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Energy analysis of a laboratory process of water desalination by pervaporation and reverse osmosis

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Abstract
Fresh water is essential for life. More and more countries around the world are facing scarcity of drinking water, which affects over 50% of the global population. Due to human activity such as industrial development and the increasing greenhouse effect, the amount of drinking water is drastically decreasing. To address this issue, various methods of sea and brackish water desalination are used. In this study, an energy analysis (specific energy consumption, *SEC*) of two laboratory membrane processes, reverse osmosis (RO) and pervaporation (PV), was conducted. A model feed system saline water at 0.8, and 3.5% wt. NaCl was used. The efficiency and selectivity of membranes used in PV and RO were examined, and power of the devices was measured. The desalination processes were found to have a high retention factor (over 99%) for both PV and RO. For PV, the permeate fluxes were small but they increased with increasing feed flow rate, process temperature and salt content in the feed. The calculated *SEC* values for both laboratory processes ranged from 2 to 70 MWh/m^3. Lowering the process temperature, which consumes 30 to 60% of the total energy used in the PV process, can be an important factor in reducing energy consumption.

Keywords
specific energy consumption, water desalination, pervaporation, reverse osmosis, laboratory processes

1. INTRODUCTION

Desalination of sea and brackish water is a process known since ancient times. The process of evaporation from salt water and condensation of fresh water was already known to Aristotle and was used in practice by sailors (Aristotle, 1952). Throughout history, humanity has fought for access to drinking water. Both ancient and modern texts mention armed conflicts over access to drinking water (Balima et al., 2022; Borek, 2018; Buthelezi and Bulthelezi-Dube, 2021).

Fresh water is essential for life, and a human being can survive only three days without it. More and more countries in the world are struggling with drinking water scarcity, which affects over 50% of the world's population (Li et al., 2018). Only 2.6% of all water resources is fresh water, of which only 0.5% can be directly used for consumption. Most of the fresh water is stored in glaciers, ice caps, and underground waters, which are costly to extract (Weckroth and Ala-Mantila, 2022). According to the WHO report, in the near future another 1.5 million people will face a problem with access to drinking water, including in Mediterranean countries (World Health Organization, 2019). Unfortunately, the amount of fresh water has been drastically reduced due to human activity and industrial development. The scarcity is also aggravated by the rapid increase in the greenhouse effect (WWF, 2022). Various methods of desalination and treatment of sea, brackish, mining and geothermal water are available to help solve this problem (Goosen et al., 2010; Prajapati et al., 2021; Tyszer et al., 2021). In the current crisis on the Odra River, a separate problem is the desalination of post-production wastewater (Kojzar, 2023).

Desalination techniques are based on thermal, membrane and alternative methods, e.g. freezing and ion exchange techniques. Combined methods are also being developed which work by combining membrane and thermal processes, such as membrane distillation (MD) (Usman et al., 2021). Commercial thermal methods include multistage flash distillation (MSF), multiple-effect distillation (MED) and vapour compression (VC), which can be either mechanical (MVC) or thermal (TVC). For these processes (excluding MVC), energy in the form of heat (to reach the boiling temperature of brine) and electricity (to drive the pump) is required (Nassrullah et al., 2020; Xiao et al., 2013). Operating costs of thermal desalination methods increase over time due to the aging of the installation and the production of a large amount of boiler scale, which causes a higher failure rate of the system (Bobik and Labus, 2014).

