Journal of
Chemical Engineering & Process Technology

Amhamed and Abotaleb, J Chem Eng Process Technol 2017, 8:4
DOI: 10.4172/2157-7048.1000358

Research Article | Open Access

Novel Heat Harvesting for Low Energy Draw Solution Regeneration: Simulation Study

Abdukarem Amhamed* and Ahmed Abotaleb

Qatar Environment and Energy Research Institute, Hamad Bin Khalifa University, Doha, Qatar

Abstract

In hot regions like the Middle East, the road asphalt pavement experience many fluctuations in their temperature profile that provides the large dark surface area with intensive heat absorption capacity, which warms the roads up to 75°C or more in summer. This phenomenon is negatively affecting the performance and urban heating. On the other hand, the most amount of water available (about 97%) is low-quality water or seawater, which needs to be treated in an efficient way to cope with the dramatic increase on demand of clean water due to population growth and agriculture requirements. Several techniques have been used for water desalination and most are thermally based techniques. Therefore, they are consuming high energy per water desalinating volume.

The aim of this study is to design a novel heat harvesting system combined with a membrane based unit, to produce clean water from impure water. The heat will be harvested from the roads and buildings, by a low-grade system through Forward Osmosis (FO) unit. The diluted draw solution (SD) will be regenerated at low operating temperature, while the road and building's roofs surfaces are cooled and maintained at a lower temperature.

The proposed technology will save energy and enhance microclimate conditions as well. The innovative DS regeneration system was simulated by HYSYS V8.8 and the results show a 1.17 m^3/hr of treated water can be recovered for each one-m^2. The quality of water depends on the amount of heat harvested and, consequently the surface temperature. Potable water is achievable only when the surface temperature is higher than 70°C and, therefore a trim heater is recommended for the winter season otherwise, the water will be used for non-drinking applications. Although the required Capex for this technology is around \$13778/m^2, but the payback is two years.

Keywords: Heat harvesting; Forward osmosis; Draw solution; Regeneration; Low boiling point; Absorber

Introduction

One-fifth of the world will face severing water shortage by 2040 as climate change and population growth increases demand [1]. The water crisis is rising along different regions of the world. The Middle East countries are located in a harsh environmental condition in terms of waters resources, which are becoming strained and stressed as some countries get only seven inches of rain per year [2]. Furthermore, World Resources Institute (WRI) ranked all the countries in the world according to the severity of water crisis and the Middle East was one of the worst regions.

The most amount of water available is low-quality water or seawater, which needs to be treated. In fact, the majority of Middle East countries have less than 500 m^3 per capita water requirement of renewable natural water sources, whilst the minimum limit set by UN is 1700 m^3 [3]. In addition to the limitation of freshwater resources, the demand for clean water increased steadily due to population growth, higher standards of living, and agriculture and industrials requirements [1].

Desalination is a process utilized to remove salts from seawater. Several technologies have been used for water desalination and most are thermally based techniques. Therefore, they are consuming high energy. Accordingly, fossil fuel is the main energy source exploited in such processes, which has environmental impacts along with a high price and maintenance issues.

On the other hand, advanced technologies, which is membrane-based desalination methods such as reverse osmosis RO is widely applied as an alternative for water treatment due to the relatively low cost compared to thermal methods [4]. In this technology, a high-applied force is needed to push the saline or low-quality water through the membrane. Therefore, high electric power consumption as well as the requirement of a specialized material to resist the high pressure is inescapable, which leads to high capital and operational cost [5]. Additionally, RO has a relatively low water recovery, which is about 35-50% from seawater feed [6] and produces concentrated brine that makes the RO process limited due to the environmental issues. The US National Research Council initiated research and development in the utilization of novel membrane-based techniques to minimize the energy consumption, operation, capital costs and brine disposal [7].

Tackling water issues became a high priority for the researchers to utilize advanced technologies, using alternative and unlimited water sources such as impaired water and seawater [8]. Recently, forward osmosis (FO) process is an emerging technique for water desalination, which has several advantages over reverse osmosis (RO) in terms of power consumption and fouling formation [9-14]. In fact, any technology or process has limitations and challenges, the main experienced challenge with FO is the draw solution regeneration process, the structure, and material of membrane, membrane fouling as well as concentration polarization in the membrane [15]. The draw solution regeneration and recycle processes were proved in both

***Corresponding authors:** Abdukarem Amhamed, Qatar Environment and Energy Research Institute, Hamad Bin Khalifa University, Doha, Qatar, Tel: +97444546109; E-mail: aamhamed@hbku.edu.qa

Received November 10, 2017; **Accepted** November 14, 2017; **Published** November 20, 2017

Citation: Amhamed A, Abotaleb A (2017) Novel Heat Harvesting for Low Energy Draw Solution Regeneration: Simulation Study. J Chem Eng Process Technol 8: 358. doi: 10.4172/2157-7048.1000358

batch and continuous modes [15]. In early days, the initial work was limited and focused on the screening and selections of draw solutions, which are used directly for consumption without being cautions to the regeneration process, while the recent research studies aim to develop a self-sustainable energy mode for the DS regeneration and recycling process [16].

