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Saline brine desalination: application of sweeping gas membrane distillation (SGMD)

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ABSTRACT

In this work, desalination of saline brines using the sweeping gas membrane distillation (SGMD) process is investigated. The Taguchi method was applied for optimization of the operating parameters. An L_9 orthogonal array was used to investigate the influence of pertinent variables, including feed temperature (T_f: 45°C, 55°C and 65°C), feed flow rate (Q_f: 200, 400 and 600 mL/min), feed concentration (C_f: 10, 25 and 50 g/L) and sweeping gas flow rate (Q_c: 4, 10, and 16 SCFH) on the distillate flux. Results of the experiments showed that maximum distillate flux, which was about 10 L/m^2 h, obtained at 65°C feed temperature, 16 SCFH sweeping gas flow rate and brackish water with 10 g/L salt concentration were used. Feed temperature with a contribution of 52.8% had the major effect on the distillate flux. Moreover, the sweeping gas flow rate was found to be more effective compared with the feed flow rate, indicating the significance of the distillate side role in the SGMD process when it is used for brine desalination.

Keywords: Desalination; Saline brine; Sweeping gas membrane distillation; SGMD; Distillate flux

1. Introduction

As time goes by, the development of countries has increased human life standards. This issue has caused an increase of energy and fresh water demand throughout the world. Considering the abundant seawater sources, desalination of brackish water and seawater is an attractive alternative to solve water shortage in arid regions, particularly, such as the Middle East and Persian Gulf [1–3].

Desalination processes are classified into two categories, including thermal-based (multi-effect distillation and multi-stage flash) [4,5] and membrane-based [6] methods (reverse osmosis [RO], nanofiltration [NF], electrodialysis, membrane contactors). Among membrane-based desalination processes, RO and NF applications have been highlighted during the last decade [7–9]. These mentioned desalination methods are very energy consuming, and due to the reduction of fossil energy resources and environmental concerns [10], alternative considerations seem necessary. RO and NF, in particular, require high operating pressures and osmotic pressure limitation reduces their efficiencies and

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increases the amount of waste, i.e., high salinity brine which can cause changes in environmental salinity in the brine discharge zone.

The membrane distillation (MD) process is a hybrid and emerging separation which has been the subject of worldwide academic studies, currently, by many scientists and groups [11–18]. MD is a non-isothermal membrane process which can utilize low grade waste and/or alternative energy sources such as solar, wind and geothermal energy to provide the vapor pressure difference as a mass transfer driving force [19,20]. A hydrophobic microporous membrane separates two sides in the membrane module, i.e. feed (hot) side and distillate (cold) side. Although this membrane has no effect on the process selectivity, it acts as an interface between liquid–vapor and distillate. Various applications for the MD process have been introduced [21]; however, drinking water production through desalination of saline brines (e.g. brackish water and seawater) is highlighted [22–29].

He et al. [23] studied the performance of nine types of commercially available membranes made of PVDF, PP and polytetrafluoroethylene (PTFE) for the production of drinking water through direct contact membrane distillation (DCMD) of the MD process. In their work, some properties of membranes, such as liquid entry pressure, contact angle and gas permeability, were analyzed to understand, comprehensively, the membrane characteristics. The effect of membrane module design through three module depths (in the feed side) as well as the effect of operating variables was investigated through several experiments. Results indicated that the PTFE membrane with 0.22 μm pore size, hot-side inlet temperature of 60°C, cold-side inlet temperature of 20°C and feed flow rate of 0.6 L/min led to the highest distillate flux and salt rejection. However, it should be noted that the heat loss through membrane conduction is the most important drawback of the DCMD mode.

Vacuum membrane distillation (VMD), another configuration of the MD process which uses vacuum pressure in the distillate side to impose the driving force, studied by Mericq et al. [24] for water recovery of RO brines with a concentration up to 300 g/L. For the membrane studied in this work, temperature and concentration polarization were shown to have little effect on distillate flux, and after a 6–8 h operation no organic fouling or biofouling was observed. Authors indicated that at high salt concentrations, scaling occurred mainly due to calcium precipitation and 24% decrease for distillate flux was observed. Moreover, an 89% recovery factor was obtained by coupling RO and VMD. It is worth quoting that, due to the vacuum pressure in the distillate side of the MD module, the most important limitation of the VMD mode is the pore wetting.

