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Mechanical Vapor Compression Desalination Process: Approaches to Optimize Compressor's Consumption for Brine Valorization

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***Abstract* – Valorization of residual brines is one of the proposed solutions for minimizing the environmental effects of desalination plants, reducing the volume of wastewater generated at the time it increases both the freshwater production and the final concentration of the residue. Nevertheless, it is an energy-demanding process: the higher the final concentration of the fluid, the higher its energy consumption. We can approach this challenge from two different perspectives, either focusing on the final amount of concentrated residue or focusing on the energy demand of the installation. In this work, the behaviour of the compressor and the variables that affect its operation in a mechanical vapor compression (MVC) desalination system are studied. Using an own develop TRNSYS model of a compressor and adjusting with a real MVC desalination plant, it is done by analysing the connections between the final volume of residual brine and its energy consumption, comparing them with the values available from the LIFE Desirows experimental facilities as well. Moreover, the paper also explores some of the environmental and economic benefits of residual brines valorization.**

***Keywords* – Carbon Neutrality; energy efficiency; model; seawater; Sustainable Development Goals (SDGs); TRNSYS; Zero Liquid Discharge (ZLD).**

Nomenclature		
MVC	Mechanical Vapor Compression	–
ΔP	Pressure difference	mbar
ΔT	Temperature increase	K
$\dot{m}$	Mass flow rate	kg/s
$\dot{V}$	Volumetric flow rate	m^3/min
T	Temperature	°C
ν	Specific volume	m^3/kg
$\dot{Q}$	Power (heat x time)	kJ/s=kW
h	Enthalpy	kJ/kg
Δh_{evap}	Enthalpy of vaporization	kJ/kg
$\dot{W}$	Work for gas compression along time	kW

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η	Performance	% base1
Refri	Refrigerant used for cooling the compressor	–
Steam	Steam entering the compressor from the evaporator	–

1. INTRODUCTION

Climate change intensifies the effects of water scarcity in the environment and human communities, degrading soils and depleting aquifers [1]. This challenge is addressed in one of the seventeen sustainable development goals (SDGs), a list of goals created in 2015 with the aim of reducing the effects of climate change for future generations [2]. The main solution purposed for this problem is expanding the deployment of desalination plants in places suffering from water scarcity [3].

Desalination is the process of removing salts and other minerals from water sources to produce freshwater suitable for various uses, such as human consumption, irrigation and other industrial applications. Nevertheless, it comes with the costs of high energy demands and the challenge of managing its residual brines [4]. Aiming for net-zero emissions and residues from desalination is crucial to ensure the sustainability of this expanding technology, as seen on recent papers from Alawad and Al-Saidi [5], [6]. One of the proposals is treating these residual brines through an industrial circular economy perspective, managing the wastewater while valorizing the content of its residues. Zero liquid discharge (ZLD) technology represents a promising approach for the valorization of residual brines from desalination processes; despite being an energy-demanding activity, it represents a significant advance at reducing freshwater consumption in desalination plants, reducing its production costs as well [7]. ZLD systems are divided in various stages, each of them focusing on treating a specific part of the brine. One stage within ZLD, Mechanical Vapor Compression (MVC) desalination, utilizes distillation processes fully powered by electricity for further brine concentration [8]. This study focuses on optimizing a MVC stage within a ZLD system designed for a small-scale desalination experimental plant, treating brackish water from a polluted aquifer in Campo de Cartagena region (Spain) in a project called *LIFE Desirows* [9]. MVC's potential lies in its ability to fully operate with renewable energy sources, aligning with sustainability goals. However, existing research on small-scale MVC plants is limited, prompting the need for further exploration to find potential break-through results for this technique [10]. There are currently two operation visions for this technology: the traditional one seen at Aly and El-Fiqi case study [8], that aims to reduce the operating temperature as much as possible, lower than 70 ºC, in order to reduce corrosion effects of hot brine, while the newer perspective aims to increase the operating temperature in order to reduce the energy consumption of the compressor stage [11].