The most widely used desalination membrane techniques in the industry are reverse osmosis (RO) and electrodialysis (ED). Reverse osmosis is an effective method for desalination of both salty and contaminated (post-production) water. It is characterized by a high yield and retention of the obtained permeate. However, at elevated salt concentrations, due to scaling phenomenon, the efficiency of the process decreases. The decrease in flux can be compensated by increasing the transmembrane pressure, which in turn raises the operational costs of RO (Karabelas et al., 2018). The RO process, which has been used in industry for 50 years, has been optimized to reduce energy consumption to less than 3 kWh/m^3, as reported by Nassrullah et al. (2020). One idea to lower operating costs is to use energy from renewable sources. This has been supported by studies from Ali et al. (2018), Al-Karaghouli and Kazmerski (2013), Fornarelli et al. (2018) and García-Rodríguez (2003). The use of solar energy for desalination primarily involves a combination of photovoltaics and reverse osmosis, or the use of solar collectors with thermal methods, as noted by Zheng and Hatzell (2020).

Another possibility for reducing energy in reverse osmosis systems is optimizing pumps that operate under various process conditions such as varying temperature, pressure, feed water type, and membrane aging, as noted by Li et al. (2021). Additionally, devices such as turbines or rotary isobaric heat exchangers are becoming increasingly popular to minimize costs and energy (ERD) for seawater desalination (SWRO) (Reddy and Ghaffour, 2007). The use of hybrid systems, such as evaporator/RO or using steam for water evaporation or to power turbines, is also an important aspect (Karagiannis and Soldatos, 2008; Reddy and Ghaffour, 2007; Zarzo and Prats, 2018).

New methods of seawater desalination are constantly being sought. Pervaporation is a new approach to desalination. PV is an alternative membrane technology to RO and MD for desalination of water with high salinity ($>$ 7 wt%). Above this salinity value, vapour pressure based processes (MD or PV) become competitive with RO. Pervaporation desalination uses hydrophilic membranes with high selectivity, which allows to obtain a permeate of high purity. The absence of pores in PV membranes makes the process more resistant to treating water containing impurities and membrane scaling due to mineral deposition (Li et al., 2023).

In the 1990s, Sulzer developed a hydrophilic membrane based on polyvinyl alcohol (PVA) for the dehydration of alcohols. In this paper, commercial PERVAP membranes (Sulzer) are used for desalination of seawater (Wang et al., 2016). During the PV process, there is a phase change of the permeate, which is then condensed to produce pure water (Basile et al., 2015). Many analyses of the energy consumption of RO or MD processes have been carried out, but there have been no studies to date calculating the energy consumption of pervaporation systems. Energy consumption is essential to assess the economic viability of any process. Calculations by Kaminski et al. (2018) indicated that the enthalpies and specific changes of Gibbs energy are similar in the RO, PV and MD desalination processes. Differences in pressure and salinity are only slightly responsible for the change in enthalpy. There should be no difference in energy consumption when only the energy of the pump is considered. However, this analysis did not take into account the energy cost of increasing process temperature. Another study (Thomas et al., 2020) compared the specific energy consumption (*SEC*) of different desalination technologies. The authors estimated that pervaporation and MD had a similar *SEC* of about 7.7 kWh/m^3, while the *SEC* for RO was 3.0–4.0 kWh/m^3. The *SEC* at the experimental and pilot levels for MD systems ranged up to 10.5 MWh/m^3. Heat recovery efficiency, fouling, plant size and degree of optimization of the MD system can have a large impact on the energy consumption of vapour pressure driven processes (Jantaporn et al., 2017).

The aim of this study was to perform an energy analysis of laboratory-scale desalination processes using two different membrane techniques, i.e. reverse osmosis and pervaporation. The hydrodynamic properties of the membranes used were determined and the specific energy consumption was calculated for each process.

