generally focused on extracting freshwater with human-consumption standards from natural sources, such as seawater and brines, by removing both salts and materials dissolved in it, where books by Kucera [12] and Belessiotis [13] resume the vast majority of desalination technologies available. Desalination thus stands out as the most appealing option for freshwater generation, as it is stated in Jones *et al.* [14] and Eke *et al.* [9] papers analyzing the current status of this technologies.

The initial concentration of the fluid plays a pivotal role in determining the optimal desalination technology [15], and they can be categorized into two primary groups. The first involves thermally or electrically driven distillation and evaporation processes. The second entails water extraction through the application of pressure against a permeable membrane. Further details can be found in Belessiotis *et al.* [13]. Since the source of freshwater for the majority of locations is seawater, with concentrations around 35 g/L, the reverse osmosis emerges as the most favorable technology for this cases, providing optimal specific energy consumptions [15]. In fact, around 70% of current desalination plants use this technology. Traditionally, and stated in Jones paper, residual brine from desalination were sent back to the ocean [14], but their high salinity level affects considerably to the area where these discharges happen, increasing society's concern about its long-term effects on the environment. A remarkable solution to this problem is based on the desalination process.

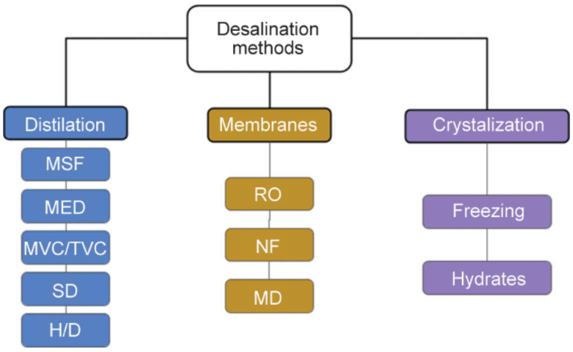

Figure 1. Desalination methods based on water separation

However, reverse osmosis gives unfavorable conditions for concentrations higher than 70 g/L [15]. Other technologies provided in fig. 1 can handle larger salinities. Among the potential solutions, the mechanical vapor compression (MVC) technology is accepted to be used for high-salinity brine processes. Some of the advantages of this technology is that it only requires electricity to power the whole operation process and, since it is a distillation process, the final water has minor amount of dissolved salts [16]. There are no breakthrough events surrounding this technology for the past decades and the operational costs are quite similar to other technologies, which increases the interest for developing improvement strategies in desalination processes such as reducing its energy demand.

The LIFE-Desirows Project. General overview

The LIFE-Desirows (LIFE19 ENV/ES/00447) is a demonstration project to reduce first osmosis brine, crystallize salts, remove nitrates, and recover water resources. This global proposal is based on renewable energy resource integration, mainly solar and biomass resources. In this way, the project, financed by the *Life Program* of the *European Union*, combines various technologies from an industrial perspective to minimize energy consumption, based on zero liquid discharges (ZLD) [17]. In addition, the project complies with the circular economy strategy as long as no waste is generated since it is proposed to reuse all the salts, the researchers point out [18]. The LIFE-Desirows project has a solar PV installation connected to the grid, and its nominal power is 35 kWp. Given the energy-intensive nature of desalination processes, the implementation of energy efficiency strategies results in improved operational conditions. Moreover, by considering the energy demand as a limiting factor of the plant while modeling the installation, it is possible to ensure an optimal use of the limited electricity generated by the solar PV installation, achieving lower freshwater production costs.

The brine from the desalination of groundwater has a multitude of dissolved salts that, when properly separated, can be used, also allowing the generation of additional water resources. The LIFE-Desirows project aims to recycle the brine by first eliminating the nitrates, recovering part of the less soluble salts for later use as fertilizers and allowing the rest of the salts to be used industrially [19].