Since desalination processes are power demanding industrial processes, they require an optimization of operation stage if we want to improve the sustainability of the plant. Small scale plants allow experimenting with different ranges of operation while keeping the investments as low as possible [12]. Those operating conditions must be trusted and chosen by other technical means, supporting the hypothesis by previous calculations. Modelling the installation represent the best option to support the changes in the real-life plant, therefore is important to fully understand how the plant works in order to replicate the conditions the closest to reality as possible. Creating a virtual model of the MVC plant allows the researchers developing new configurations without the risk of damaging the installations, whose components are expensive [13]. Over the years, some researchers have worked on this topic, most of them based on MATLAB® programming such as El´Khatib and Farahat models

[14], [15]. Nevertheless, there are other powerful software available for these purposes such as TRNSYS®, specialized in simulating the behavior of transient systems, mostly for assessing the performance of thermal and electrical energy systems using its library of components [16]. For the specific case study, the required expertise is not available in the TRNSYS® library. However, TRNSYS® allows for the incorporation of custom programmed elements, in Fortran 90 code, known as Types.

In this paper, a Type modeling a compressor from a real MVC experimental plant is programmed in order to perform parametric studies. This component is the most sensitive part of the MVC plant, and its operating conditions directly affect to the rest of the system's components. This new Type has been programmed following previous literature findings from respected researchers on MVC modelling, adapting it to a particular case and software operation protocols [17], [18]. Regarding to some relevant values of the compressor, it is part of a small-scale plant, with operating temperatures greater than 80 ºC, ΔP up to 500 mbar and the main target is reducing its energy consumption. The results provided by *LIFE Desirows* project give the chance to understand the steps to follow for developing a strategy to optimize compressor's operation.

2. METHODOLOGY

Since both parametric studies and a real-life case study are considered for this contribution, the purpose of this paper is optimizing the power consumption of the compressor by simulating various operating ranges of this components in terms of speed, temperature, and pressure difference. Starting from the outcomes of the parametric studies, a comparison of those values with the ones available from the real plant is created, proposing new input settings for this essential component of the MVC desalination process.

The information available from the manufacturer of the real compressor provides design diagrams for various ranges of ΔP and speeds but using air as its operating fluid, and without considering refrigeration for the compressor. It is necessary to convert these values with air towards values based on steam to model the MVC plant conditions. The model of the compressor, using TRNSYS® software, shares input and output variables with the real case-study compressor from *LIFE-Desirows*, allowing to implement easier the new settings proposed on this paper on the real compressor.

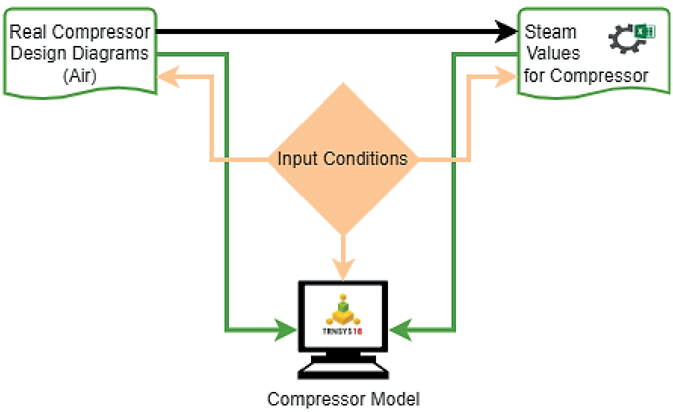

Fig. 1. Graphical abstract.

2.1. Mechanical Vapor Compression Desalination System

The MVC is a thermal desalination process based on distillation that can be used for crystallization processes, operating with salinities up to 300 g/kg [19]. Some of the advantages of using MVC technology for desalination processes are the purity of the distillate obtained, since it has been obtained by evaporation, and the possibility of working with high salinity brines. As a result, its concentrated residue must be handled carefully since high salinities and high temperatures may cause corrosion and scaling inside the components. That is why these systems operate in vacuum conditions, so that the evaporation temperature reaches safer temperatures for the components used in the MVC desalination plant.