A mixture of dissolved glucose in seawater, concentrated fructose, glucose, and fructose were used as a draw solution to produce drinkable water in emergency cases [17-19]. Moreover, a concentrated mixture of NH_3 and CO_2 was used as draw solution in FO desalination process and the diluted mixture is recovered through distillation method [20]. Also, KNO_3 and SO_2 were utilized as a draw solution in two-stage FO desalination process but the separation method for this draw solution needs a significant amount of energy for cooling and heating processes [21,22]. In another case brackish water was desalinated by the use of Na_2SO_4 as draw solution through the hybrid FO-NF system, the result showed more advantages including lower operating pressure, less flux decline, nil chemical cleaning consumption, no pre-treatment requirement and higher permeate quality in hybrid FO process compared to a pressure-driven desalination RO unit.

Furthermore, thermally responsive ionic liquids were investigated as novel draw solutes for seawater FO desalination [23]. The results showed that the electrical energy consumption was calculated to be as low as 16% of that required for the RO desalination, enabling the treatment of tough industrial wastewater with high salinities.

Although the rapid progress in membrane technology development, which is used for water desalination processes, like RO [24-27], MD[28-30], NF [31-33] and UF[34] for the purpose of enhancing the performance and reducing the energy consumption, but the FO applications still have some critical limitation related to the diluted draw solution separation and regeneration. Several attempts have been conducted for applying different methods to recover draw solutions, like heating [35], air stripping [36], distillation [37], chemical reaction [38], low pressure RO [39], Moderate heating (about 60°C) [29,36], de-swelling of the [40,41] polymer hydrogels [42] and thermal [43]. The results showed that most of these methods consumed energy as a form of heat or hydraulic pressure, which was required to recover the diluted draw solution. Therefore, finding the optimum DS regeneration technique is one of the main challenges for the future of FO desalination.

On the other hand, Alcoholic-water solution has a high osmotic pressure with a relatively low alcoholic concentration, which generates high permeated or freshwater flux across a membrane by natural osmosis [44]. Ethanol can be used as a draw solution due to its lower enthalpy of vaporization 42.32 kJ/Mol, compared to water 43.99 kJ/Mol at 298.15 K besides its boiling point at atmospheric pressure compared to water [45]. Therefore, those two factors facilitate the separation process between ethanol and water in case of using existing aqueous-dehydration technique of ethanol separation technologies such as the pervaporation, distillation or adsorption to re-concentrate the draw solution [44].

Although the alcoholic-water mixture provides a high osmotic pressure but the separation of ethanol-water, the mixture is energy intensive especially when ethanol concentration is lower than 5% by weight [46,47]. Therefore, it is clear that the development of DS regeneration process is significantly desirable to make the FO technologies more competitive and attractive compared to other methods. To obtain that, a low energy consumption process suggested in this study to regenerate the diluted agent from the FO process. This process based on adding a low boiling point hydrocarbon such as n-pentane or iso-pentane as an entrainer to the diluted draw solution through the principle of direct contact, vapor-liquid heat, and mass transfer. Furthermore, a novel heat energy harvesting process technology suggested. It is integrating the FO DS-regeneration system with heat harvested from roads and buildings in a closed cycle using a low energy technique for FO agent regeneration. The proposed system provides a great ease of separation between the ethanol and water compared to the conventional separation processes.

Methodology

Benchmark FO DS-regeneration

In Forward Osmosis (FO) Desalination Process (Figure 1), the contaminated water is fed to the osmosis FO unit after some pretreatment. The draw solution (DS) which is considered in this study as Ethanol (EtOH) aqueous solution is fed to the osmosis unit side. Due to osmosis, pure water moves from low quality (contaminated water) side towards the DS side through the semi-permeable membrane (FO). This is achieved mainly by the osmotic pressure difference between the two fluids on both sides of the membrane. Accordingly, an increase in the fluid volume due to water flux through the membrane dilutes the DS, where a further technique is needed to separate the draw solution from the fresh water for desalination application.

The benchmark process for draw solution regeneration is by thermal distillation where pure ethanol is the overhead/distillate product and potable water is the bottom product, this process is highly efficient and reliable but energy-intensive it requires a condenser and reboiler driven by cold water and low pressure saturated steam, respectively. Thermal regeneration is the bottleneck of the whole process as most of the FO process energy consumption occurs at the regeneration step, which needs to be optimized.