The mechanical vapor compression for desalination purposes

As previously indicated, this is an electrically driven desalination process employing distillation. The procedure involves the boiling of seawater or brine to generate vapor, subsequently compressed utilizing a compressor. During this phase, the vapor undergoes an increase in both temperature and pressure, facilitating its transformation back into freshwater. The vapor compression process aids in recovering the energy expended during evaporation, rendering MVC highly energy efficient. The compressed vapor is then condensed, and the resultant freshwater is collected. Operating within a closed-loop system, MVC minimizes water consumption and wastewater discharge. It stands as a scalable, cost-effective, and environmentally friendly desalination method well-suited for high salinity brines, making it particularly advantageous for the revalorization of residual brines [13]. For this case-study, the number of elements present in the system was lowered to the fullest to address the dependence between the two major components: the compressor and the evaporator. The brine evaporator uses the latent heat from the compressed distillate steam to evaporate new brine and bring it to the compression stage, and the steamer is supported by an electrical resistor to compensate for losses and keep the process running. In addition, the prototype has three tanks, inlet brine, distillate and concentrated brine, as well as the recirculation pump linked to the evaporator. The diagram depicted in fig. 2 not only represents the connections between all the modeled elements, but also includes a numeric value of the stages for the distillation-concentration process explanation. The different points, from 1 up to 6, represent the corresponding stages that the initial brine suffers along the desalination process until it is converted into distillate water and stored in a tank. These stages are properly defined in tab. 1, for a better comprehension of the global process.

The MVC system within the LIFE-Desirows project, depicted in fig. 3, encompasses additional elements compared to the model in fig. 2, with a specific focus on enhancing energy efficiency. Despite its small-scale nature, this plant incorporates the same components found in large-capacity desalination plants based on this technology solution. This feature enables researchers to analyze performance metrics, making easier the extrapolation of results to larger capacity installations with a more cost-effective initial investment.

The mechanical vapor compression modeling

This section describes the adequacy of the parameters provided by the manufacturers of the MVC system elements to perform the modeling properly taking into account the properties of the input brine. The MVC for desalination purposes operates in two distinct stages:

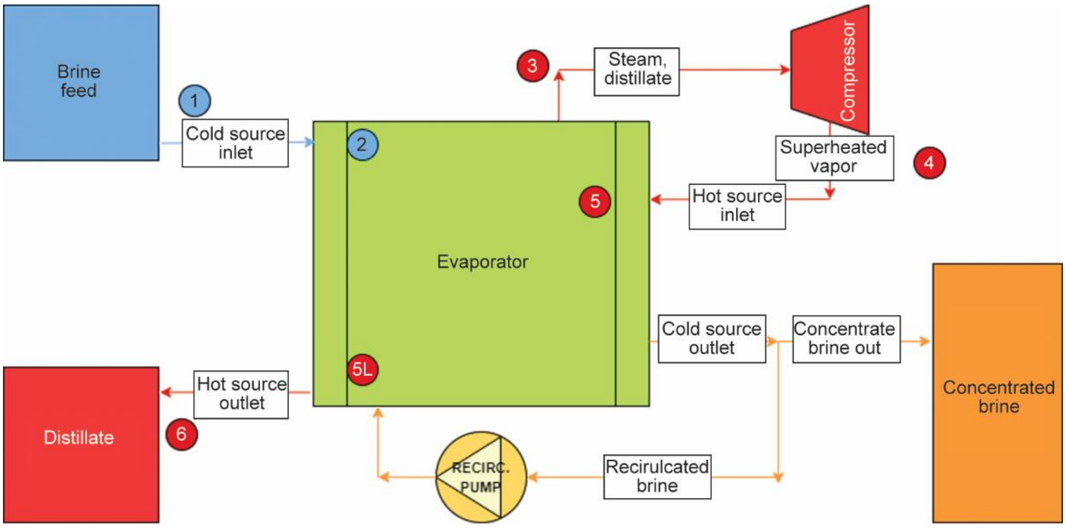

Figure 2. Diagram of the case-study MVC desalination system

Table 1. Stages of the MVC for desalination purposes

Item	Explanation of the stage
1	Initial brine exiting the storage tank
2	Initial brine entering the evaporator (cold source inlet)
3	Steam exiting the evaporator (cold source outlet)
4	Superheated vapor exiting the compressor
5	Superheated vapor entering the evaporator (hot source inlet)
5L	Vapor converted towards liquid distillate (phase change)
6	Liquid distillate exiting the evaporator (hot source outlet)

Figure 3. Installation of the MVC equipment. LIFE-Desirows project (Cartagena, Spain)

the stationary stage and the transitory stage. Each stage involves specific system components, such as preheaters, recirculation pumps, and transitory stage heaters. However, the fundamental functionality of the MVC relies on two critical components in both situations: the evaporator and the compressor. Using the TRNSYS® software [20], the researcher can effectively model these components from a thermodynamic perspective, since packages available do not contain these elements. Furthermore, the software facilitates the analysis of interactions among system components, the behavior of variables, and the performance of the elements. This comprehensive analysis enables the generation of a parametric study focused on the most relevant variables.