1.1. Operating parameters of membrane processes

Membrane techniques involve a separation process: a feed stream flows onto the membrane, which is separated into a permeate stream (the portion that passes through the membrane) and a retentate stream (the portion that remains behind). The following formulas were used to assess desalination efficiency, providing the permeation flux (J_p) (also known as productivity) which determines the efficiency of the process and the rejection factor, R – retention factor or salt-rejection which determines the selectivity of the membrane.

$$J = \frac{V_p}{A \cdot t}, \ \frac{\mathrm{m}^3}{\mathrm{m}^2\mathrm{h}} \quad \text{or} \quad J_p = J \cdot \rho = \frac{m_p}{A \cdot t}, \ \frac{\mathrm{kg}}{\mathrm{m}^2\mathrm{h}} \tag{1}$$

$$Q_p = J \cdot A, \ \frac{\mathrm{m}^3}{\mathrm{h}} \tag{2}$$

$$R = \left(1 - \frac{c_P}{c_F}\right) \cdot 100, \ \% \tag{3}$$

The energy intensity of desalination, which is part of the operating costs, is defined as the specific energy consumption, *SEC*, kWh/m^3. *SEC* is the amount of energy consumed during the production of a unit volume of desalinated water (Karabelas et al., 2018; Wang et al., 2021) and the formula for its calculation is presented in Equation (1).

$$SEC = \frac{P}{Q_p}, \quad \frac{\mathrm{kWh}}{\mathrm{m}^3} \tag{4}$$

The method of determining the permeate flow rate (Q_p), used in the *SEC* definition (4) was shown in Equation (2).

2. EXPERIMENTAL

In this study, laboratory experiments were conducted to desalinate seawater using pervaporation and reverse osmosis techniques, and the energy consumption of these processes was measured. Previous research is referenced in Kaminski et al. (2018).

2.1. Materials

Commercial PERVAP 2210, 4510 hydrophilic flat membranes were used for PV and AG-RO for RO experiments. The PV membranes designed for alcohol dehydration were obtained from Sulzer Chemtech (PERVAP 2210) and DeltaMem (Switzerland) (PERVAP 4510). The manufacturer (DeltaMem) claims that the currently purchased PERVAP 4510 membranes are equivalent to the former PERVAP 2210 membranes (Yave, 2017). The RO membranes were purchased from Sterlitech (USA). Sodium chloride for preparing model saltwater solutions was purchased from Chempur (Poland). A model feed system corresponding to the average salinity of Baltic Sea and Adriatic Ocean water (0.8, and 3.5% wt. NaCl) was used. For comparison, the pervaporation process was also investigated for distilled water.

2.2. Experimental methods

Experiments on water desalination by pervaporation and reverse osmosis were conducted using laboratory equipment for PV and RO. The refurbished PV equipment came from Sulzer Chemtech (Switzerland) and the RO equipment came from Osmonics (USA). The setups of the installations are shown in Figures 1 and 2. In both setups, the feed solution was introduced into the tank and heated to the desired temperature using a thermostat. Then, it was fed into the membrane module with a dosing pump. There is a different pressure on each side of the membrane, resulting in a transmembrane pressure. In the case of our PV apparatus, the feed side is at atmospheric pressure, while the permeate side is at lowered pressure (1–5 kPa). For our RO apparatus, the applied transmembrane pressure may be high (3–10 MPa) and is regulated by a throttling valve located at the retentate outlet. In the process of PV, there is a phase change of the substance permeating through the membrane, resulting in the production of vapour. The vapour of the permeate is sucked in by a vacuum pump and frozen in a collector with liquid nitrogen. In the case of RO, there is no phase change and the liquid permeate is collected on the other side of the membrane.

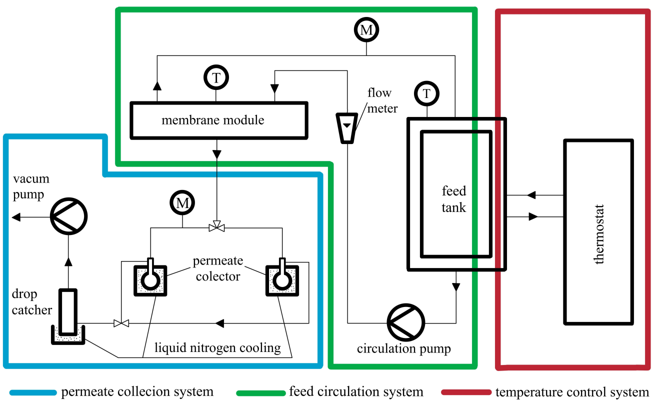

Figure 1. Diagram of the laboratory pervaporation installation.