Despite this kind of plants can have different configurations, all of them share 4 common components: boiler, preheater, compressor, and evaporator. The boiler is used for creating steam from a source of freshwater, generally during the plant start-up phase, but also for supplying extra amounts of steam to the compressor when required. The preheater is used to increase the inlet temperature of the brine we want to evaporate, using the residual heat from the distillate obtained at the end of the desalination process. The compressor stage is the most relevant one, it is the responsible of generating the superheated steam used for the distillation process; it also indicates the vacuum pression at which the system operates and, finally, the evaporation temperature of the brine and the exit temperature of the super-heated steam. Last but not least, the evaporator, which is a heat exchanger where a change of phase happens on both the cold (inlet brine) and hot (superheated steam) sources. Considering the stationary state of the plant as fully powered by the compressor, we can remove the boiler from this model to focus on the optimization of the compressor.

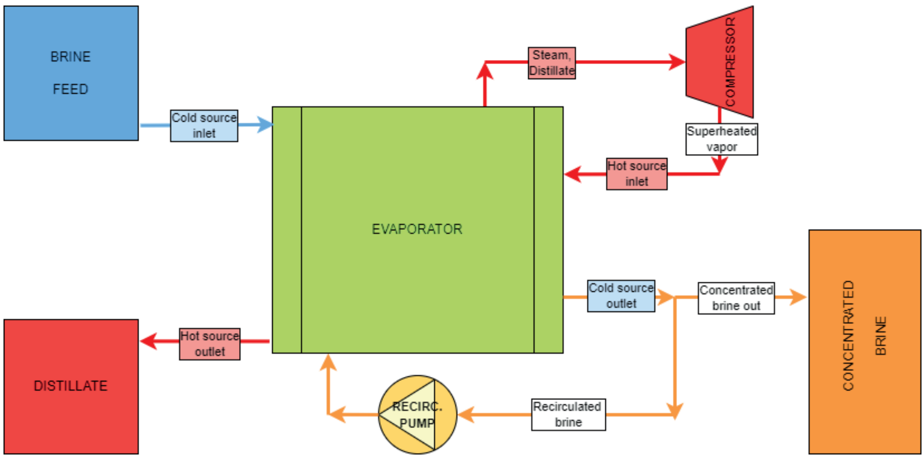

Fig. 2. Elements present in the simple MVC modelled desalination plant.

Except for the recirculation pump that sends the concentrated brine back to the evaporator, which has fixed operating conditions of power consumption and flow rate, the rest of components present in the system do not have power demand. Everything relies on the operating conditions of the compressor: from pressure inside the evaporator to vaporization temperature, MCV plant variables are dependent on the input conditions fixed in the compressor. Moreover, since the mission of this research is optimizing the energy consumption on a desalination plant, focusing on its most energy-demanding element will supply not only crucial information for using the energy available with a better efficiency, but also about how it affects the final concentration in the residual brine.

2.2. Circular Economy in Desalination Processes

As mentioned prior, there are increasing environmental concerns regarding to the extensive use of desalination plants worldwide [6], [20]. Discharges of residual brine far from the seashore have been used in the past, but nowadays there are strategies called zero liquid discharge (ZLD) technologies, whose main purpose is reducing freshwater consumption in desalination plants, concentrating even more the residual brines and transform them into raw materials for industrial purposes, promoting both circular economy and development of desalination projects [21].

This paper uses data from a real case study from Cartagena, Spain. The brine from groundwater desalination in Campo de Cartagena has multitude of dissolved salts that, when properly separated, can be repurposed for economical revenue, at the same time it allows generating additional water resources in a desertic climate. The *LIFE-Desirows* demonstration project aims to recycle residual 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. The project combines various ZLD technologies from an industrial perspective to minimize energy consumption at the same time it creates flow incomes from the desalination residues. 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 [9].