Prior to the modeling stage, we must define the input variables and its values properly. The most relevant input variables of the compressor, for the modelling process, are its speed and the pressure difference achieved. These values allow the researcher accessing the data base provided by the manufacturer, obtaining variables such as its volumetric flow rate, shaft power and temperature increase. However, the fluid used by manufacturer is air, whose properties are not the same as steam ones. We have to extrapolate the initial results given by manufacturer to obtain the ones we need: inlet volumetric flow rate for steam, $\dot{V}_{\text{comp.inlet}}$, shaft power, $Power_{\text{shaft}}$, and temperature increase, $\Delta T_{\text{Norefri}}$, where $Power_{\text{shaft}}$ will remain constant for both fluids. Moreover, manufacturer did not use refrigeration for their testing, so these values require extra processing in order to be used on the model. The steam values obtained, without considering refrigeration, are the ones we will analyze on this paper, but we will present some of the model equations so that the reader can comprehend the relevance of adopting an energy efficiency vision for improving the MVC operating costs.

Starting with compressor model itself, we can obtain the outlet temperature, $T_{\text{out,Norefri}}$, and mass-flow rate, $\dot{m}$, without refrigeration using:

$$\dot{m} = \frac{\dot{V}}{v} \tag{1}$$

$$T_{\text{out,Norefri}} = T_{\text{steam}} + \Delta T_{\text{Norefri}} \tag{2}$$

where v is the specific volume, T_{steam} – the inlet temperature of steam entering the compressor, and $\Delta T_{\text{Norefri}}$ – the temperature increase for steam without considering refrigeration (interpolation of manufacturer's values). In our model, we set the outlet temperature of the compressor, which is the inlet hot source of the evaporator. Since we know that temperature, we can obtain the amount of refrigerant required for cooling the super-heated steam up to the desired temperature using energy balance equations. The amount of heat (energy) absorbed by the refrigerant is obtained by:

$$\dot{Q} = \dot{m}h \tag{3}$$

$$\dot{Q}_{\text{refri}} = \dot{Q}_{\text{out,NOrefri}} - \dot{Q}_{\text{set}} \tag{4}$$

where h is the specific enthalpy, $\dot{Q}_{\text{refri}}$ – the energy absorbed by the refrigerant, $\dot{Q}_{\text{out,NOrefri}}$ – the energy in the outlet conditions without refrigeration, and $\dot{Q}_{\text{set}}$ – the energy with output set condition. As a result, we can obtain the amount of refrigerant required for achieving the set outlet temperature with eq. (5), where Δh_{evap} is the enthalpy of vaporization:

$$\dot{m}_{\text{refri}} = \frac{\dot{Q}_{\text{refri}}}{(h_{\text{steam}} - h_{\text{refri}}) + \Delta h_{\text{evap}} + (h_{\text{out}} - h_{\text{steam}})} \tag{5}$$

From mass-flow rate of refrigerant, we can calculate its volumetric flow rate, and considering the inlet volumetric flow rate for the compressor is one of our compressor manufacturer's inputs, the volumetric flow rate of steam entering the compressor is the difference between the compressor total volumetric flow rate minus the refrigerant volumetric flow rate. Reversing the calculation process, we use eqs. (6)-(8) to obtain steam mass-flow rate.

$$\dot{V} = \dot{m} \times v \tag{6}$$

$$\dot{V}_{\text{steam}} = \dot{V}_{\text{comp,inlet}} - \dot{V}_{\text{refri}} \tag{7}$$

$$\dot{m}_{\text{steam}} = \frac{\dot{V}_{\text{steam}}}{v_{\text{steam}}} \tag{8}$$

During the compression process, the inlet fluids in vacuum conditions suffer its recompression, reaching atmospheric pressure and suffering changes in the process. On the one hand, its temperature and volume increases. On the other hand, its mass remains constant, allowing us calculating with eq. (9) the outlet conditions of the super-heated steam exiting the compressor and entering the evaporator:

$$\dot{m}_{\text{out}} = \dot{m}_{\text{steam}} + \dot{m}_{\text{refri}} \tag{9}$$

There are more equations used on the TRNSYS® model, but this paper focuses on the analysis of input data available for that model since the experimental facilities was not operating yet, more insights and equations from this case-study can be seen in recent publications [21].

