Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.993725

57 (2016) 4303–4312
February

Taylor & Francis
Taylor & Francis Group

Ultra-low energy reverse osmosis with thermal energy recovery from photovoltaic panel cooling and TFC RO membrane modification

Hiren D. Raval[a,*], Subarna Maiti[b]

[a]*Reverse Osmosis Discipline, CSIR-Central Salt and Marine Chemicals Research Institute (CSIR-CSMCRI), Council of Scientific & Industrial Research (CSIR), Gijubhai Badheka Marg, Bhavnagar 364 002, Gujarat, India, Fax: +91 0278 2566970; email: hirenraval@csmcri.org*
[b]*Scale-up and Process Engineering Unit, CSIR-Central Salt and Marine Chemicals Research Institute (CSIR-CSMCRI), Council of Scientific & Industrial Research (CSIR), Gijubhai Badheka Marg, Bhavnagar 364 002, Gujarat, India, Fax: +91 0278 2566970; email: smaiti@csmcri.org*

Received 25 July 2014; Accepted 26 November 2014

ABSTRACT

The electrical efficiency of solar photovoltaic (PV) panel decreases with increase in its temperature, and therefore transfer of heat from the panel is very important. The capitalization of the transferred heat for useful purpose is of prime importance since the conventional solar PV panel has the conversion efficiency of only 5–17%, and therefore the larger part of incident solar radiation remain unutilized. The present paper addresses the temperature control of solar PV panel by direct contact heat exchange with flowing feed water to reverse osmosis (RO) from top of the panel, thus recovering energy together with improving the performance of PV panel. The RO at higher temperature resulted in the improvement in the flow performance of the membrane. Further, the modification in membrane morphology by controlled sodium hypochlorite treatment improved the flow performance by increasing hydrophilicity of the membrane as evident by decline in contact angle from 48.05˚ to 26.22˚. Thus, a two-pronged technique of controlling the PV panel temperature by heat transfer and tuning the membrane morphology toward more hydrophilicity helped in significant improvement in RO permeate flow and better electrical performance of PV panel. As a result, the overall energy consumption of RO has been reduced by about 40%. This novel approach opens up the avenues for significantly reducing the overall energy consumption for brackish water RO systems.

Keywords: Solar PV panel; Heat transfer; Direct contact; Hydrophilicity; Energy; Efficiency

1. Introduction

The devices used in photovoltaic (PV) conversion are called solar cells, when solar radiation falls on these devices; it is converted directly into direct current (DC) electricity. The advantages of PV conversion are: no moving parts, little maintenance, work quite satisfactorily with beam or diffuse radiation and modular.

The mechanism of electricity generation by solar PV includes the following steps:

(1) Photons in sunlight hit the solar panel and are absorbed by semiconducting material i.e. silicon.

*Corresponding author.

(2) Electrons (negatively charged) are knocked loose from their atoms, allowing them to flow through the material to produce electricity.
(3) An array of solar cells converts solar energy into a usable amount of DC electricity.

If the temperature of solar PV panel increases, the efficiency of solar PV panel decreases because of negative temperature coefficient (−0.5% per ˚C rise in temperature) of solar PV panel with temperature. Only 5–17% of incident radiation gets converted to electricity and the rest heat up the solar PV panel raising its temperature in case of crystalline technology. Thus, it can be argued that the panel generates more of thermal energy rather than electrical energy.

Solar-powered reverse osmosis (RO) has been studied by the researchers world over. For example, optimization of solar-powered RO plant has been done by response surface methodology [1]. Desalination by solar-powered RO has been attempted at Sultanate of Oman, where the average cost of desalinating water has been reported $6.52 per cubic meter [2]. Laboratory demonstration of PV powered RO system without batteries has been studied [3,4].

Modeling of a standalone solar-powered RO with/without battery has been done. Also, time resolved power characteristic of system component has been examined [5]. It has been reported that the performance of RO changes with local climatic conditions [6]. Thermoeconomic analysis of combined solar organic Rankine cycle desalination with different energy recovery configuration has been reported, where pressure exchanger configuration has been found more economical than Pelton wheel turbine [7]. The need for making solar-powered RO has been acknowledged. To address this, the indirect methodologies like clubbing the solar-powered RO with solar water heating system to get the higher temperature feed water, increasing the membrane permeability to decrease the energy consumption for given output can make the significant cost-cutting to make it more attractive.

On the other hand, the cooling of solar PV panel has been attempted by various researchers world over. Solar PV panel has been cooled by air by Tonui and Tripanagnostopoulos for performance improvement of solar PV/T collector with natural flow operation and it has been demonstrated that fins improve efficiency of heat transfer by air cooling [8]. Desiccant cooling system equipped for application in hot and humid climate has been studied [9]. A liquid connected to a heat exchanger placed in the housing of the PV module and unwanted wavelengths of solar radiation were filtered out to minimize overheating of the cells [10]. A cooling method for the solar cells under concentrated solar flux is proposed where the surplus heat is removed from both front and back surfaces of the module by directly immersing the cells in a dielectric liquid [11]. A profile for the reflecting surfaces has been developed such that the solar cells are evenly illuminated under any degree of concentration to control its temperature [12].