Novel heat harvesting FO DS-regeneration

Asphalt experience severe issues in hot climate, due to many fluctuations in temperature profile as asphalt has the capability to absorb huge amounts of heat in addition to, its low thermal conductivity and large heat capacity. Asphalt will be an ideal platform for harvesting the wasted thermal energy. The proposed study will minimize the heat in buildings and roads inner structure, avoiding premature deteriorations and the roads will be having a longer lifetime. Furthermore, applying and utilizing this process could reduce the maintenance cost and frequency of roads including airports runways.

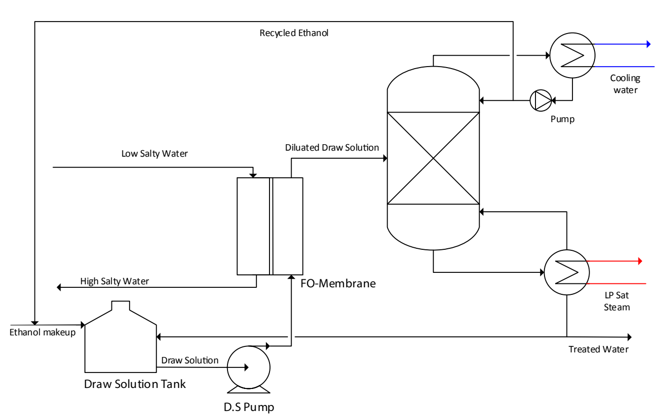

Figure 1: Benchmark FO Thermal DS. Regeneration.

Citation: Amhamed A, Abotaleb A (2017) Novel Heat Harvesting for Low Energy Draw Solution Regeneration: Simulation Study. J Chem Eng Process Technol 8: 358. doi: 10.4172/2157-7048.1000358

The proposed innovative separation technique uses heat harvested from buildings, houses, schools, roads and parking areas along with light low boiling point hydrocarbon (n-pentane), direct contact absorber and plate-plate heat exchanger economizer. The principle of the process is as follow; the heat is harvested from roads and building by embed water-filled pipelines beneath the asphalt surface and on buildings' roofs. The heat absorbed on asphalt surfaces will be dissipated to surroundings and under-surface water pipelines. Then, the heated water, which collected from roads and nearby building piped to the main storage insulated tank via pipelines network. At this stage, the temperature of roads and buildings will be significantly cooled and reduced to a suitable temperature. On the other hand, (Figure 2) n-pentane is used as the economizer plate-plate coolant fluid to cool heated circulated water from buildings and roads while its temperature will increase accordingly; it is fed from the pentane tank as a vapor at (34°C) to cool heat harvested from roads (45-70°C) based on seasonal temperature changes. The heated pentane (40-65°C) then contacts with diluted draw solution in a new direct contact absorber with ten stages to absorb ethanol from draw solution to produce clean water and recycle DS again. Figure 3 reflect the temperature distribution through the contactor. The absorber bottom product is high-quality water with nil pentane and (3.5E-06 ppm, wt.) ethanol while the top product is pentane, ethanol and water mixture which is recycled back to pentane tank.

Results and Discussion

Mass and heat balance for DS-regeneration

Table 1 reflect the design basis for one square meter area of a building, road or parking area. The pipe diameter selected to be one inch made of carbon steel and the interconnecting pipes will be polyvinyl chloride pipes (PVC) to save cost as carbon steel is not needed; it will be only included in heat harvesting areas and in economizer. The velocity through pipes assumed to be 1 m/sec and 6 cm clearance between each pipe, so for each one m^2, there are 11 pipes with 20567 kg/hr of total circulated water. The economizer temperature approach kept at 5°C so the ratio between harvested hot water to exchanged n-pentane is [(3.5-4):1].

To ensure complete separation, a thorough study has been conducted to find the optimum n-pentane to diluted draw solution mass ratio. The study started from the mass ratio ranging from 1:1 to 10:1 pentane to draw solution and it was concluded with 4:1 as increasing the pentane ratio more than 4:1 have no significant change on absorbing ethanol from water. Furthermore, a 93% by wt. water recovery could be achieved as a bottom product "Treated Water" with ethanol concentration less than 3E-06 ppm, wt. and nil pentane, while the top product is a mixture of pentane, ethanol, and water with the weight composition of 96%, 3%, and 2%, respectively. Which is recycled back to pentane tank.

It is worth mentioning that, the benchmark thermal regeneration requires 0.34 kg.steam/kg.treated water and 10.9 kg.cold water/kg.treated water (Table 1). The steam used is saturated low-pressure steam at five bars and the cold water supply shall be 31°C.

On the other hand, Figure 3 reflect the temperature profile of the novel FO heat harvested low-temperature heat regeneration system and conventional FO regeneration system "Distillation column", where the absorber top product recorded 33.8°C and bottom product at 45°C while in conventional system it recorded 79°C and 102.6°C, respectively.