Due to the high heat loss in DCMD through the membrane thermal conductivity which reduces the thermal efficiency of the process, an air gap was imposed in the distillate side between the membrane and a condensing plate with a cooling liquid stream behind it to reduce this heat loss. This configuration is known as the air gap MD (AGMD) process. Alkhudhiri et al. [25] used AGMD for the treatment of high salinity solution of NaCl, $MgCl_2$, Na_2CO_3 and Na_2SO_4. Distillate fluxes were measured for different feed concentrations and membrane pore sizes (0.2 and 0.45 μm). Results indicated that the distillate flux, on the one hand declined as the concentration of salt increased, and on the other hand increased as the pore size increased. Moreover, authors concluded that the energy consumption was found to be independent to membrane pore size, salt type and salt concentration in the feed stream. However, due to the mass transfer resistance which occurs in the air gap, low distillate flux will be achieved by the use of AGMD mode, especially in the case of desalination purposes.

The fourth major MD configuration which has received the least attention, despite its promising features in comparison with other MD configurations, is the sweeping gas MD (SGMD). In SGMD, the feed side of the membrane, i.e. active hydrophobic surface, is in direct contact with the process liquid. An inert and dry gas stream in the distillate side sweeps the vapor molecules. This strategy not only can reduce the conductive heat loss, but also improve the MD productivity, significantly, through higher distillate flux generation [19,20]. Basini et al. [26] studied the application of porous hydrophobic membranes, both flat sheet and tubular ones, for SGMD desalination. In another work, Charfi et al. [27] developed numerical simulation and carried out an experimental study on heat and mass transfer using SGMD. In this work, a plate and frame module was used. The developed model focused on modeling of heat, momentum and mass transfer through three major parts namely feed, membrane and distillate side. The model was based on Navier–Stokes equations coupled with the Darcy–Brinkman–Forchheimer formulation in transient regime in two dimensions. Good agreements between the model results and experimental distillate fluxes are found [27]. In another work, Shirazi et al. used SGMD for concentration of glucose syrups [28] and ethanol removal from dilute aqueous streams [29] through a plate and frame module equipped by a 0.22-μm PTFE membrane. In both works, a comprehensive experimental study on the effect of operating conditions on the distillate flux through several tests is conducted. All mentioned examples indicated the promising features of SGMD process, not only for solvent recovery but also for solute concentration purposes.

In this work, the SGMD process is used as an alternative for desalination of saline brines (e.g. brackish water and seawater). The effect of pertinent operating variables including temperature, flow rate and concentration of feed stream as well as sweeping gas flow rate on the distillate flux through several experiments were considered. In order to time and cost saving, the Taguchi optimization method was used to design the experiments, and an L_9 orthogonal array was conducted based on operating variables (four variables each one at three levels).

2. Materials and methods

2.1. Materials

Feed samples were prepared by dissolving analytical reagent grade of sodium chloride (NaCl; Merck, Germany), as the major salinity agent in brines, in distilled water in three different concentrations, including 10 g/L (similar to brackish waters), 25 and 50 g/L (similar to seawaters, samples on behalf of seawater in north and south of Iran, respectively). A flat sheet microporous PTFE membrane (Millipore, USA) with 0.22 μm pore size was used for the experiments. Table 1 shows the specifications of the applied membrane in this work.

2.2. Experimental setup and procedure

A plate and frame SGMD module made of Plexiglas™ (for the corrosion and heat loss prevention) with 0.0170 m^2 active area mounted horizontally was used for desalination experiments. A diaphragm pump (So Pure, Korea) was used for re-circulation of hot feed in the closed loop of the feed tank–SGMD module–feed tank. An oil-free compressor (Gast, USA) provided sweeping gas (dried and filtered air flow). Two regulators and flow meters were used for controlling the process liquids, respectively, inlet pressures and flow rates. The inlet and outlet temperatures were monitored by the use of a digital temperature controller (Autonics, Korea) and PT-100 temperature sensors which were located as close as possible to the membrane module. Fig. 1 shows a general scheme of the experimental setup.