To eliminate the contact thermal resistance, liquid immersion cooling has been attempted to improve cell performance [13]. Tanaka suggested using a liquid layer or a gel layer surrounding solar cells for light trapping and also cell surface wetting [14–16]. Carcangiu and co-workers patented a liquid immersion PV panel. The liquid-tight chamber to house solar cells immersed in a poly-dimethylsilicone liquid, which circulates through inlet and outlet passages has been reported [17].

Water has been used as an immersion liquid on the panels with liquid super-concentrators having outwardly disposed liquid imaging lenses. Ignacio and co-workers used curved and optically transparent covers to enhance the concentrating effect of the immersion dielectric liquid [18]. Falbel patented a surrounding reflective surface for a solar cell, which reflects back the light rays, not absorbed by the solar cell [19]. Besides the liquid and gel, Cherney et al. even extended the refractive medium to a solid [20].

Apart from the optical and surface wetting advantages of liquid immersion, the direct contact between cells and their surrounding liquid make the solar panel operate at high concentrations [21]. Eliminating the thermal resistance of the contact wall between solar cell and fluid of conventional active cooling approaches, control the rate of heat dissipation, the cells could be effectively cooled down for a desirable sunlight to electricity conversion efficiency [22].

The attempt has been made to mimic plant leaves as they control temperature when exposed to sun [23]. An active cooling of PV module by blowing air above the module with CFD analysis has been attempted [24].

It has been attempted to improve the PV panel performance by covering the array surface with a thin film of water. However, the comparison with the modeled data has not been done and overall energy efficiency derived out of the system has not been worked out. Improvement in PV panel efficiency by direct water cooling has been reported; however, the application of recovered energy is missing [25,26].

On the other hand, there are many reports on improvement of membrane morphology to make it more hydrophilic. It has been demonstrated that sodium hypochlorite exposure in controlled environment i.e. controlled chlorine concentration in alkaline pH for controlled time at normal temperature can improve membrane performance by enhancing its flux with some penalty in terms of decrease in solute rejection [27].

It has been worked out from the first principle that the specific energy consumption for RO can be reduced by the following methods from the first principle [28].

(1) Increasing.

$$\gamma = A_{\text{total}} LP \Delta\pi_0 / Q_{\text{f}} \tag{1}$$

(2) Increasing number of stages.
(3) Using energy recovery device.

Hydraulic permeability (LP) can be found by the equation below [29].

$$\text{LP} = C_{\text{LP}} \cdot \exp(-Ea^{\text{LP}}/RT) \tag{2}$$

where C_{LP} = Constant, Ea^{LP} = Activation energy represents the per mole difference in enthalpy of a molecule which is necessary to overcome the transport barriers during its passage across the membrane, T = Temperature.

Substituting Eq. (2) in Eq. (1)

$$\gamma = A_{\text{total}} C_{\text{LP}} \cdot \exp(-Ea^{\text{LP}}/RT) \Delta\pi_0 / Q_{\text{f}} \tag{3}$$

Therefore, T has to be maximized for maximizing γ. Hydraulic permeability increases at higher temperature which in turn results in improved γ. Increasing number of stages and/or using energy recovery devices will also reduce the specific energy consumption for RO. The rise in feed water temperature and consequent rise in hydraulic permeability of membrane can be achieved by low-grade heat such as thermal energy available from feed water heating when it passes over the solar PV panel. Also, the dynamic viscosity of water decreases from 0.7194 to 0.5960 mPa-s when its temperature increases from 35 to 45°C [30]. The decline in viscosity indicates that the resistance to flow decreases; which in turn, results in increased flow performance of the membrane.

There is also another dimension to increase in feed water temperature viz. increase in osmotic pressure of feed water. Osmotic pressure can be found by $\Pi = C \times R \times T$.

where Π = osmotic pressure in atm, C = Concentration in mol/l, R = Constant in lt×atm/mol×K, T = Temperature in °K.

Thus, with 10°K rise in temperature, there will be an increase in feed water osmotic pressure by 0.01052 atm for 750 mg/l feed water concentration. This counters the above effect. However, the increase in osmotic pressure is not significant as compared with the benefit achieved by increase in flow performance owing to decline in viscosity of feed water.

Solar panel heat transfer with water cooling from top surface and the application of heated water for RO to reduce the energy consumption of RO opens the possibility of indirect capture of solar thermal energy. Further, the modification in membrane morphology to increase its permeability reduces the energy consumption of the RO process. Thus, the present paper demonstrates for the first time that the seemingly different parts i.e. thermal energy recovery from solar PV panel and improvement in membrane morphology for higher permeability can be combined together to achieve synergy in brackish water RO performance.

2. Experimental

2.1. Materials

Solar PV panel—70 W peak output, calcium silicate for insulation, frame structure, domestic RO pump, 5 μ cartridge filter, water tanks, Rheostat, Thermometer, temperature sensor, pyranometer, and Testo 876 thermal imager.