Effect of seasonal variation on heat harvesting

The standard asphalt pavement cannot be considered as a black body as part of the incident radiation is reflected. Therefore, a grey body is considered where the emissivity and absorptivity are equal, while the transmissivity is zero. Furthermore, the emissivity of asphalt pavements is considered 0.9 [48]. In fact, the pavement surface collects most of the incident solar radiation. However, if it is with a high albedo then a small amount of heat is absorbed. While, if the surface is painted

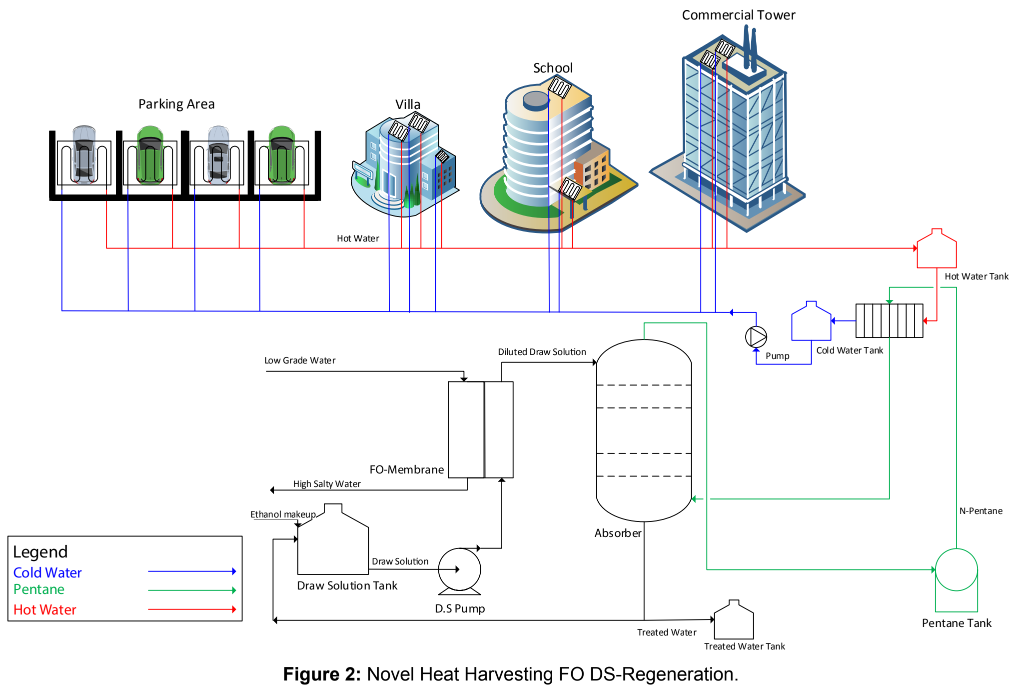

Figure 2: Novel Heat Harvesting FO DS-Regeneration.

Item	Unit	Value
Heat Harvesting		
Area	m^2	1
Pipe D	m	0.0254
No of pipes		11
Spacing	cm	6.005
v	m/s	1
Density	kg/m^3	1025
Flow. Hot water	kg/hr	20567
n-Pentane	kg/hr	5676
Draw Solution	kg/hr	1400
Treated Water	kg/hr	1174
Thermal Regeneration		
Steam Consumption	kg/hr	394
Cooling Water	kg/hr	12876

Table 1: Summary of Regeneration Calculation and Assumptions.

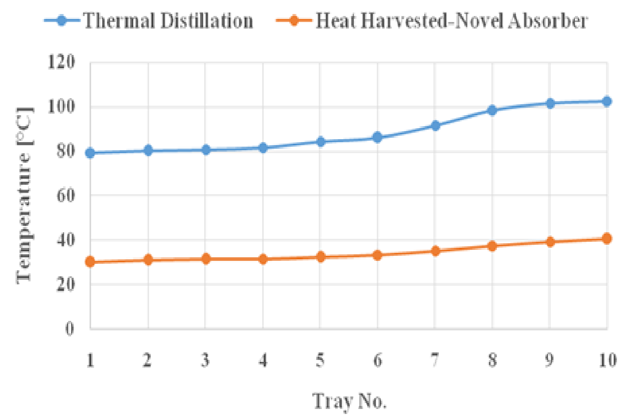

Figure 3: Temperature Profile for Benchmark and Novel Regeneration Systems.

with a black paint the absorptivity will increase and more heat energy will be harvested have conducted a study [49] to investigate the effect of painting the pavement surface with black sealer to enhance surface absorptivity, the laboratory results show that the use of black acrylic paint can increase the difference between incoming and outgoing circulated water (through asphalt pavement) by almost 50%.