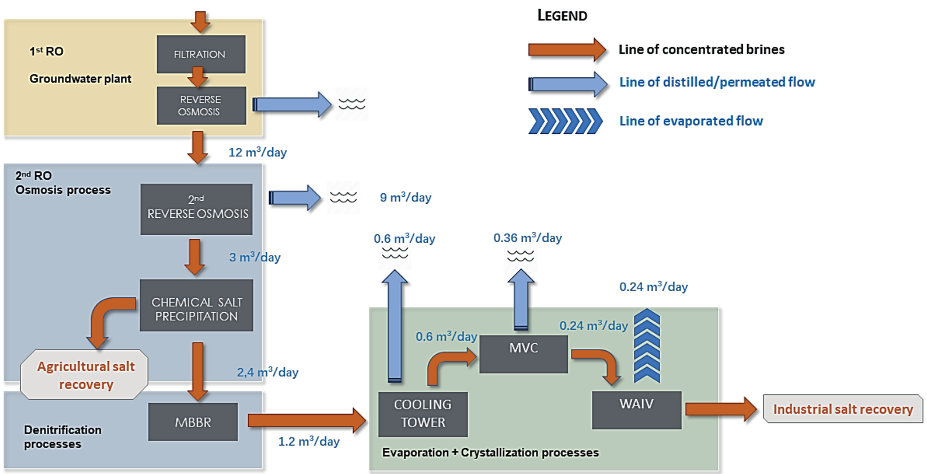

Fig. 3. Stages of the *LIFE Desirows* project, circular economy with desalination's residues.

This paper is focused on the crystallization stage based on MVC technology, whose inlet fluid is the residue from Fig. 3 cooling tower stage. The main purpose of using these two technologies is improving the crystallization process for industrial salt recovery, at the same time MVC produces more freshwater in a desertic environment that can be reintroduced in the local environment.

2.3. Modeling the Compressor

Considering real-life data from an experimental site are available, the optimization process should be managed in a way the improvements obtained from the model can be implemented on the real desalination plant easily. The first step is to analyse the data provided by the manufacturer of the project's compressor, whose testing fluid is air where, after getting the same results but for steam, the modelling of the compressor can be started. In Table 1 are summarized the series of input variables that can be introduced in both the experimental plant and in the model once the parametric studies have been completed, to finally compare the theoretical results from the model with the ones registered in the *LIFE Desirows* experimental plant.

TABLE 1. VALUES FROM THE REAL CASE-STUDY

Data	Value	Units
Maximum Pressure Difference	500	mbar
Maximum Compression Ratio	2	–
Maximum Volumetric Flow Rate	4.73	m^3/min
Speed Ranges	1200–3000	rpm
Maximum Outlet Temperature (Steam)	130	°C
Maximum Temperature Difference (ΔT)	115	°C
Maximum Refrigerant Inlet Temperature (Steam)	85	°C
Fluid Used in Manufacturer's Design Diagrams	Air	–
Minimum Inlet Temperature (TT0104)	80	°C
Maximum Outlet Temperature (TT0106/7)	110	°C
Frequency Ranges of the Compressor	20–50	Hz
Compressor's Frequency Ramp	5	Hz
Time-step for Compressor's Frequency Ramp	120	s
Electromechanical Performance of the Compressor	96.5	%

From the user's perspective, the most important input variables of the compressor are rotational speed and the pressure difference achieved since they can be fixed on the real plant's user screen. Those conditions allow accessing the data base provided by the manufacturer for obtaining its volumetric flow rate, shaft power and temperature increase with those inlet conditions. Nevertheless, as mentioned in the previous section, the fluid used by manufacturer is air, whose properties does not match with steam ones. It is required to extrapolate the initial results given by manufacturer to obtain the ones needed for the model: inlet volumetric flow rate for steam ($V_{\text{comp, inlet}}$), shaft power ($Power_{\text{Shaft}}$) and temperature increase $\Delta T_{\text{Norefri}}$, where $Power_{\text{Shaft}}$ will remain constant for both air and steam.

Moreover, manufacturer didn't use refrigeration for their testing, so the mass flow rate of steam entering the compressor cannot be used directly from the extrapolation. It is required to obtain the outlet temperature and mass flow rate without refrigeration using Eq. (1) and Eq. (2) formulas:

$$\dot{m} = \frac{\dot{V}}{v \times 60.0}, \tag{1}$$

$$T_{\text{out,NOrefri}} = T_{\text{Steam}} + \Delta T_{\text{NOrefri}}, \tag{2}$$

where T_{Steam} is the temperature of inlet steam from the flash tank (in °C) and $\Delta T_{NOrefri}$ is the temperature increase for steam without refrigeration (interpolation from Kaesser values, in K).