2.2. Method

The experimental procedure is described below:

(A) PV panel has been kept horizontal with water chamber on top to retain water on the panel surface continuously as shown in Fig. 1A. The water used in the experiment is feed water to RO with total dissolved solids concentration of 750 mg/l. The experiments were done at Bhavnagar, India 21.7600°N and 72.1500°E. Photographs of the setup have been shown in Figs. 1A and 1B. The concentrating mirrors (reflectors) have been provided at top and bottom of the panel as shown in the photograph in all the experiments. The angle of top and bottom reflector with reference to panel is 95° and 135°, respectively, to concentrate the radiation on PV panel. The water exiting from the panel goes directly to micron cartridge filter by gravity and the outlet of micron cartridge filter (5 μm) goes to the suction of booster pump that pumps water in RO membrane at

Fig. 1A. Horizontal PV Panel with cooling from top.

Fig. 1B. Domestic RO plant associated with solar PV panel.

1.8 l/min flow rate as shown in Fig. 1B. The domestic RO membrane element was Dow make. The performance output of domestic RO in terms of flow and solute rejection has been monitored during the experiment. One PV panel was kept without cooling to compare the *V–I* performance of PV panel with and without cooling at the same time. The variable resistance system (Rheostat) has been used to measure the *V–I* (Voltage–Ampere) performance of PV panel. Thermal images of the PV panel with and without cooling were taken by the instrument.

(B) Membrane permeability improvement: The domestic RO membrane element (Dow make) was subjected to controlled oxidation where 325 mg/l of sodium hypochlorite solution of pH 11.5 was circulated in membrane element for 30 min at 25˚C temperature to improve the flow performance of the membrane element. And then, the experiment was carried out as explained in point (A) above using the modified membrane.

The schematic of experiment is shown in Fig. 2.

2.3. Membrane characterization

Flat-sheet thin-film composite (TFC) RO membrane is prepared by interfacial polymerization between *m*-phenylenediamine and *tri*-mesoylchloride on polysulfone support membrane at CSIR-CSMCRI Bhavnagar. It was subjected to sodium hypochlorite exposure with concentration 325 mg/l at pH 11.5 for 30 min to identify the effect of sodium hypochlorite on hydrophilicity of the TFC membrane. The concentration of sodium hypochlorite was determined by standard iodometric titration. The contact angle of TFC RO membrane and hypochlorite-treated TFC RO membrane was analyzed by the instrument—Drop shape analyzer KRUSS/DSA-100—at different locations, and the average contact angle has been reported.

Atomic force microscope images of flat sheet TFC RO membrane and sodium hypochlorite-treated membrane (325 mg/l NaOCl for 30 min) to understand the surface morphological changes as a result of membrane modification.

3. Results and discussion

Heat transfer from solar PV panel should be facilitated in such a manner that the panel efficiency should improve and the maximum possible thermal energy is recovered. To address this, the direct contact heat exchanger system has been designed with water as a coolant. Since radiations are falling from top, the heat exchange from panel top surface can effectively control the temperature of PV panel. The sides and back of the panel have been insulated with calcium silicate insulation to abate heat losses. Rationale is to