Chen et al. reported the max heat at one inch depth [49]. Therefore, the circulated water pipes will be located under the surface at approximately one inch depth. Calculating the temperature at any depth depends on the surface temperature and surface material. Furthermore, the surface temperature depends on many factors including the location, surface; wind speed and cloud cover [49]. In this study, surface temperature and pavements temperatures at different depths were calculated based on Ref. [50,51].

The ambient air temperature was measured at the meteorological station at the solar test facility located at Qatar Science and Technology Park (Doha, Qatar). The data acquisition system provides at one-minute time interval.

$$T_{surface}=T_{air}-0.00618\ lat^2+0.2289\ lat+24.4 \quad (1)$$

Where, $T_{surface}$ and T_{air} are expressed in °C and the latitude is in degrees. The latitude of Qatar is 25.286106.

$$T_{depth}=T_{surface}(1-0.063\ d+0.007\ d^2-0.0004\ d^3) \quad (2)$$

Where, T_{depth} and $T_{surface}$ are in °F and the depth, d, is in inches.

To note the seasonal variation, a complete year analysis used in this study for the year 2015. Figure 4 reflect the measured ambient air temperature, the calculated surface temperature and temperature at one inch depth where the water pipes will be located. The air temperature reaches its highest value around 50°C in summer season and accordingly surface temperature reaches approximately 76°C and one inch depth temperature around 71°C, while the lowest summer ambient temperature records around 30°C and consequently, the surface temperature is 56°C and one inch depth temperature is 52°C. On the other hand, in winter season the lowest ambient temperature, surface temperature and one inch depth temperature is around 9.6°C, 35.8°C and 32.8°C, respectively. In fact, the surface temperature is mostly higher than 50°C from March until October 2015. Therefore, the potential of heat harvesting in the Middle East proved to be promising and viable for different applications.

Effect of varying surface temperature

Table 2 reflect the effect of varying the heat harvested "Hot Water" on mass and heat balance of the system. If heat harvested load "temperature" decreases, the exchanged pentane will decrease and maximum draw solution flow received will decrease. In addition to that, the quantity and quality of treated water will decrease. Furthermore, Figure 5 reflect the effect of hot water temperature on treated water flow and quality. Clearly, pure potable water is obtained only when the hot water/heat harvested water temperature reaches 70°C but when it gets lower than 70°C the treated water quality could be used in purposes other than drinking. In fact, the trim electrical heating coil would be highly required to work only when the harvested water temperature gets lower than 70°C and that in case of the constant amount and quality of treated water is needed along the year.

Economic analysis

An economic analysis has been conducted on the proposed novel heat harvesting DS regeneration to assess the feasibility of this proposal. The low pressure steam cost, cooling water cost and electricity cost were taken from [52]. While total equipment cost were calculated based on [53]. The economic study is built on a basis of 1 m^2 area, which is equivalent to 1.17 m^3/hr of treated water (Table 1).

Four equipment in benchmark FO plant were eliminated in regeneration section; distillation column, condenser, reboiler and condenser pump, while four equipment have been added; absorber with ten stages (sieve valve or bubble cap trays), economizer and spherical tank, water tank in addition to water pipes. On the other hand, the proposed system will provide huge savings with respect to operational cost such as cooling water pumping cost, steam consumption and cooling water makeup. However, a minor electrical cost is needed to run the circulated pump. The total Capex added for new plants is approximately \$13778/m^2, while annual net Opex savings is around \$6938/m^2. The expected payback for the proposed system is 24 month (Table 3).

Conclusion

Forward Osmosis (FO) has appeared as one of the potential technologies to mitigate the clean water shortage. However, there are many challenges facing the development of the FO technology, the main one is the suitable regeneration process for draw solutions as the regeneration process is the bottleneck because of the high-energy consumption.

Case	Temperature (°C)		Flow (kg/hr)			Ethanol Conc in treated Water (wt. %)
	Hot Water	n-C5	n-C5	Draw Solution	Treated Water	
A	45	40	935	234	211	5.29%
B	50	45	2044	511	455	4.46%
C	55	50	3007	752	661	3.55%
D	60	55	3932	983	852	2.56%
E	65	60	4820	1205	1029	1.50%
F	70	65	5676	1400	1174	0.00%

Table 2: Summary of Varying Heat Harvested load.