After setting the temperature, it is time to obtain the amount of refrigerant required for cooling the super-heated steam up to the desired temperature. The first step is calculating the amount of heat (energy) the refrigerant needs to absorb by applying Eq. (3)–Eq. (4):

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

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

where $\dot{Q}_{Refri}$ is the energy absorbed by the refrigerant, $\dot{Q}_{out,NOrefri}$ is the energy in the outlet conditions without refrigeration (with $T = T_{out,NOrefri}$ and $P = P_{atm}$, in kJ/kg and $\dot{Q}_{set}$ is the energy with output set condition ($T = T_{set}$ and $P = P_{atm}$, in kJ/kg. As a result, it is possible to obtain the amount of refrigerant required for absorbing that amount of heat with Eq. (5):

$$\dot{m}_{Refri} = \frac{\dot{Q}_{Refri}}{\left(h_{Steam} - h_{Refri}\right) + \Delta h_{evap} + \left(h_{out} - h_{Steam}\right)} \,, \tag{5}$$

where Δh_{evap} is the enthalpy of vaporisation (phase change, in kJ/kg).

After calculating the mass flow rate of refrigerant, it is the time for its volumetric flow rate. Considering the inlet volumetric flow rate for the compressor is one of our inputs, the volumetric flow rate of steam entering the compressor is the difference between the compressor's total volumetric flow rate minus the refrigerant volumetric flow rate. Doing the reverse procedure, using Eq. (6)–Eq. (8) steam's mass flow rate is calculated:

$$\dot{V} = \dot{m} \times \nu \times 60.0 \,, \tag{6}$$

$$\dot{V}_{Steam} = \dot{V}_{Comp,inlet} - \dot{V}_{Refri} \,, \tag{7}$$

$$\dot{m}_{Steam} = \frac{\dot{V}_{Steam}}{\nu_{Steam} \times 60.0} \,. \tag{8}$$

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, which allows to calculate with Eq. (9) and Eq. (10) the outlet conditions of the super-heated steam.

$$\dot{m}_{out} = \dot{m}_{Steam} + \dot{m}_{Refri} \tag{9}$$

$$\dot{V}_{out} = \dot{m}_{out} \times \nu_{out} \times 60.0 \tag{10}$$

Since fluid variables in the compressor have been defined correctly, it is time for the power-related variables. Power demand refers to the amount of electric energy required for powering the compressor. It is calculated thanks to the electro-mechanic performance of the compressor, parameter that shows the amount of power that finally reaches thew compressor. Considering the power developed by the shaft is an input variable (thanks to correlations), power demand (in kW) can be obtained by relating both concepts as seen in Eq. (11).

$$Power_{\text{Demand}} = \frac{Power_{\text{Shaft}}}{\eta_{\text{Electro-Mechanic}}} \tag{11}$$

Work for gas compression, calculated in Eq. (12), is another variable of interest. It represents the amount of power that finally reaches the exiting super-heated vapor, since not all shaft power is transferred towards the fluid, and it is measured in kW.

$$\dot{W}_{\text{gas,kW}} = \left(\dot{m}_{\text{Steam}} \times \left(h_{\text{out}} - h_{\text{Steam}}\right) \right) + \left(\dot{m}_{\text{Refri}} \times \left(h_{\text{out}} - h_{\text{Refri}}\right) \right) \tag{12}$$

The final variables regarding to the compressor are obtaining both the performance of the compressor and the isentropic performance of the compressor. For the first case, the performance of the compressor with Eq. (13) represents the proportion of available power from the shaft that is finally used by the fluid, while the isentropic performance is defined with Eq. (14) as the correlation between the work done by the compressor under ideal (isentropic) conditions and the actual work done by the compressor under real conditions.