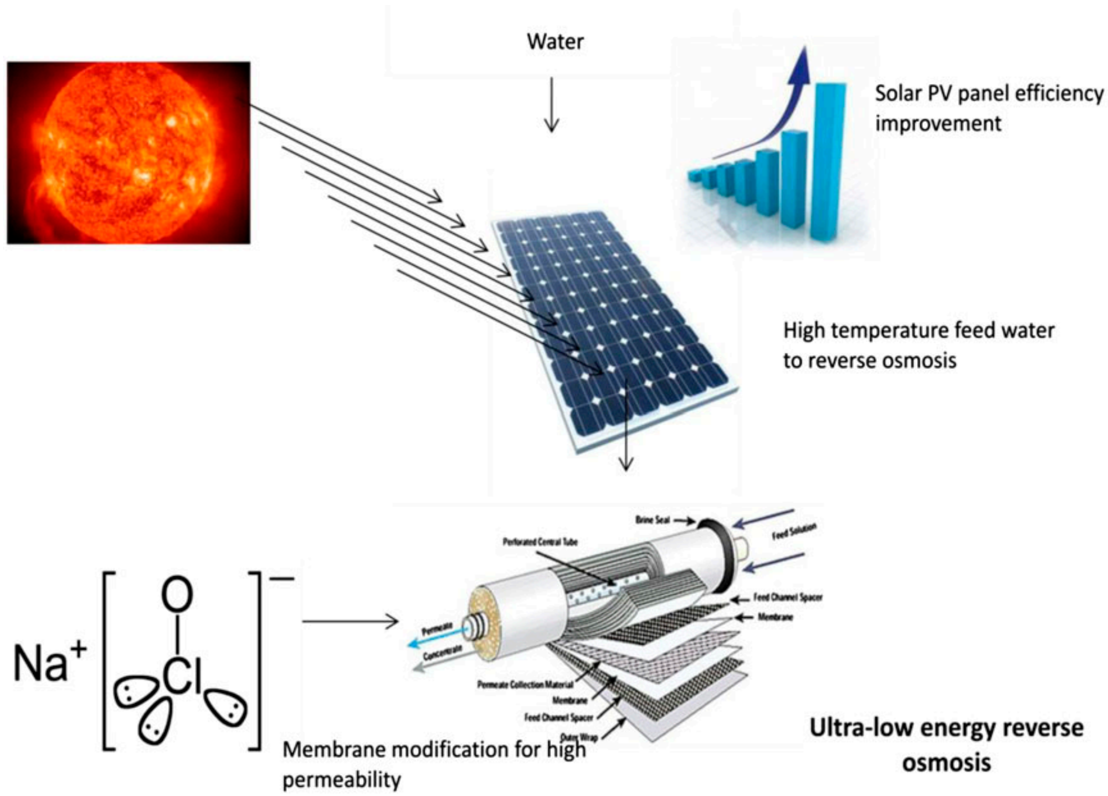

Fig. 2. Schematic of the experiment.

utilize the maximum thermal energy and control the rise in temperature of the PV panel.

The temperature of PV panel with and without cooling was monitored by thermal imager. The thermal images on one typical day 11 November 2013 at 1,100 h are shown below.

It is evident from the Figs. 3A and 3B that the temperature of PV panel is well under control by cooling from top. Fig. 3A indicates that the average temperature of PV panel is close to 30˚C with cooling, whereas Fig. 3B indicates that the temperature of PV panel is more than 45˚C at many places and it is close to 55˚C at some places without cooling.

The performance of PV panel is assessed by *V–I* Performance. In Figures below, the performance of PV panel has been demonstrated.

It is explicit from Figs. 4A–4D that the panel performance has been improved because of cooling. The increment in the peak power at 1,100 h is from 26 to 32 W, 1,200 h is from 30 to 46 W, 1,300 h is from 42 to 67 W, and at 1,500 h is from 29 to 46 W. It is understandable from the data that the rise is particularly significant when the difference between the panel temperatures is high.

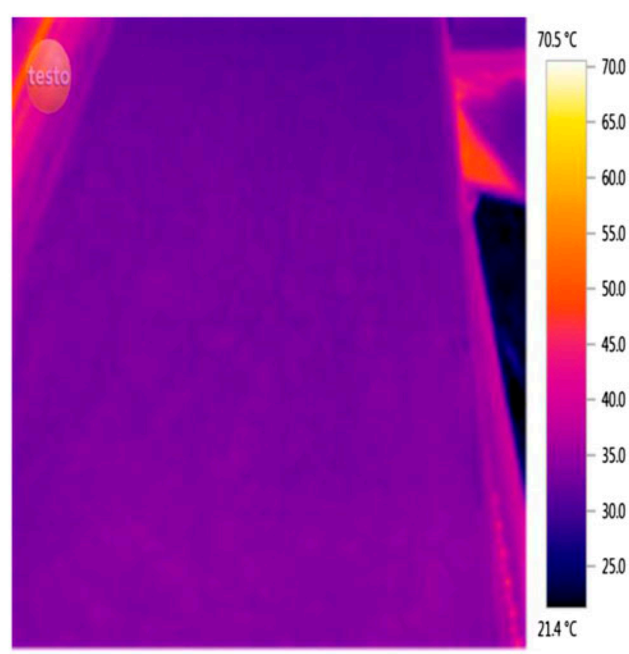

Fig. 3A. Thermal image of PV panel with cooling.

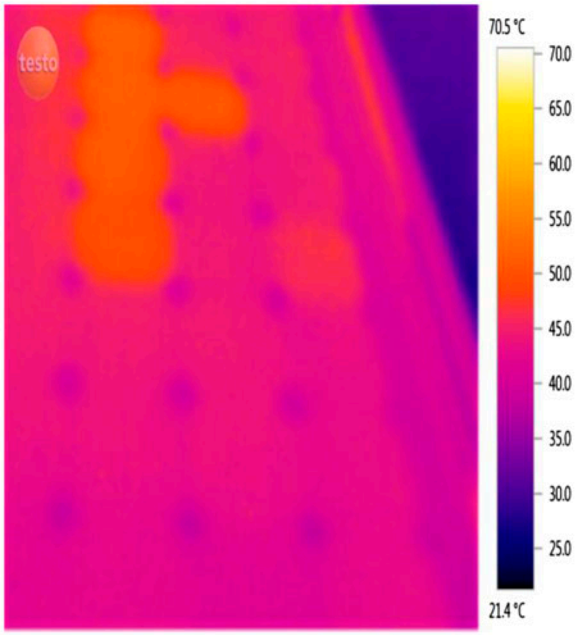

Fig. 3B. Thermal image of PV panel without cooling.