Capex (Total Equipment Cost)			
Saved	Distillation Column	$	6,896
Saved	Condenser	$	1,379
Saved	Reboiler	$	1,724
Saved	Condenser Pump	$	690
Added	Absorber	$	6,206
Added	Economizer	$	2,414
Added	Cold Water Pump	$	1,379
Added	Piping	$	1,379
Added	Pentane Spherical Tank and collected water Tank with Trim-Electric Heating coil running by solar energy	$	2,400
Opex			
Saved	Cooling water pumping Cost	$/year	126
Saved	Steam Consumption	$/year	3,449
Saved	Cooling water makeup in CT	$/year	3,564
Added	Cold Water Pump	$/year	202
Summary for 1 m² Area			
Total Capex Added		$	13778
Total Operating Cost Savings per m²		$/year	6,938
Payback		month	24

Table 3: Economic Analysis.

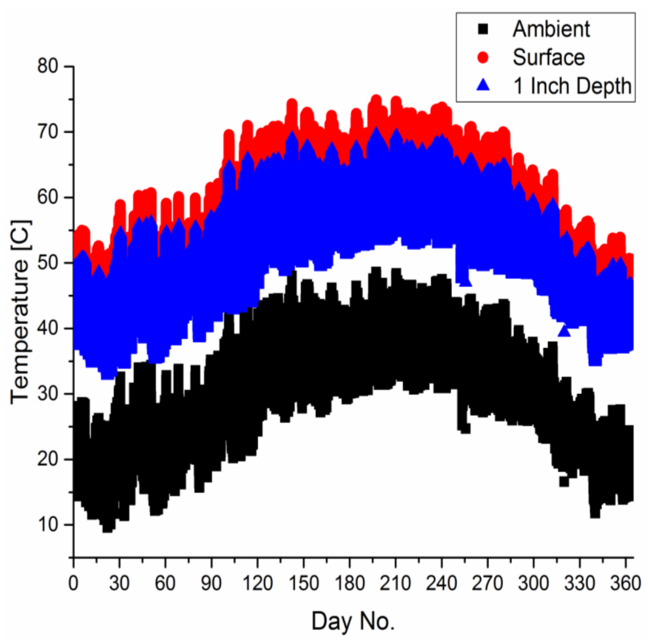

Figure 4: Effect of Seasonal Variation on Heat Harvesting.

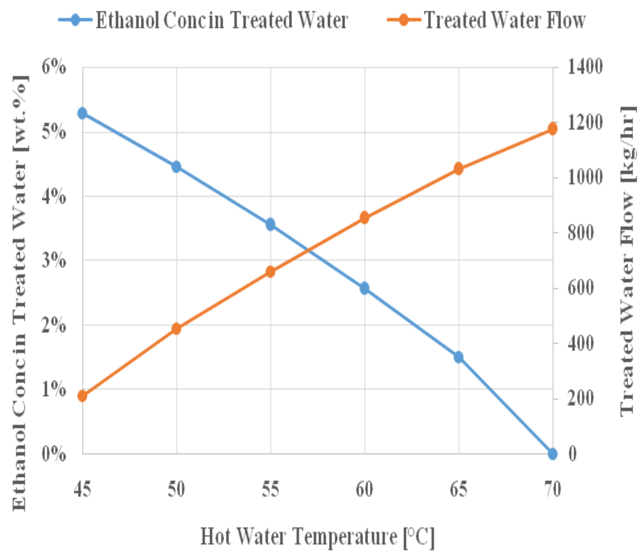

Figure 5: Effect of Heat Harvested Temperature on Treated Water flow and Quality.

On the other hand, In the harsh environment like Middle East, the asphalt pavement experience many fluctuations in their temperature profile with intensive heat absorption capacity, which warms the roads up to 75°C or more in summer and this negatively impact the performance and urban heating.

A novel heat harvesting system was proposed for clean water utilizing ethanol as a FO draws solution coupling with low boiling point regeneration process. The developed process is utilizing the heat energy harvested from the roads and buildings, through a novel low-grade temperature system for water purification by regenerating the diluted DS in FO unit to get pure water and recycle DS. Therefore, the developed technology will save energy and enhance the microclimate conditions changes as well.

This novel process facilitates water-ethanol separation with a projected separation efficiency >99% of ethanol from water; a 93.6% by wt. diluted draw solution could be recovered as a high quality treated water with ethanol concentration less than 3.5E-06 ppm, wt. and nil pentane.

The result shows that, the quality of treated water depends on the ratio of n-C5 to DS and the magnitude of heat harvested, so to ensure complete ethanol absorption from clean water the ratio of n-C5 to DS must be higher than 3.76. Furthermore, potable water is achievable only when the surface temperature is higher than 70°C, thus a trim heater is recommended for the winter season otherwise, the water will be used for non-drinking applications. The required Capex for this technology is approximately $13778/m^2$, while annual Opex is around $202/m^2$. The expected payback for the proposed system is around two years.

Acknowledgements

Authors would like to thank Dr. Amir Abdallah for providing the meteorological data measured at Qatar Science and Technology Park, Qatar Foundation (Doha, Qatar). Authors also would like to thank prof. Adel Sharif for his valuable discussion.