Following the methodology of previous researchers, the primary objective is to achieve the lowest possible evaporation temperatures in order to operate at reduced temperatures, minimizing corrosion-related damages, with the power consumption of the compressor being a dependent output variable [22]. Additionally, a key goal is to maximize freshwater production while minimizing concentrated brine output. The lowest temperature can be identified by employing the maximum compression ratio provided by the compressor manufacturer, while the desired evaporation ratio remains as a fixed value. However, achieving these temperature conditions comes at the expense of high energy consumption. To enhance energy efficiency in the modeling stage, the power consumption of the compressor is designated as an input variable, and it varies based on the amount of energy available from solar panels. To illustrate the considerable potential of this innovative methodology, we will show in the Results section different power consumption profiles obtained at different pressure regimes while achieving comparable distillate production levels. This comparative analysis serves as an illustrative example of the significant advantages offered by the proposed approach in contrast to conventional procedures. For this purpose, we will compare various sets of inputs and parameters, analyzing the outputs achieved with those combinations. The list of variables is summarized in tab. 2, where we can expect higher energy consumptions associated with lower evaporation temperatures, with energy consumption serving as an output variable.

Table 2. Input/output variables and ranges considered for the MVC modeling

Input variables	Value	Parameters	Value	Output variables
Temperature inlet brine	Ambient temperature	Evaporation rate	30%	Power (compressor)
ΔP (compressor)	100-200 mbar	Power (pump)	0.82 kW	Temperatures
Rotational speed (compressor)	1200-5000 rpm	Initial concentration	13%	Final concentration
		Recirculation flow rate	0.26 kg/s	Flow rates

Note that challenges abound in the implementation of MVC for desalination. The primary concern lies in the substantial energy requirements of the compression stage. The energy-intensive nature of this process, particularly at lower evaporation temperatures, may limit the overall cost-effectiveness and environmental sustainability of MVC systems. Furthermore, the economic feasibility of MVC in desalination is contingent upon the local energy landscape. In regions with limited access to cost-effective energy sources, MVC may prove economically impractical compared to alternative desalination technologies. With this aim, most relevant input and output variables targeting these aspects were selected for our case study.

Results and discussion

In line with previous contributions and methodologies, the main objective is to optimize the compressor performance by maximizing the pressure difference, ΔP, to achieve the lowest possible evaporation temperature. However, during the analysis of power consumptions at varying ΔP values, it became evident that operating with higher temperatures resulted in more substantial energy savings than initially anticipated. This observation introduces a novel perspective when working with MVC systems in desalination processes. To proceed, leveraging information from the project suppliers becomes imperative. The compressor manufacturer has conducted comprehensive testing on their products before market distribution, providing documentation to consumers for informed product selection based on specific operational requirements. Note that the compressor testing involves air as the working fluid, and its properties do not align with those of steam used in our application. Consequently, there is a need to convert the compressor operating results from air-based metrics to steam-based metrics for accurate integration into our desalination system.

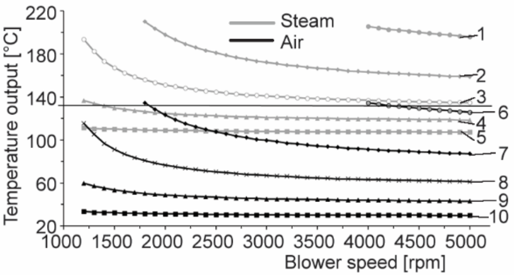

Figure 4. Compressor temperatures at different pressures, ΔP, for both air: *1 – ΔP = 500 mbar, 2 – ΔP = 400 mbar, 3 – ΔP = 300 mbar, 4 – ΔP = 200 mbar, 5 – ΔP = 100 mbar,* **and steam:** *6 – ΔP = 500 mbar, 7 – ΔP = 400 mbar, 8 – ΔP = 300 mbar, 9 – ΔP = 200 mbar, 10 – ΔP = 100 mbar*