$$\eta_{\text{Comp}} = \frac{W_{\text{gas,kW}}}{Power_{\text{shaft}}} \tag{13}$$

$$\eta_{\text{isen}} = \frac{h_{\text{isen,Steam}} - h_{\text{Steam}}}{h_{\text{out,NOrefri}} - h_{\text{Steam}}} \tag{14}$$

The last parameter included, that doesn't belong to the compressor, is the final salinity of the concentrated brine. Since it is measured from the storage tank values, it will be calculated using formulas Eq. (15)–Eq. (16) that relate the concentration with volumes of brine.

$$C_2 = C_1(V_1/V_2) \tag{15}$$

$$C_{\text{final}} = (C_1V_1 + C_2V_2 + \ldots + C_nV_n)/(V_1 + V_2 + \ldots + V_n) \tag{16}$$

3. RESULTS

Once the input values have been introduced in the model, it is time to analyze the results extracted from the different parametric studies. Since the main values of interest for the MVC system are its power consumption and the amount of distillate produced with that operating conditions, a figure comparing both parameters in the compressor can be valuable. Fig. 4 presents the correlation between these two parameters for a constant speed of 3000 rpm (50 Hz) and various ΔP, where higher power demands can be found for lower flow rates. From this figure, a deduction can be made regarding to the size of the MVC plant: to operate with lower pressure differences and higher evaporation temperatures, plants with big evaporators should be chosen in order to produce the required demand of flow rate and to avoid the use boilers to produce the remaining steam necessary to complete the compressor's demands with lower ΔP's settings.

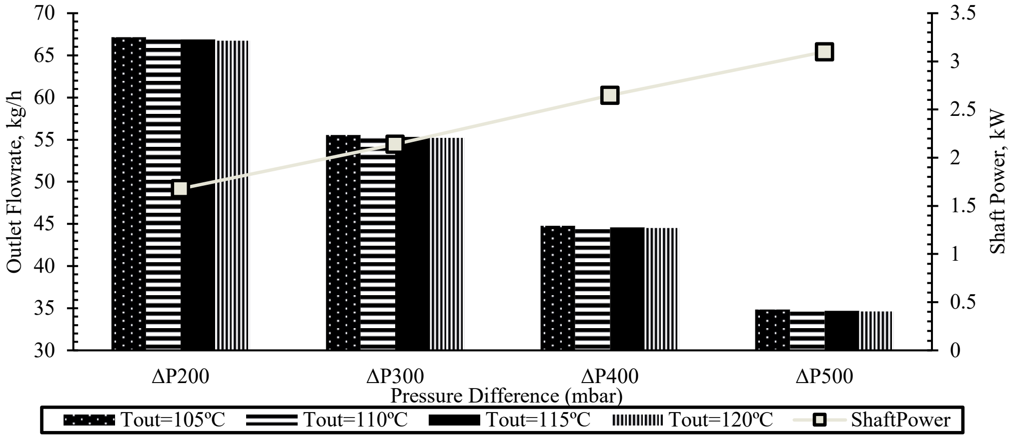

Fig. 4. Steam flow rate in the outlet of the compressor and shaft power for different pressure and temperature conditions.

The performance of the compressor at different operating conditions is also an important factor in terms of energy efficiency. It allows the user to adapt the regime of operation in the compressor depending on the infrastructure capabilities available at each case study. The results in Fig. 5 show the performance of the compressor is higher for lower pressure differences and higher temperatures of operation. The higher the pressure difference, the lower the operating temperature, the higher the amount of refrigerant required to stabilize the outlet temperature and the lower the efficiency of conversion.