References

1. Anezi A (2012) Performance Enhancement of Air Bubbling and Vacuum Membrane Distillation for Water Desalination. PhD Thesis, University of Surrey, UK.
2. The Gulf Intelligence (2016) Report.
3. World Water Development Report: Water for People water for Life (2003) UNESCO-WWAP. United Nations Educational, Scientific and Cultural Organisation.
4. Altalyana N, Brian J, John B, Long DN (2016) Removal of volatile organic compounds (VOCs) from groundwater by reverse osmosis and nanofiltration. Journal of Water Process Engineering 9: 9-21.
5. Fritzmann C, Löwenberg J, Wintgens T, Melin T (2007) State-of-the-art of reverse osmosis desalination. Desalination 216: 1-76.
6. Bruggen V, Lejon B, Vandecasteele LC (2003) Reuse, treatment, and discharge of the concentrate of pressure-driven membrane processes. Environmental Science and Technology 37: 3733-3738.
7. National Research Council of the National Academies (2004) The Desalination and Water Purification Technology Roadmap. The National Academic Press, Washington DC.
8. Shannon MA, Bohn PW, Elimelech M, Georgiadis JG, Marinas BJ, et al. (2008) Science and technology for water purification in the coming decades. Nature 452: 301-310.
9. Ginnis RLM, Elimelech M (2008) Global challenges in energy and water supply: The promise of engineered osmosis. Environ Sci Technol 42: 8625-8629.
10. Achilli A, Cath TY, Childress AE (2010) Selection of inorganic-based draw solutions for forward osmosis applications. J Membr Sci 364: 233-241.
11. Tang CY, She Q, Lay WCL, Wang R, Fane AG (2010) Coupled effects of internal concentration polarization and fouling on flux behavior of forward osmosis membranes during humic acid filtration. J Membr Sci 354: 123-133.
12. Ginnis RL, Elimelech M (2007) Energy requirements of ammonia-carbon dioxide forward osmosis desalination. Desalination 207: 370-382.
13. Choi YJ, Choi JS, Oh HJ, Lee S, Yang DR, et al. (2009) Toward a combined system of forward osmosis and reverse osmosis for seawater desalination. Desalination 247: 239-246.
14. Lay WCL, Chong TH, Tang CY, Fane AG, Zhang J, et al. (2010) Fouling propensity of forward osmosis: investigation of the slower flux decline phenomenon. Water Sci Technol 61: 927-936.
15. Aryafar M (2014) A novel forward osmosis desalination process with thermal-depression regeneration. PhD Thesis, University of Surrey, UK.
16. Chekli L, Phuntsho SH, Shon HK, Vigneswaran S, Kandasamy J, et al. (2012) A review of draw solutes in Forward Osmosis process and their use in modern applications. Desalination and Water Treatment 43: 167-184.
17. Kessler JO, Moody CD (1976) Drinking water from sea water by Forward Osmosis. Desalination 18: 297-306.
18. Stache K (1989) Apparatus for transforming seawater, brackish water, polluted water or the like into a nutritious drink by means of osmosis. US Patent 4879030.
19. Kravath RE, Davis JA (1975) Desalination of seawater by direct osmosis. Desalination 16: 151-155.
20. Cutcheon MJR, Ginnis RL, Elimelech M (2006) Desalination by ammonia-carbon dioxide Forward Osmosis: Influence of draw and feed solution concentrations on process performance. J Membr Sci 278: 114-123.
21. Ginnis R (2002) Forward osmotic desalination device using membrane distillation method. Osmotic desalination process: US Patent 7: 560.
22. Cormick P (2008) Water, salt, and ethanol diffusion through membranes for water recovery by forward (direct) osmosis processes. J Membr Sci 325: 467-478.
23. Yufeng C, Wenming S, Jing W, Tzyy HC, Rong W, et al. (2015) Energy-efficient desalination by forward osmosis using responsive ionic liquid draw solutes. Environmental Science Water Research & Technology.
24. Achilli A, Cath TY, Childress AE (2010) Selection of inorganic-based draw solutions for forward osmosis applications. J Membr Sci 364: 233-241.
25. Yong JS, Phillip WA, Elimelech M (2012) Coupled reverse draw solute permeation and water flux in forward osmosis with neutral draw solutes. J Member Sci, pp: 392-393.
26. Bamaga OA, Yokochi A, Beaudry EG (2009) Application of forward osmosis in pretreatment of seawater for small reverse osmosis desalination units. Desalination Water Treat 5: 183-191.
27. Yangali QV, Li Z, Valladares R, Li Q, Amy G (2011) Indirect desalination of Red Sea water with forward osmosis and low pressure reverse osmosis for water reuse. Desalination 280: 160-166.
28. Wang KY, Teoh MM, Nugroho ATS (2011) Integrated forward osmosis-membrane distillation (FO-MD) hybrid system for the concentration of protein solutions. Chem Eng Sci 66: 2421-2430.
29. Cutcheon JR, Ginnis MRL, Elimelech M (2005) A novel ammonia-carbon dioxide forward (direct) osmosis desalination process. Desalination 174: 1-11.
30. Ge Q, Wang P, Wan C, Chung TS, Amy G (2012) Polyelectrolyte-promoted forward osmosis-membrane distillation(FO-MD) hybrid process for dye waste water treatment. Environ Sci Technol 46: 6236-6243.
31. Tan CH (2010) Novel hybrid forward osmosis-nano filtration (FO-NF) process for sea water desalination: draw solution selection and system configuration. Desalination Water Treat 13: 356-361.
32. Zhao S, Zou L (2011) Effects of working temperature on separation performance, membrane scaling and cleaning in forward osmosis desalination. Desalination 278: 157-164.
33. Zhao S, Zou L, Mulcahy D (2012) Brackish water desalination by a hybrid forward osmosis-nanofiltration system using di valent draw solute. Desalination 284: 175-181.
34. Ling MM, Chung TS (2011) Desalination process using super hydrophilic nano- particles via forward osmosis integrated with ultrafiltration regeneration. Desalination 278: 194-202.