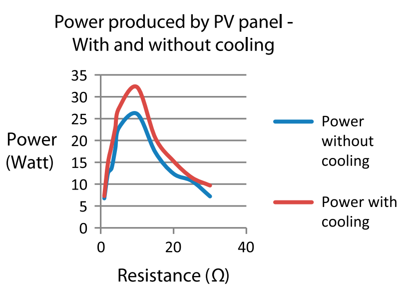

Fig. 4A. Power produced by PV panel at 1,100 h—11.11.2013.

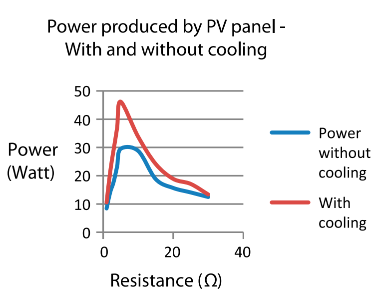

Fig. 4B. Power produced by PV panel at 1,200 h—11.11.2013.

Table 1 indicates that the difference in panel temperature (with and without cooling) increases as the day progresses. The difference in panel temperature is highest at 1,300 h i.e. 22˚C. The electrical efficiency of PV panel is better at lower temperature. Therefore, the % rise in peak power is highest at 1,300 h i.e. 59.8%.

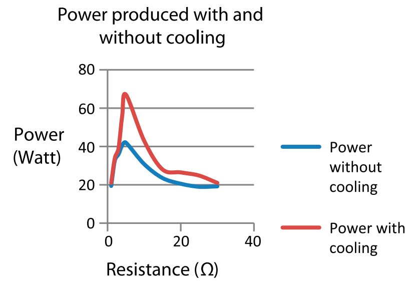

Fig. 4C. Power produced by PV panel at 1,300 h—11.11.2013.

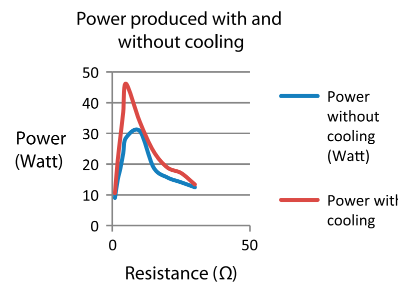

Fig. 4D. Power produced by PV panel at 1,500 h—11.11.2013.

The tap water of about 500 mg/l total dissolved solids concentration is passed over the panel. Since the panel is horizontal and outlet is 9 mm above the panel top surface, there is liquid hold up. As soon as, the water reaches the height of opening the water starts flowing out from the exit point. The water from exit passes through micron cartridge filter by of 5 µ size by gravity, and thereafter, it is pumped to domestic RO membrane element. The RO permeate is collected in the separate vessel and RO concentrate is recycled back to the panel to increase the recovery.

Table 2 indicates that the flow performance improves with temperature whereas the effect on solute rejection is minimal. There is 41.67% increase in flow when the temperature rises from 31 to 43˚C during the day, whereas the solute rejection declines from 95.23 to 94.75% when the temperature rises from 31 to 43˚C.

The controlled hypochlorite treatment for improving TFC RO membrane permeability has been reported earlier by author [27]. The TFC RO membrane has been subjected to 325 mg/l sodium hypochlorite solution for 30 min at pH 11.5. The flow performance of the membrane has been improved as shown in Table 4.

Table 1
Average temperature with and without cooling and its effect on peak power

Time (h)	Average panel temperature		Temperature difference (℃)	% rise in peak power
	Without cooling (℃)	With cooling (℃)		
1,000	31	26	5	14.5
1,100	35	27	8	23.6
1,200	48	27	21	56.3
1,300	51	29	22	59.8
1,400	49	30	19	49.9
1,500	46	29	17	44.2
1,600	36	28	8	23.8
1,700	31	26	5	14.7

Table 2
Domestic RO membrane performance with horizontal panel

Sr. No.	Time (h)	Water temperature (℃)	Solute rejection (%)	Flow (ml/min)
1.	1,000	31	95.23	84
2.	1,100	34	95.21	92
3.	1,200	38	95.01	101
4.	1,300	43	94.75	119
5.	1,400	41	95.03	113
6.	1,500	39	95.20	104
7.	1,600	33	95.15	89

Table 3 indicates the performance of modified membrane where the flow performance improves with temperature, whereas the effect on solute rejection is minimal. There is 34.28% increase in flow when the temperature rises from 31 to 41℃ during the day, whereas the solute rejection declines from 94.15 to 94.25% when the temperature rises from 31 to 43℃.

In totality, the flow performance of the membrane has improved from 84 ml/min at 31℃ to 141 ml/min at 43℃ i.e. 67.86% rise in flow performance, whereas the solute rejection has minimally affected (decreased from 95.23 to 94.25%) by the synergistic combination of modification in membrane morphology and higher temperature of feed water.