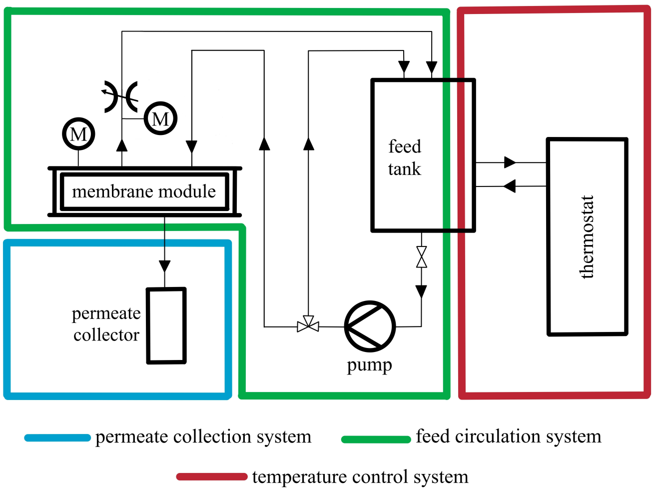

Figure 2. Diagram of the laboratory installation for reverse osmosis.

2.2.1. PV and RO experiments

During desalination studies, the pressure on the low-pressure side of the PV membrane was 1, 2 or 3 kPa and the transmembrane pressure in the RO was held at a constant 3 MPa. Experiments were performed at 40, 60, 80 °C for PV and at 40 °C for RO. The feed flow rate (Q_F) was set to 20, 40 and 60 dm^3/h for the PV. In both cases, a model aqueous solution containing 0.8, 3.5, 7% NaCl and distilled water was used. The PV and RO processes were carried out for 2 hours, collecting permeate samples and testing active power as well as total and individual energy consumption every 0.5 hour. The active surface area of the membrane was 0.005 m^2 for PV and 0.015 m^2 for RO. Salt concentration in the collected samples was measured with the universal Elmetron CPC 501 apparatus using the conductometric method.

2.2.2. Power measurements

To calculate energy consumption of the process, the PV station was divided into 3 power consumption blocks: feed temperature control (thermostat), feed circulation (pump) and permeate collection (vacuum pump). The costs of cooling the permeate with liquid nitrogen were also taken into account. The RO station was also divided into 3 blocks: feed temperature control (thermostat), feed circulation (pump and valve) and permeate collection system. The transmembrane pressure was achieved by adjusting the throttle valve. Energy is lost due to the feed flow restriction. The division of the equipment into subsystems is shown in Figures 1 and 2. Energy consumption measurements were carried out for electric devices using SilverCrest IAN66149 (UK) power meter.

3. RESULTS AND DISCUSSION

3.1. Selectivity and efficiency of RO and PV

The desalination process exhibited very high selectivity. The retention factor, calculated according to Eq. (4), was 98.26% for reverse osmosis (RO) and over 99.99% for pervaporation (PV). According to the Regulation of the Minister of Health in Poland (2015) and the Council Directive EU (Council Directive, 1998), the permissible amount of salt in drinking water should not exceed 0.25 for Cl^- and 0.2 g/dm^3 for Na^+ ions.

In the case of RO, the permeate flux (27.8 for 0.8 and 14.3 kg/(m^2/h) for 3.5% wt. NaCl) decreased with increasing salt content in the feed within the analyzed range of salt concentrations. These relationships are shown in Fig. 3. The flux drop during the process is related to the phenomenon of concentration polarization in a thin film, close to the membrane surface. The layer of concentrated salt ion solution causes an increase in membrane resistance and a decreased permeate flow rate.