For sensitivity analysis of the SGMD process, it is, obviously, necessary to identify which variables have the most influence on the distillate flux in order to optimize the SGMD desalination experiments. Taguchi experimental design was used to reveal this approach. Two important objectives must be satisfied by using the Taguchi method, the number of trials must be determined and the conditions for each trial must be specified. It determines which variable has more influence and which has less. Therefore, the optimum level for each factor will be determined.

Table 1
Specifications of the applied membrane in this work

Type	PTFE
Pore size (μm)	0.22
Porosity (%)	70
Thickness (μm)	175
Bubble point at 23°C (psi)	20.9
Max. operating temperature (°C)	130
Contact angle (°)	132.2 ± 0.1[a]

[a]Measured by the authors.

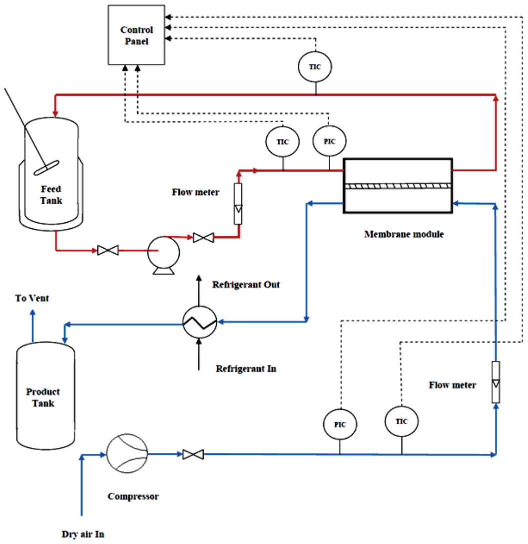

Fig. 1. The general scheme of the experimental setup applied in this work.

Based on the Taguchi design methodology, an L_9 orthogonal array (four variables each one in three levels, see Table 2) was considered. Table 3 shows the conditions of each experiment, and Fig. 2 shows a brief overview of the process followed by the Taguchi method.

It is indicated in the literature that, despite other concerns for MD process, the distillate flux is the worthy target parameter that should be investigated [21]. This is due to critical role of the distillate flux mainly for developing the MD process and scaling up its applications into industrial scale. Therefore, the quality characteristic in this study was distillate flux which was defined as the collected permeate (based on mass or volume; in kg or L) per unit time (h) per membrane effective area (m^2).

2.3. Analysis

Feed and distillate compositions were measured with an EC470-L EC meter (Istek, Korea). Scanning electron microscopy (SEM) (VEGA\\TESCAN, Czech Republic) and atomic force microscopy (AFM) (DUALSCOP 95-200E, DEM, Denmark) were used for morphology observation of the virgin membrane (see Fig. 3). Hydrophobicity was tested by a contact angle measuring system (Krüss G-10, Germany).

3. Results and discussion

3.1. Preliminary tests and equilibrium time measurement

As the first step, a series of experiments were conducted to reach the highest salt rejection and equilibrium time in this work. The results indicated that using 0.25 bar inlet pressure

Table 2
Operating conditions and their levels

Factor	Level 1	Level 2	Level 3
T_f (°C)	45	55	65
Q_f (mL/min)	200	400	600
C_f (g/L)	10	25	30
Q_c (SCFH)[a]	4	10	16

[a]SCFH: Standard cubic feet per hour.

Table 3
Operating conditions of each experiment based on the Taguchi L_9 orthogonal array

Run no.	T_f (°C)	Q_f (mL/min)	C_f (g/L)	Q_c (SCFH)
1	45	200	10	4
2	45	400	25	10
3	45	600	50	16
4	55	200	25	16
5	55	400	50	4
6	55	600	10	10
7	65	200	50	10
8	65	400	10	16
9	65	600	25	4

Note: Each row indicates an experiment.