The above results indicate that the pump has to be operated for 198.41 h for generating 1 cubic meter of water, whereas the pump has to be operated for 118.20 h for generating the same amount of water. The pump rating is 12 W. Thus, the power requirement for producing a cubic meter of water is 2.381 kWh, whereas the same diminishes to 1.418 kWh for the

Table 3
Domestic RO membrane performance of modified membrane with horizontal panel

Sr. No.	Time (h)	Water temperature (℃)	Solute rejection (%)	Flow (ml/min)
1.	1,000	31	94.15	105
2.	1,100	34	94.20	114
3.	1,200	38	94.17	126
4.	1,300	43	94.25	141
5.	1,400	41	94.18	134
6.	1,500	39	94.28	127
7.	1,600	33	94.30	111

Table 4
Assessment of contact angle of TFC RO membrane before and after treatment

Membrane	Average contact angle (Left)	Average contact angle (Right)
TFC RO membrane	48.05°	49.50°
Sodium hypochlorite-treated TFC RO membrane (325 mg/l, 30 min at pH 11.5)	26.22°	28.60°

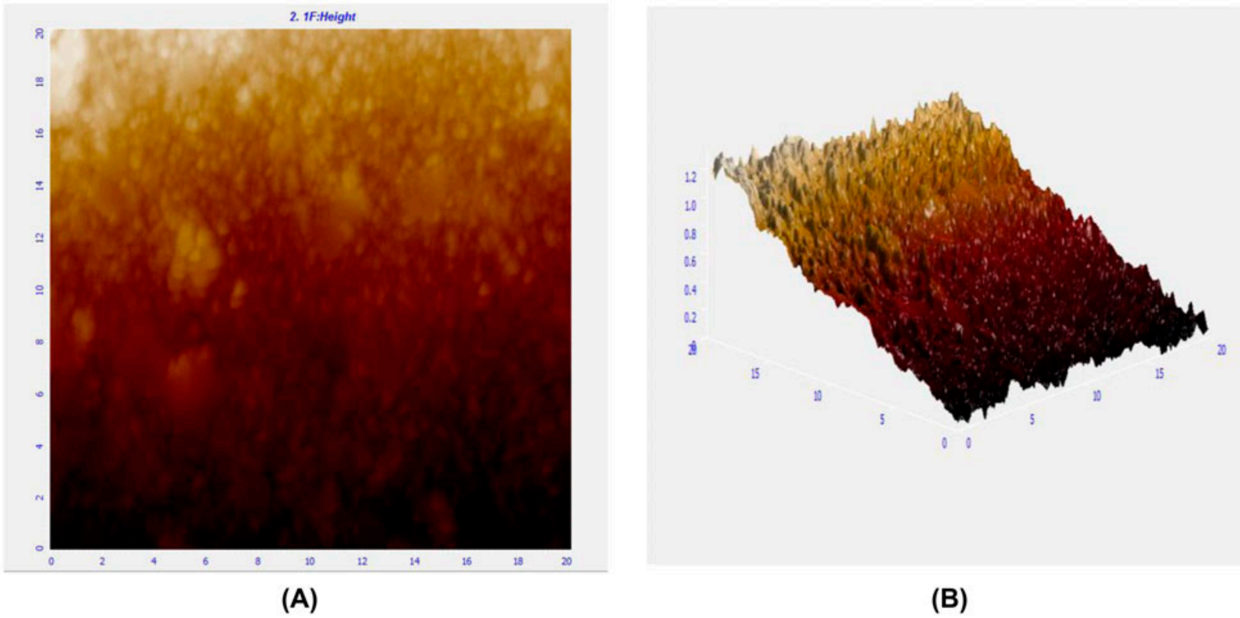

Fig. 5. (A, B) Atomic force microscope images of sodium hypochlorite-treated TFC RO membrane.

improved synergistic combination of highly hydrophilic membrane and higher temperature feed water. In this way, the power requirement decreases ca. 40% by following this novel methodology.

3.1. Hydrophilicity of membrane

The hydrophilicity of TFC RO membrane can be determined by contact angle analysis. The contact angle of TFC RO membrane and sodium hypochlorite-treated TFC RO membrane has been reported in Table 4.

Table 4 clearly demonstrates that the contact angle has reduced substantially by the treatment i.e. from 48.05˚ to 26.22˚. It shows the membrane becomes very hydrophilic by sodium hypochlorite treatment and thus the water flux increases.

3.2. Atomic force microscope images

Figs. 5(A, B) and 6(A, B) show the atomic force microscope images of sodium hypochlorite-treated membrane and TFC RO membrane.