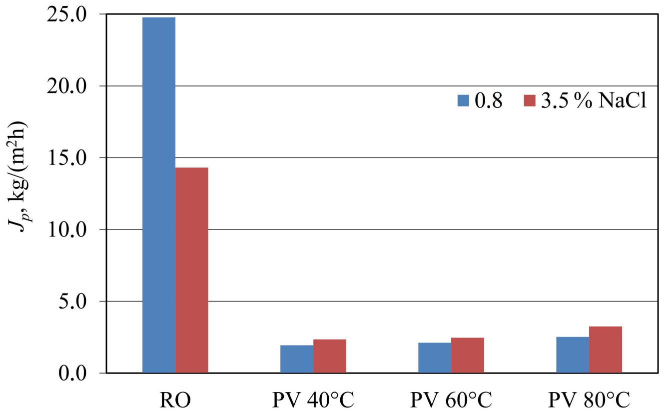

Figure 3. Comparison of permeate flux (J_p), obtained using RO and PV ($Q_F = 80$ dm^3/h) during water desalination at a temperature of 40 °C and a concentration of 0.8 and 3.5% wt. NaCl in the feed.

The reverse trend was observed in the case of PV on the PERVAP 4510 membrane, which according to the manufacturer's information is a substitute for the 2210 membrane (Yave, 2017). The permeate flux, slightly increased depending on the temperature of the process for the analyzed range of salt content in the feed and was 1.9–2.5 for 0.8 and 2.3–3.2 kg/(m^{2}h) for 3.5% wt. NaCl. Presumably, as in the case of RO, concentration polarization occurred on the PV membrane. A similar initial increase in flux for low salt content in the feed was observed in experiments carried out on the PERVAP 2210 membrane (Łuczak, 2017), where with further increases in salinity up to 7% wt. NaCl, the flux value decreased. This trend is also characteristic of other hydrophilic PERVAP membranes made of PVA: 2201, 2202 on our apparatus (Lachowska, 2022). The characteristics of the membranes provided by the manufacturer show that membranes with an active PVA layer work better at higher concentrations of water in the feed. However, these membranes are not dedicated to the desalination process, but to dehydration. The solution diffusion model is widely used to describe the transport of substances in PV, but it does not describe the complicated mechanisms of transport of water molecules and ions through the membrane. Understanding the mechanisms of salt water separation in PV membranes will be crucial for the further development and optimization of this technique. In the case of RO, we observed 2 to 19 times higher permeate flux values, compared to PV, depending on the pervaporation membrane used.

More detailed results of pervaporation desalination on the commercial PERVAP 4510 membrane are presented in Figure 4 (Rosiak, 2022). For PV, the permeate flux increased with an increase in the feed flow rate (40, 60, 80 dm^3/h), process temperature (40, 60, 80 °C), and salt content in the feed, c. For higher salt content (3.5%), temperature and flow rate of the feeding solution had a visible impact on the PV process efficiency, as higher values of these parameters positively affected the amount of obtained permeate.

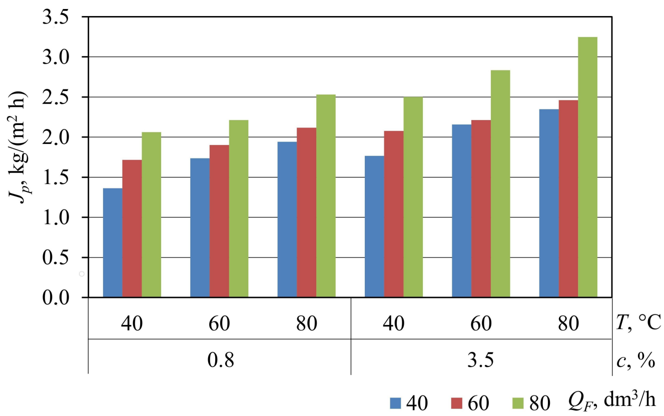

Figure 4. Dependence of the permeate flux (J_p) on the process temperature (T) and the feed flow rate (Q_F) for PV with a model salt concentration in the feed, $c = 0.8\%$ and 3.5% wt. NaCl.