Given the vacuum compression ratios provided by the compressor manufacturer, set at two, our objective is to achieve a ΔP of 500 mbar when operating with steam. Simultaneously, we aim to maintain an optimal evaporation ratio of 30%. However, upon calculating the outlet temperatures at this specified pressure difference, we encountered an additional constraint from the manufacturer regarding the maximum allowable outlet temperature for the compressor. Specifically, the compressor ceases operation for temperatures exceeding 130 °C, necessitating careful consideration to prevent operational failures. Note that the correlations derived for these calculations were established without employing any cooling mechanisms for the compressor. Consequently, the steam results presented do not account for refrigeration effects. In summary, upon analyzing the results depicted in fig. 4, it becomes apparent that for pressure differences exceeding 200 mbar, the outlet temperature surpasses the stipulated maximum, leading to a reduction in the desired compression ratio and an increase in the evaporation temperature. The manufacturer did not provide any value higher than 135 °C, since they were higher than the maximum temperature for the compressor performance, 130 °C.

According to the established the maximum ΔP for the system, the following analysis was focused on the TRNSYS® model, with particular emphasis on the evaporator and compressor as the key elements. Concerning freshwater production, it was observed increased productivity when operating with lower ΔP. Additionally, there was a significant reduction in energy consumption at lower ΔP values. Both findings diverge from the conventional approach followed by previous researchers, who have historically prioritized lower energy consumption over lower evaporation temperatures. However, when assessing energy efficiency, it became evident that an alternative approach was warranted. The steps outlined in the analysis suggest that, despite the advantages in freshwater production and reduced energy consumption with lower ΔP, a reconsideration of the prioritization of lower evaporation temperatures was necessary to enhance overall energy efficiency. Across various pressure ranges, maintaining a constant distillate production, the utilization of a lower ΔP is shown to yield nearly a 50% reduction in the power consumption demanded by the compressor compared to higher ΔP scenarios. This effect is manifested in the decreased temperature at the compressor outlet and a simultaneous elevation in the evaporation temperature for the brine. Additionally, the lower ΔP configuration contributes to a reduction in the compressor speed, consequently aiding in the mitigation of overall energy consumption. The detailed observations and comparative data are presented in tab. 3.

Table 3. Power demand and distillate flow rate under different pressures, ΔP

ΔP [mbar]	Compressor rotational speed [rpm]	Distillate flow rate [kgs^{-1}]	Power compressor [kW]	Temperature outlet compressor [°C]
100	**1600**	**1.14**	**0.143**	**111.3**
200	1600	0.96	0.323	132.4
100	1800	1.33	0.161	110.5
200	**1800**	**1.15**	**0.364**	**128.8**

Another crucial variable for consideration is the initial temperature of the brine upon entering the evaporator. Given that the source of heat is the superheated vapor exiting the compressor, the available energy is inherently constrained, necessitating judicious utilization. In the current model, the ambient temperature is employed as the initial temperature for the brine. This ambient condition is derived from a typical meteorological year dataset specific to the location of the LIFE-Desirows installations in Campo de Cartagena (Southeast of Spain), obtained using the PVGIS software [23]. Examining the trends depicted in fig. 5, it becomes evident that higher initial temperatures result in a diminished requirement for energy transfer at the evaporator. This effect leads to an elevation in the final temperature of the distillate. Thus, optimizing the initial temperature of the brine is imperative for efficient energy utilization within the system. The interplay between this variable and other system parameters demands careful consideration to achieve a comprehensive understanding of the energy dynamics within the desalination process.

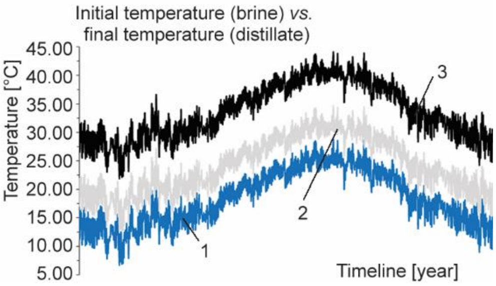

Figure 5. Distillate final temperature variations depending on the ambient temperature;
1 – T. brine, 2 – ΔP = 100, 1800 rpm, 3 – ΔP = 200, 1800 rpm