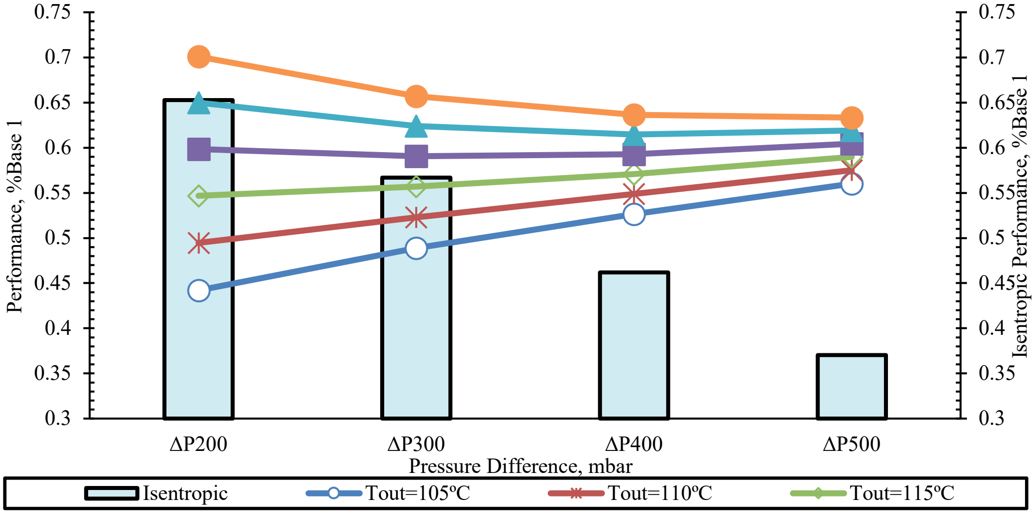

Fig. 5. Performance of the compressor at different pressure and temperature ranges, isentropic performance of the compressor for each pressure difference is incorporated.

The outlet temperature for the compressor is also another relevant factor that contributes to the performance results. For higher outlet temperatures, the flow rates of refrigerant will be lower at while the performance of the compressor increases.

Another important factor that influences both the power consumption and the outlet flow rate is the speed of the compressor. For higher speeds, the amount of fluid treated increases significantly, whilst the refrigerant flowrate does not suffer such a big difference. Fig. 6 compares the results obtained by the model with a Δ*P* of 460 mbar, extracted from the values available in the *LIFE Desirows* project experimental plant, and other Δ*P* of 400 mbar in order to compare both power demand and flowrates in the compressor at different speeds and inlet pressure conditions.

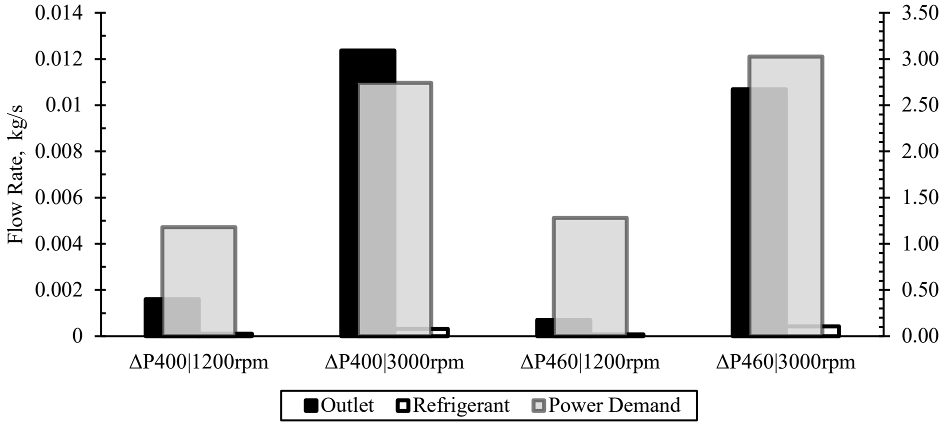

Fig. 6. Mass flow rate vs power demand for various pressures, ΔP in mbar.

Despite the energy consumption increases, it is worth increasing the speed of the compressor because the amount of steam treated is considerably higher than using lower speed during longer periods of time, allowing concentrating more brine in less time while producing more freshwater. Nevertheless, the previous premises shown on the paragraphs above must also been considered when setting the operating conditions of the compressor.

Finally, salinity levels on the final concentrated brine are relevant in terms of valorization of the residual product. Standard seawater salinity is considered as 35 g/kg, but for our case study we will be using an initial salinity of 38 g/kg from a particular sample of brine [22]. Analyzing the results from Fig. 7, it is observed that for bigger pressure differences we achieve lower final concentrations, which makes sense considering the amount of steam passing through the compressor and removed from the initial brine is lower for these ranges of operation. The lower the pressure difference, the bigger the steam flow rates evaporated and the higher the final concentrations obtained. In the case of *LIFE Desirows* project, after a series of concentrating cycles, salinities of 62.22 g/kg are achieved in the final concentrated brine, improving even further the results obtained from a single MVC cycle by concentrating an already concentrated brine.