35. Neff RA (1964) Solvent Extractor. US Patent 3: 130-156.

36. Cutcheon JR, Ginnis RLM, Elimelech M (2006) Desalination by a novel ammonia-carbon dioxide forward osmosis process: influence of draw and feed solution concentrations on process performance. J Membr Sci 278: 114-123.

37. Batchelder GW (1965) Process for the Demineralization of Water. US Patent 3171799.

38. Hough WT (1970) Process for Extracting Solvent from a Solution. US Patent 3532621.

39. Yaeli J (1992) Method and Apparatus for Processing Liquid Solutions of Suspensions Particularly Useful in the Desalination of Saline Water. US Patent 5098575.

40. Ginnis RL, Cutcheon JR, Elimelech MA (2007) Novel ammonia-carbon dioxide Osmotic heat engine for power generation. J Membr Sci 305: 13-19.

41. Li D, Zhang X, Yao J, Simon GP, Wang H (2011) Stimuli-responsive polymer hydrogels as a new class of draw agent for forward osmosis desalination. Chem Commun 471: 710-712.

42. Li D, Zhang X, Yao J, Zeng Y, Simon GP, et al. (2011) Composite polymer hydrogels as draw agents in forward osmosis and solar dewatering. Soft Matter 7: 10048-10056.

43. Iyer S, Linda Y (2011) Systems and Methods for Forward Osmosis Fluid Purification Using Cloud Point Extraction. US Patent 8021553.

44. Arce A, Martinez AJ, Soto A (1996) VLE for water plus ethanol plus 1-octanolmixtures. Experimental measurements and correlations. Fluid Phase Equilib 122: 117-129.

45. CRC Handbook of Chemistry and Physics (1993) 74th edn.

46. Vane LM, Alvarez FR, Rosenblum L, Govindaswmy S (2013) Efficient ethanol recovery from yeast fermentation broth with integrated distillation-membrane process. Ind Eng Chem Res 52: 1033-1041.

47. Gil D, Uyazan AM, Aguilar JL, Rodriguez G, Caicedo LA (2008) Separation of Ethanol and water by Extractive Distillation with Salt and Solvent as Entrainer. Brazilian Journal of Chemical Engineering 25: 207-215.

48. Solaimanian M, Kennedy TW (1991) Predicting Maximum Pavement SurfaceTemperature Using Maximum Air Temperature and Hourly Solar Radiation. Transportation Research Record, No. 1417.

49. Chen BL, Sankha B, Rajib BM (2008) Harvesting energy from asphalt pavements and reducing the heat island effect. Worcester Polytechnic Institute (WPI) 2: 214-228.

50. Huber GA (1994) Strategic Highway Research Program Report SHRP 648A: Weather Database for the Superpave Mix Design System. Transportation Research Board, National Research Council, Washington DC.

51. Solaimanian M, Bolzan P (1993) Strategic Highway Research Program Report SHRP -A-637: Analysis of the Integrated Model of Climate Effects on Pavements. Transportation Research Board, National Research Council, Washington, DC.

52. Turton R, Bailie RC, Whiting WB, Shaeiwitz JA, Bhattacharyya D (2012) Analysis, Synthesis and Design of Chemical Processes. 4th edn. Prentice Hall, Upper Saddle River, NJ, USA.

53. Coulson JM, Richardson JF (1999) Chemical Engineering. Volume 6. 3rd edn. Chemical Engineering Design.