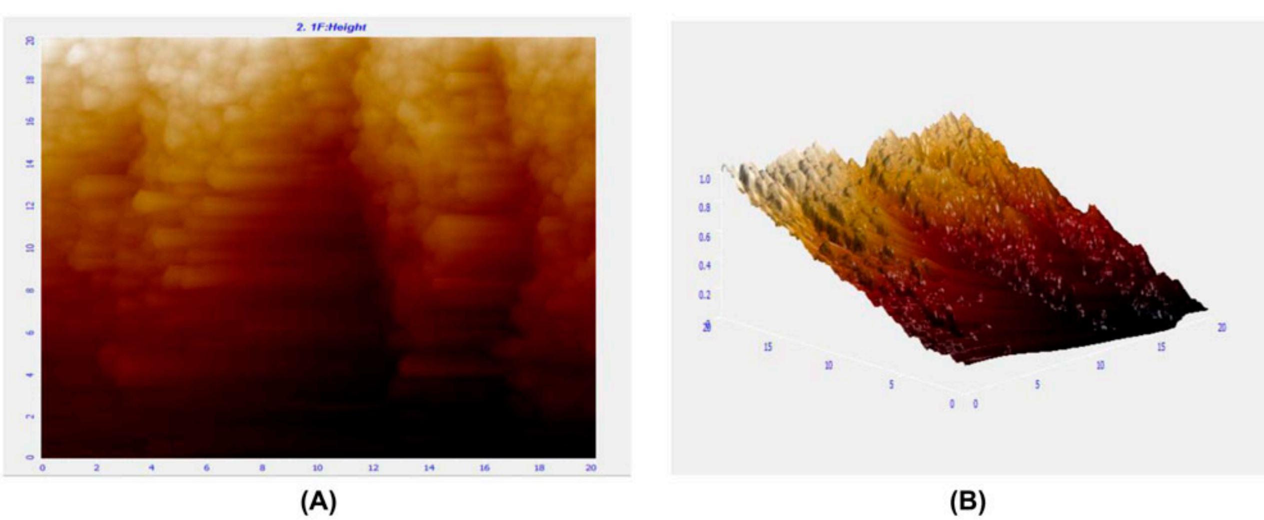

Fig. 6. (A, B) Atomic force microscope images of TFC RO membrane.

The author's previous work reported that the chemical structure of TFC RO membrane changes with sodium hypochlorite treatment as the CO–NH bond in polyamide structure is vulnerable to oxidative attack. [27] We tried to investigate whether the morphology of such membrane changes as compared with virgin TFC RO membrane by atomic force microscope images as shownin Figs. 5(A, B) and 6(A, B). It is clear from the images that the surface features also transform as the chemical structure changes. The surface skewness decreases from 0.423 to 0.205 as height distribution asymmetry decreases. Mean summit curvature increases from 2.5301 to 4.3751. Surface area ratio increases from 1.328 to 5.505. This shows that the larger membrane area is available for water molecules to pass through resulting in improved flux. This explains why the permeability increases substantially with modification in membrane morphology.

4. Conclusion

The following conclusions can be derived from the results:

(1) PV panel temperature can be effectively controlled by transferring heat from top and insulation at the back surface and sides of the panel. The insulation makes sure that the heat is not lost from bottom and the direction of heat transfer is bottom-up. The electrical efficiency of PV panel improves at the lower temperature and minimum 20% improvement in power output was observed.

(2) The rise in water temperature reported indicates that there is a potential to tap the thermal energy. The higher temperature water can be used for RO where higher feed water temperature offers the advantage of higher product water flow.

(3) Controlled oxidation of polyamide layer at high pH results in improved flow performance of the membrane. The TFC RO membrane becomes more hydrophilic by this treatment. This can synergistically increase the flow of domestic RO membrane module along with higher temperature feed water.

(4) Overall, 67.86% rise in flow with ca. 1% decline in solute rejection has been observed by increasing the feed water temperature by 12˚C and treating the membrane with sodium hypochlorite solution at exposure level of 162.5 ppm-h at pH 11.5. The novel combination of altering the membrane morphology and using high-temperature feed water improves the overall energy efficiency and the power requirement is decreased by ca. 40%. Also, the overall recovery of domestic RO system increases as the concentrate is recirculated back to the panel.

(5) The present work opens the possibility of further work for larger scale brackish water RO systems.

Acknowledgment

CSIR-CSMCRI communication no CSIR-CSMCRI-099/2014. The authors thank Council of Scientific and Industrial Research and Department of Science and Technology, Solar Energy Research Initiative India—project no. DST/TM/SERI/2K11/101 for providing funding support. The authors thankfully acknowledge the suggestions and guidance given by Dr AVR Reddy, Head-RO discipline, Dr SP Bhatnagar Professor, Physics Department MK Bhavnagar University, and Dr PK Ghosh Ex Director CSMCRI. Authors thank Mr Rathod, Mr Bharadia, and Dr Babulal Rebary for their help in experiments and AFM analysis.

References

[1] M. Khayet, M. Essalhi, C. Armenta-Déu, C. Cojocaru, N. Hilal, Optimization of solar-powered reverse osmosis desalination pilot plant using response surface methodology, Desalination 261(3) (2010) 284–292.

[2] Z. Al Suleimani, V. Rajendran Nair, Desalination by solar-powered reverse osmosis in a remote area of the Sultanate of Oman, Appl. Energy, 65(1–4) (2000) 367–380.

[3] M. Thomson, D. Infield, Laboratory demonstration of a photovoltaic powered seawater reverse osmosis system without batteries, Desalination 183(1–3) (2005) 105–111.