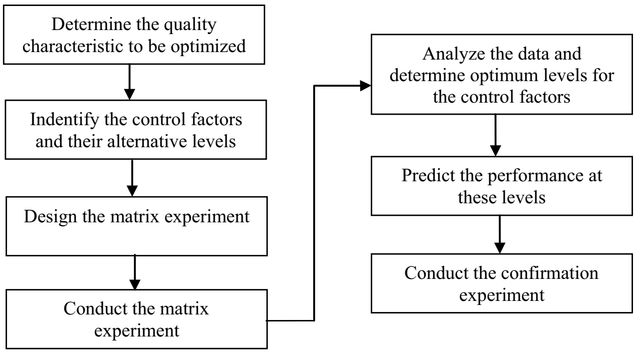

Fig. 2. Flowchart of the Taguchi method.

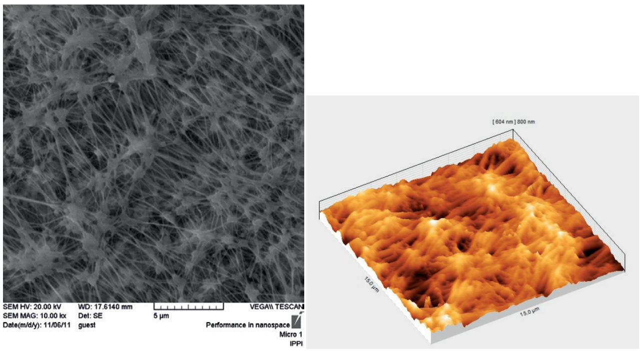

Fig. 3. SEM and AFM images of the PTFE membrane with 0.22 μm nominal pore size.

for feed stream revealed the highest salt rejection (99.9%) when 65°C, 600 mL/min, 50 g/L and 16 SCFH were used as operating conditions during 3 h operation. Moreover, the inlet pressure for the sweeping gas stream was set as 0.2 bar. The equilibrium time was measured as 1 h in which data were logged after this period and every 30 min.

3.2. Main effect of operating variables

As the MD process is a non-isothermal separation, the driving force that should be provided by a temperature difference which leads to the pressure difference between two sides of the membrane's pores. Therefore, feed temperature is considered as the first operating variable. Fig. 4(a) shows the main effect of the feed temperature on the target parameter, i.e. the distillate flux. As it could be observed (see Fig. 4(a)), an increase in the feed temperature led to increase the distillate flux. This is due to an increase in the vapor pressure caused by increasing feed temperature. This behavior can be explained by the well-known Antoine equation

$$\log P^* = A - \frac{B}{C+T} \quad (1)$$

where A, B and C are Antoine's constants (8.07131, 1,730.63 and 233.426 for water, respectively), and T and P^* are the related temperature (°C) and pressure (mm Hg), respectively.

This function expresses that higher vapor is provided at higher temperature and this increase, however, is exponential. Therefore, increasing the feed temperature from 55°C