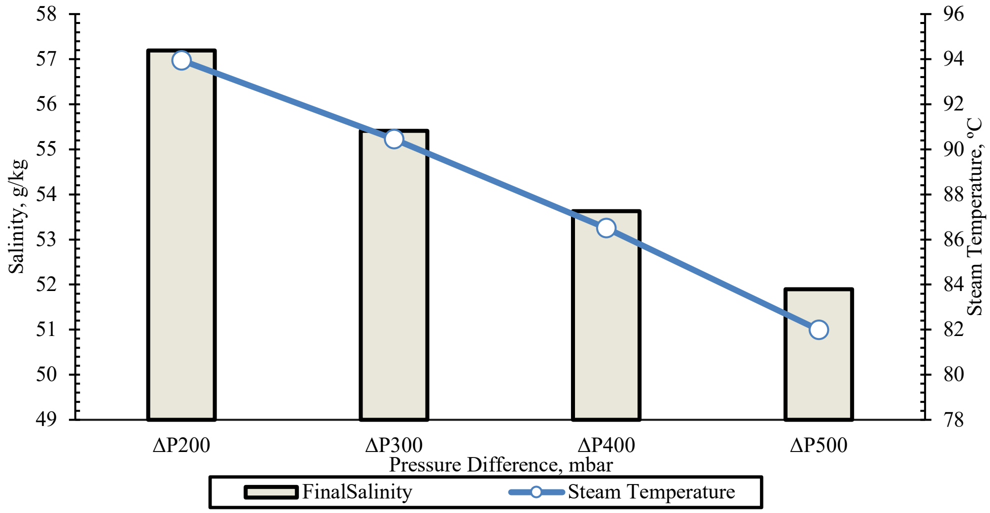

Fig. 7. Final salinity of the residual brine depending on the pressure difference achieved. The evaporation point at those conditions is included, and the initial salinity is 38 g/kg.

4. Conclusion

Implementing MVC desalination systems for valorizing residual brines is a realistic option for reducing the environmental impact of desalination technology. Optimizing MVC's energy consumption is crucial for future breakthrough events, reducing its energy demand and allowing sustainable carbon neutrality operations if coupled to renewable energies sources.

According to the results of the present paper, it is possible to conclude that the more relevant variables to improve optimization of a MVC desalination plant are the rotational speed of the compressor and the void pressure produce by the compression process.

Regarding to the rotational speed of the compressor, it is recommended to select the highest setting possible in order to reduce energy cost of production. Focusing on the pressure difference for the compressor, it should be adapted to the capacity of steam production of the selected desalination plant: for big scale plants, with higher steam production capabilities, operating with lower pressure saves more energy and improves the system's overall performance while, for smaller scale plants, the steam production forces to select higher pressure differences settings, at the cost of higher energy demands. Both variables also impact the final salinity of the residual brine, where bigger steam flowrates generate higher salinities on the residual brine, it is possible to concentrate further the residue.

In terms of refrigerant demand to avoid high temperature in the compressor outlet, the refrigeration demand will be dependent on the selected outlet temperature of the compressor but always must be less to restrictions imposed by the compressor material. The correct selection of outlet temperature is relevant in the final result of the system, selecting higher outlet temperatures reduces energy costs by producing more fresh water with MVC technology but may reduce the working life of the compressor when subjected to high working temperatures.

The original data for this paper comes from a real small-size plant, where steam production remains low, set temperature is 105 ºC and the pressure difference stays almost constant at 500 mbar, with losses of steam through its vents higher than expected. Comparing it with the results obtained by the model, greater results could be achieved by improving the configuration of the compressor. Further work in both the real plant and the full model is required to optimize the MVC desalination system, but using the knowledge acquired on this paper the researcher will continue by lowering pressures differences and increasing outlet temperatures of the compressor.

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