[4] M. Thomson, D. Infield, A photovoltaic-powered seawater reverse-osmosis system without batteries, Desalination 153(1–3) (2003) 1–8.

[5] D.P. Clarke, Y.M. Al-Abdeli, G. Kothapalli, The effects of including intricacies in the modelling of a small-scale solar PV reverse osmosis desalination system, Desalination 311 (2013) 127–136.

[6] S. Abdallah, M. Abu-Hilal, M.S. Mohsen, Performance of a photovoltaic powered reverse osmosis system under local climatic conditions, Desalination 183(1–3) (2005) 95–104.

[7] A.S. Nafey, M.A. Sharaf, Lourdes García-Rodríguez, Thermo-economic analysis of a combined solar organic Rankine cycle reverse osmosis desalination process with different energy recovery configurations, Desalination 261(1–2) (2010) 138–147.

[8] J.K. Tonui, Y. Tripanagnostopoulos, Performance improvement of PV/T solar collectors with natural air flow operation, Solar Energy 82(1) (2008) 1–12.

[9] M. Beccali, P. Finocchiaro, B. Nocke, Energy and economic assessment of desiccant cooling systems coupled with single glazed air and hybrid PV/thermal solar collectors for applications in hot and humid climate, Solar Energy 83(10) (2009) 1828–1846.
[10] S. Maiti, K. Vyas, P.K. Ghosh, Performance of a silicon photovoltaic module under enhanced illumination and selective filtration of incoming radiation with simultaneous cooling, Solar Energy 84 (2010) 1439–1444.
[11] X. Han, Y. Wang, L. Zhu, The performance and long-term stability of silicon concentrator solar cells immersed in dielectric liquids, Energy Convers. Manage. 66 (2013) 189–198.
[12] A. Akbarzadeh, T. Wadowski, Heat pipe-based cooling systems for photovoltaic cells under concentrated solar radiation, Appl. Therm. Eng. 16(1) (1996) 81–87.
[13] L. Zhu, R.F. Boehm, Y. Wang, C. Halford, Y. Sun, Water immersion cooling of PV cells in a high concentration system, Sol. Energy Mater. Sol. Cells 95(2) (2011) 538–545.
[14] K. Tanaka, Solar energy converter using a solar cell in a shallow liquid layer, Patent US6583349B2, 2003.
[15] K. Tanaka, Solar energy converter using optical concentration through a liquid, Patent US 2003/005957A1, 2003.
[16] K. Tanaka, Solar energy converter using a solar cell in a shallow liquid-gel layer, Patent US7244888B1, 2007.
[17] G. Carcangiu, M. Sardo, I. Carcangiu, R. Sardo, Photovoltaic panel and solar- panel unit made using photovoltaic panels of the same sort, Patent US2008/0092876A1, 2008.
[18] A.H. Ignacio, S.P. Gabriel, D.D. Cesar, V.P. Marta, Photovoltaic concentrator with a high efficiency immersed into a reflective optical dielectric liquid, Patent 2302656, 2008 (in Spanish).
[19] G. Falbel, Immersed photovoltaic solar power system, Patent US6035319, 2000.
[20] M. Cherney, M. Stiles, N. Williams, Solar collector for solar energy systems, Patent US6700054B2, 2004.
[21] W.J. Mook J.R, Solar panels with liquid super-concentrators exhibiting wide fields of view, Patent US 2006/0185713 A1, 2006.
[22] T.Y. Wang, Liquid immersion method for solar photovoltaic electricity generation and the device, Patent CN1302089A, 2001.
[23] M. Zähr, D. Friedrich, T.Y. Kloth, G. Goldmann, H. Tributsch, Bionic photovoltaic panels bio-inspired by green leaves, J. Bionic Eng. 7(3) (2010) 284–293.
[24] H.G. Teo, P.S. Lee, M.N.A. Hawlader, An active cooling system for photovoltaic modules, Appl. Energy 90 (2012) 309–315.
[25] A. Kordzadeh, The effects of nominal power of array and system head on the operation of photovoltaic water pumping set with array surface covered by a film of water, Renewable Energy 35 (2010) 1098–1102.
[26] S. Odeh, M. Behnia, Improving photovoltaic module efficiency using water cooling, Heat Transfer Eng. 30 (6) (2009) 499–505.
[27] H.D. Raval, J.J. Trivedi, S.V. Joshi, C.V. Devmurari, Flux enhancement of thin film composite RO membrane by controlled chlorine treatment, Desalination 250(3) (2010) 945–949.
[28] M. Li, Reducing specific energy consumption in reverse osmosis water desalination: An analysis from the first principles, Desalination 276 (2011) 128–135.
[29] A. Hertel, E. Steudle, The function of water channels in Chara: The temperature dependence of water and solute flows provides evidence for composite membrane transport and for a slippage of small organic solutes across water channels, Planta 202 (1997) 324–335.
[30] R.C. Weast, M.J. Astle, W.H. Beyer, CRC Handbook of Chemistry and Physics, CRC Press, Boca Raton, FL, 1988–1989, p. F-40.