The main obstacle in using PV as a desalination method on an industrial scale is the low flux of desalinated water. During RO, the permeate flux was 6–12.7 times higher than in the case of PV, respectively for 3.5% and 0.8% wt. NaCl concentration in the feed. It should be noted, however, that due to the different process principles, RO and PV were conducted on different membranes. When considering the use of PV for water desalination, in the future it will be necessary to strive for the development of more efficient pervaporation membranes based on PVA.

3.2. Energy consumption calculations

Initially, the total energy consumption (*TEC*) was determined as the product of the measured active power (*P*) and the total time of the desalination process (*t*), according to Equation (5).

$$TEC = P \cdot t, \quad \text{kWh} \tag{5}$$

The total energy consumption results are presented in Fig. 5. For laboratory desalination using reverse osmosis, *TEC* was 1.6 kWh and did not change depending on the salt content in the feed. In the case of desalination using pervaporation, an increase in energy consumption can be observed with the process temperature and the feed flow rate. The graph clearly shows higher energy consumption (1.2–1.5 kWh) for higher salt concentrations in the feed (3.5%). Small amounts of salt 0.8% wt. NaCl (representing the salinity of the Baltic Sea) indicate significantly lower *TEC* (0.3-0.5 kWh) at lower temperatures (40, 60 °C) and feed flow rates (40 and 60 dm^3/h).

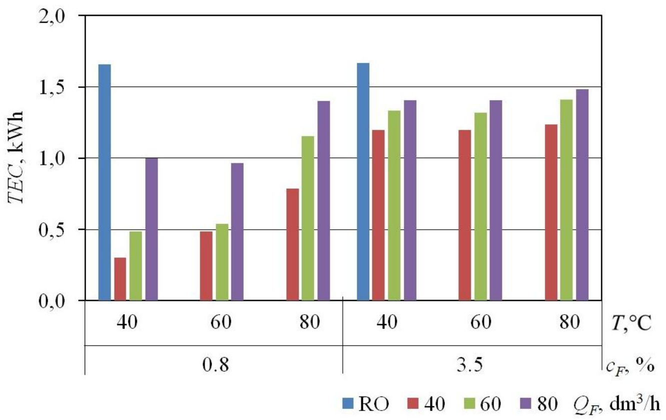

Figure 5. Total energy consumption (*TEC*) for RO processes (blue column) and PV (the rest of the results on the chart) depending on the operating temperature (*T*), feed flow rate (Q_F) for various feed salinities, $c_F = 0.8$ and 3.5% wt. NaCl.

These results clearly show a rule: lower energy consumption for PV compared to RO at the same process times. Thus, the superiority of the laboratory PV method and lower operating costs. However, further analysis leads to the calculation of an energy parameter characteristic of all desalination methods. Measurements of the active power, *P* of desalination processes, permeation flux and membrane area allowed for the determination of the specific energy consumption, *SEC* (see Eqs. (1) and (3)). The calculated *SEC* values for both laboratory PV and RO processes gave results in the range of 2.3–67.4 MWh/m^3. The *SEC* values for laboratory desalination processes (PV and RO) and the membranes used at 40 °C and various initial salt concentrations in the feed are presented in Table 1. In the case of RO, one can observe 2 to 17 times lower *SEC* values compared to PV, depending on the pervaporation membrane used. Moreover, there were no significant differences in *SEC* for different salt concentrations during the RO process.

High *SEC* values and their differences are observed for the 4510 membrane changing with temperature and feed salt content (22.0–67.3 MWh/m^3). This is shown in Fig. 6. Additionally, for a higher concentration of 3.5% wt. NaCl, there is a clear decrease in *SEC* with increasing temperature. These dependencies are also confirmed at higher feed flow rates (60 and 80 dm^3/h).