Under the proposed paradigm, as was previously introduced, the main objective is to simultaneously optimize both energy efficiency and freshwater productivity within the desalination process. The innovative solution involves the integration of variable renewables, specifically a solar PV installation, as the primary power source for this energy-intensive operation. The chosen location for this case study, Cartagena, benefits from optimal climate conditions conducive to the effective utilization of solar resource. However, it is crucial to emphasize that the integration of solar power should be approached with a focus on judicious sizing, avoiding unnecessary oversizing of the solar installation to ensure efficient electricity utilization. This paradigm shift in modeling, transitioning from the pursuit of the lowest evaporation temperature to leveraging a predetermined amount of available energy, aligns with the dual goals of enhancing efficiency and productivity. By incorporating renewable energy sources, particularly solar PV, we aim to strike a balance between sustainable energy practices and the demanding requirements of freshwater production. Note that the initial brine temperature is considered as the ambient temperature in this adjusted modeling approach, being considered as a critical parameter in the holistic evaluation of system dynamics.

Conclusions

This paper indicates the most important parameters to be considered for correct modeling of a desalination plant based on an MVC system. The correct selection of the parameters, as well as the correct conversion and adequacy of the available parameters from manufacturers, is necessary to develop a reliable and useful model. Furthermore, the correct selection of the parameters is necessary to optimize the energy consumption of a MVC system and to match these energy needs to the renewable sources used. The analysis performed is based on the identification of the conditions under which the MVC system compressor drives at the maximum outlet temperature for different pressure differences, to minimize energy consumption while maintaining the mass-flow rate of distillate produced. For examples, by lowering the compressor speed, we obtain lower energy consumptions and higher outlet temperatures, allowing the user to adapt the speed once the pressure difference has been selected.

The case study, supported by the LIFE-Desirows European project, addresses a current problem with a multidisciplinary approach, enhancing the development of more robust solutions by leveraging insights from different fields of expertise.

The preliminary parametric modelling-study does not incorporate refrigeration for the compressor. The assumed water cooling will result in lower outlet temperatures for the compressor, therefore research must be continued including these refrigeration values on the model. The following step involves exploring analogous distillate production scenarios with lower ΔP, revealing a notable reduction in power consumption in comparison to the conventional approaches, which usually target the pressure differences to achieve the lowest evaporation temperature. Further research must be undertaken, including selecting wider pressure difference ranges. Operational temperatures play a pivotal role, with higher temperatures correlating to lower energy consumption and augmented freshwater production. Leveraging renewable energies aligns with this paradigm, reinforcing the adoption of a strategy focused on energy savings, ultimately aiming for a fully variable renewable-powered installation. This strategic shift facilitates the accelerated advancement of this technology, and research must be continued to implement this strategy effectively.

Additionally, future research must be considered regarding to its residual concentrated brine. The potential repercussions of inadequate treatment should be explored, and opportunities arising from revalorization, such as energy storage in residual brine or extraction of raw materials from dissolved salts, must be considered. This holistic perspective transcends the desalination sector, engaging diverse fields of expertise in the exploration of brine revalorization.

From the experimental results, MVC systems offer notable benefits in desalination processes, as well as for brine valorization, being their success contingent upon improving its energy efficiency, addressing alternative operational strategies, and assessing the economic viability for reducing freshwater production costs.

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Nomenclature

h – specific enthalpy, [kJkg^{-1}]
H/D – humidification/dehumidification, [–]
$\dot{m}$ – mass-flow rate, [kgs^{-1}]
P – pressure, [mbar]
$\dot{Q}$ – energy each instant, [kJs^{-1}]
T – temperature, [°C]
ΔT – temperature increase, [°C]
$\dot{V}$ – volumetric flowrate, [m^{3}s^{-1}]

Greek symbol

v – specific volume, [m^{3}kg^{-1}]

Subscripts

evap – evaporation conditions
steam – steam stream at the inlet of the compressor
out – outlet stream of the compressor
refri – refrigerant stream at the inlet of the compressor
NOrefri – conditions from manufacturer without considering refrigerants
comp,inlet – inlet conditions to the compressor

Acronyms

MED – multiple effect distillation
MD – membrane distillation
MSF – multi-stage flash
MVC – mechanical vapor compression
NF – nanofiltration
RO – reverse osmosis
SD – standard deviation
TVC – thermal vapor compression
ZLD – zero liquid discharge

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