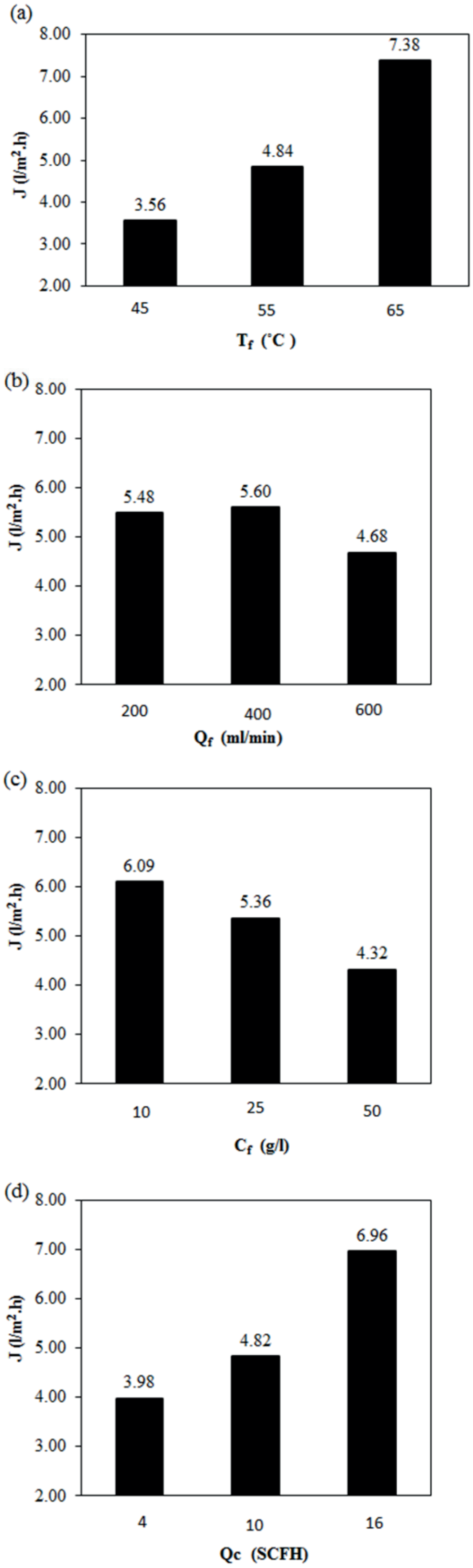

Fig. 4. Main effects of operating variables on the distillate flux of SGMD desalination: (a) feed temperature, (b) feed flow rate, (c) feed concentration and (d) sweeping gas flow rate.

to 65°C was more effective than that of 45°C–55°C. This is in good agreement with data published in the literature [30,31], which indicated that the most influencing operating variable in all configurations of the MD process is the feed temperature.

One issue that should be taken into consideration is that MD is sensitive to the concentration polarization like other membrane separations, however, less than other ones. Moreover, as MD is a non-isothermal process where vaporization takes place in the feed–membrane interface, the temperature in that area differs from the feed bulk which consequently causes temperature polarization. Both concentration and temperature polarization effects could decrease by increasing the turbulency in the feed–membrane interface. This could be provided by the use of higher feed flow rates which decrease the effect of concentration and the temperature boundary layers' effect. However, it should be noticed that using a higher feed flow rate could increase the risk of pore wetting due to higher inlet pressure requirement [30]. Fig. 4(b) shows the main effect of feed flow rate on the distillate flux. As could be observed, when the feed flow rate increased from 200 to 400 mL/min, a slight increase in the distillate flux was observed, while a further increase, i.e. up to 600 mL/min, led to a flux decline (see Fig. 4(b)). This may be explained by the membrane pore wetting at a higher flow rate, as mentioned earlier. This is in good agreement with our previously published results obtained during the application of the SGMD process for glycerol concentrating in dilute wastewaters [31].

Recently, membrane separation processes such as NF and RO have been used for desalination [7] and concentration of sugar syrups [32] while the osmotic pressure, which limits the percentage of solute rejection and provides large amounts of wastewater, is their most important drawback. Although, the MD process is not, significantly, sensitive to feed concentration [33–36], increasing the solute concentration could decrease the distillate flux. This is mainly due to an increase in the effect of concentration polarization, and solute precipitation/scaling on the membrane surface. As it can be observed in Fig. 4(c), an increase in the feed concentration from brackish water range (10 g/L) to seawater range (25 and 50 g/L) led to a flux decline from 6.09 to 4.32 L/m^{2}h. Hence, strategies which can reduce the negative effect of concentration polarization/fouling/scaling, e.g. higher shear in the feed side, using baffle and/or pulsating in the feed side of the MD module can be investigated.

In SGMD, as it was mentioned earlier, a gas flow is used to impose the mass transfer driving force through the vapor pressure reduction in the distillate side. When feed contains a volatile compound such as ethanol, variation of sweeping gas flow rate affects the selectivity. When the feed stream contains a non-volatile like glucose or salt, it can affect the distillate flux [28,29]. Fig. 4(d) shows the effect of sweeping gas flow rate on the distillate flux. As it can be observed, when air flow rate increased to 16 SCFH, the distillate flux increased up to 6.96 L/m^{2}h. It is worth noting that increasing the feed flow rate increased the flux and then decreased, while increasing the sweeping gas flow rate increased the flux, continuously. This is in good agreement with the previously obtained results [28,31].