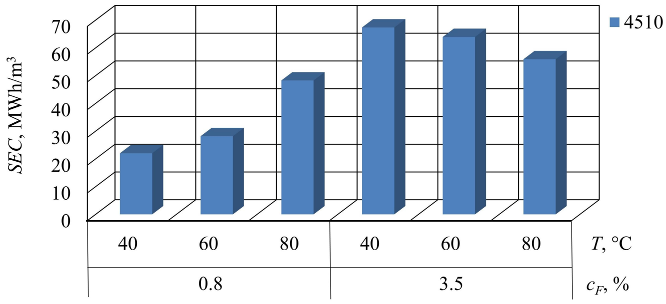

Figure 6. The relationship between specific energy consumption *(SEC)*, the process temperature (*T*), the model salt concentration in the feed solution at $c_F = 0.8$ and 3.5 wt.% NaCl, the feed flow rate (Q_F) at 40 dm^3/h, for the commercial PERVAP 4510 membrane.

The *SEC* values for different desalination processes and membranes are much higher than the data obtained in industrial installations. Depending on the origin of the water (surface water vs. sea water) and desalination methods, this parameter varies in the range of 0.4–10 kWh/m^3 in industrial conditions (Nassrullah et al., 2020). In this research, the values are three orders of magnitude higher. It should be noted that the desalination processes studied here are carried out under laboratory conditions. The equipment used in the setups comes from world-class manufacturers, but it is not optimized energetically as a system.

In the laboratory RO system, there are significant energy losses at the throttling valve. The best solution would be to rebuild the system so that high pressure is maintained in the feed loop, and variable flows are achieved using a variable speed pump. However, the RO stand is a standard test system produced by OSMONICS (USA), and currently, it is not possible to transform it into such a system.

The power consumption of individual devices during a single pervaporation (PV) process using 2210 membranes was

Table 1. Comparison of the specific energy consumption *(SEC)* for laboratory desalination processes (RO and PV) at 40 °C and different salt concentration in the feed (c_F).

c_F [% wt. NaCl]	*SEC* [MWh/m^3] RO (Osmonics AG)	PV (PERVAP 2210)	PV (PERVAP 4510)
0.8	2.29	6.42	22.02
3.5	3.99	9.09	67.35

also checked. The sum of the circulating pump (in the feed circulation system), the vacuum pump (in the permeate collection system on the low-pressure side of the membrane), and the thermostat (in the temperature control system) gives the total energy consumption of the entire PV process. The discussed systems are distinguished in Figs. 1 and 2. The energy consumed during a single pervaporation process for water desalination depends mainly on the temperature and pressure on the low-pressure side of the membrane. These dependences can be seen in Fig. 7a. The vacuum pump and thermostat have the largest share in the total power consumption of the PV apparatus. By increasing the vacuum (from 3 to 1 kPa) at the same temperature, such as 40 °C, the PV process becomes more energy-consuming (from 0.67 to 0.73 kWh), and the share of the power consumption by the vacuum pump increases by about 4%. This is compensated by a larger amount of obtained permeate, thus increasing the PV efficiency.