3.3. Interactive study of operating variables

Table 4 presents the results for the response of each level. These results indicated that there are some interactions between the operating variables. To find the interactions between investigated variables, the response of each parameter against the others shall be curved. The results are shown in Table 5. The operating variables' interactions could be evaluated based on the severity index (SI, %). The Taguchi method uses the SI values to order the interactions. As could be observed (see Table 5), among the six interactions tested, the SI values ranged between 70.13% (as the highest for $Q_c \times C_f$) and 9.88% (as the lowest for $T_f \times Q_c$). In other words, the highest interaction was observed between the sweeping gas flow rate and feed concentration, while the lowest was observed between the feed temperature and cold stream flow rate (see Table 5). This could be explained by this fact that

Table 4
Responses for the Taguchi analysis of the distillate flux

Response	Operating variable			
	T_f (°C)	Q_f (mL/min)	C_f (g/L)	Q_c (SCFH)
L_1	3.365	5.485	6.092	3.998
L_2	4.84	5.613	5.36	4.826
L_3	7.379	4.686	4.333	6.960
L_1–L_2	–1.275	–0.129	0.731	–0.828
L_1–L_3	–3.814	0.799	1.758	–2.962
L_2–L_1	1.274	0.128	–0.732	0.827
L_2–L_3	–2.539	0.927	1.027	–2.135
L_3–L_1	3.813	–0.8	–1.759	2.961
L_3–L_2	2.538	–0.928	–1.028	2.134

Table 5
Tabulated interaction between operating variables

Interactive variables	SI (%)
$Q_c \times C_f$	70.13
$T_f \times Q_f$	28.12
$C_f \times Q_c$	23.16
$Q_f \times Q_c$	15.86
$T_f \times C_f$	13.60
$T_f \times Q_c$	9.88

Table 6
Distillate fluxes obtained from Taguchi-designed experiments

Run no.	Distillate flux (L/m^{2}h)
1	3.356
2	3.58
3	3.76
4	6.86
5	3.00
6	4.66
7	6.24
8	10.26
9	5.64

Table 7
The results of ANOVA

Factors	DOF	Variance (V)	Pure sum (S)	Sum of squares	Contribution (%)
T_f	2	11.314	22.628	22.628	52.832
Q_f	2	0.756	1.512	1.512	3.532
C_f	2	2.341	4.682	4.682	10.993
Q_c	2	7.007	14.08	14.006	32.701
	8			42.83	100.00

these variables, however, different in nature, have the same effect on the response, i.e. the distillate flux in this work.

3.4. Analysis of variance

To check which operating variable had the significant effect on the process performance characteristic (distillate flux), the analysis of variance (ANOVA) analysis should be carried out. Table 6 shows the distillate flux resulted from each test. Table 7 shows the results of ANOVA for this work and indicated that feed temperature and feed flow rate are the most and the least significant operating variables based on their higher (52.83%) and lower (3.53%) contributions, respectively.

Moreover, the degrees of freedom (DOF) for all variables is 2, and F-ratio is zero. Based on the pool-factor analysis, all studied operating variables are effective, and the error for these experiments is very low that is a sign for the accuracy of the experimental results. It is worth quoting that based on the Taguchi prediction model, test 8 is the optimum, the results of which should be conducted to reach the higher distillate flux (i.e. 10.26 L/m^2 h).

4. Conclusions

MD is a non-isothermal separation which can use low grade and/or renewable energy sources to provide mass transfer driving force and it is not significantly sensitive to osmotic pressure for desalination purposes. In this work, the Taguchi method was applied for optimization of brackish water and seawater desalination through the SGMD alternative. Experimental results indicated that feed temperature with 52.83% contribution had the most effect on the target parameter, i.e. distillate flux. Based on available heat source, feed temperature up to 65°C would be suggested. Sweeping gas flow rate was the second important parameter with 32.70% contribution. Increasing the feed flow rate up to 400 mL/min had a positive effect on the distillate flux; however, a further increase led to distillate flux decline. Increasing the feed concentration could decrease the distillate flux; however, MD could be applied for water recovery from high salinity brines. Moreover, maximum salt rejection (99.9%) was achieved in this work.

Symbols

AGMD — Air gap membrane distillation
C_f — Feed concentration, g/L
DCMD — Direct contact membrane distillation
MD — Membrane distillation
PTFE — Polytetrafluoroethylene
Q_c — Cold stream flow rate, mL/min
Q_f — Feed flow rate, mL/min
RO — Reverse osmosis
SGMD — Sweeping gas membrane distillation
T_f — Feed temperature, °C
VMD — Vacuum membrane distillation

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