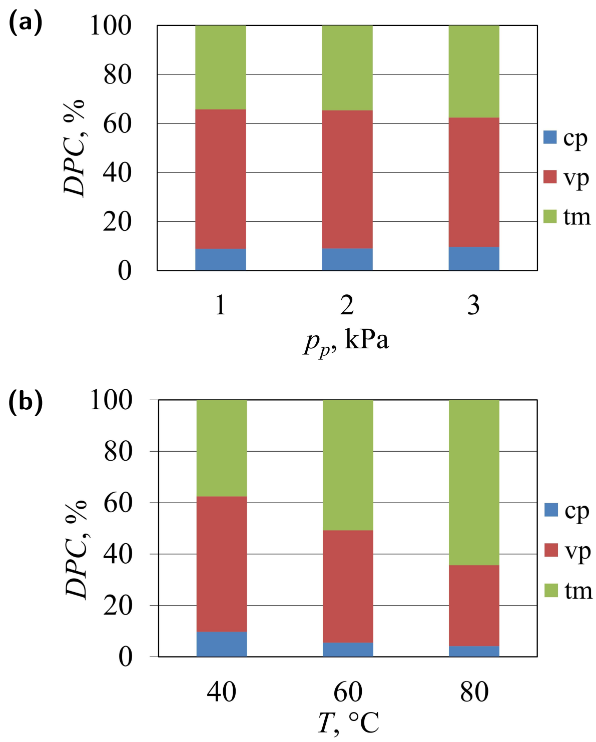

Figure 7. The percentage share of device power consumption *(DPC)* of individual devices comprising the PV setup (cp – circulation pump, vp – vacuum pump, tm – thermostat) for the PERVAP 2210 membrane, $Q_F = 40$ dm^3/h depending on: a) the vacuum applied on the low-pressure side of the membrane, $T = 40$ °C, b) the process temperature on the low-pressure side of the membrane $p_p = 3$ kPa.

An important factor in reducing energy consumption can be lowering the temperature of the thermostat (from 80 to 40 Fig. 7b), which consumes 30 to 60% of the total energy used in the PV process. Lowering the process temperature in the mentioned range reduces energy consumption by 42.7%. According to the analysis, the best temperature is 60 °C.

4. CONCLUSIONS

A high retention degree was obtained for both membrane desalination processes, regardless of the conditions and salinity of the feed solution. However, a higher degree of desalination was obtained by PV. In terms of energy, the salinity of the feed solution is not crucial in RO desalination, but it is a significant parameter in PV. Our lab experiments of RO feed desalination resulted in 1000 times higher *SEC* than in RO in the industry. However, they are still lower than the *SEC* for PV (6.5–67.4 MWh/m^3). For different PV process parameters i.e. temperature, feed flow rate, pressure on the low-pressure side of the membrane, significant differences in energy consumption (total energy consumption and specific energy consumption), can be observed. It should be noted that the research was conducted on laboratory equipment and energy consumption and operational costs may be distributed differently at a semi-technical or technical scale. The *SEC* in the PV process can be controlled by using different pressures on the low-pressure side of the membrane and by reducing or completely eliminating feed temperature control. This can be achieved by using waste heat or heat from renewable energy sources.

Higher temperatures and feed flow rates in PV result in higher permeate fluxes. PV may prove to be a more cost-effective alternative to reverse osmosis in the future if membranes with higher efficiency can be developed. There is a lack of PV membranes for water desalination on the market, and those available for other processes, e.g. alcohol dehydration, have low efficiency. Therefore, it is necessary to independently develop a selective pervaporation membrane for seawater desalination processes.

Pervaporation is an interesting option for difficult, heavily polluted saltwater compared to MD. Currently, commercial pervaporation membranes have low water permeability, limiting the use of pervaporation to desalination applications. However, the development of new membrane materials designed for high water permeability could make pervaporation an interesting alternative to RO for high salinity water treatment.

Energy analysis of a laboratory process of water desalination showed that in PV and RO processes, thermostating is not necessary and only leads to higher energy consumption. Further research will be conducted to optimize desalination processes on a laboratory scale.

SYMBOLS

m	mass obtained after time *t*, kg
A	membrane area, m^2
c	salt concentration, %wt. NaCl
DPC	device power consumption, kWh

J local flux at membrane-surface element A, $m^3/(m^2h)$
t time taken to collect permeate mass, h
p pressure, Pa
P active power, W
Q flow rate, m^3/h
R retention factor, %
SEC specific energy consumption, MWh/m^3
TEC total energy consumption, kWh
V volume, m^3

Greek symbols

ρ density, kg/m^3

Subscripts

p permeate
F feed

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