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Unlocking the desalination processes future roadmap

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ABSTRACT

Energy-water-environment nexus is very important to attain COP21 goal, maintaining environment temperature increase below 2°C, but unfortunately two third share of CO_2 emission has already been used and the remaining will be exhausted by 2050. A number of technological developments in power and desalination sectors improved their efficiencies to save energy and carbon emission but still they are operating far from their thermodynamic limits. The theoretical thermodynamics limit for seawater desalination at normal conditions is about 0.78 kWh/m^3 depending on the initial salt contents. However, practical plants are operated at several folds higher than this limit due mainly to inherent losses in the processes that were incurred in removing dissolved salts. Technological advancement in thermally driven processes hybridization have set the new bench mark for lowest energy consumption that has boosted the water production trend of desalination industry. In this paper, we presented multi-effect desalination (MED) hybridization with pressure swing adsorption (PSAD) cycle to overcome lower brine temperature limitations to boost overall performance of the system. The synergetic effect from hybridization of MED-PSAD permits a higher overall operational range and inter-stage temperature differences, leading to a boost in water production up to 2–3 folds. We showed that the proposed hybrid cycle can achieve highest performance SUPR = 20% of thermodynamic limit: one of the highest performance reported in the literature up till now. These figures can be translated to less than US$ 0.47/m^3 – a lowest specific cost ever reported in the literature. The proposed cycle is not only tested at pilot scale, but also successfully commercialized into industry and received many international awards as one of the most efficient and sustainable desalination technology.

Keywords: Hybrid desalination; Energy efficiency; Desalination sustainability; Thermodynamic limit

1. Introduction

Water and energy are closely interlinked and interdependent valuable resources that underpin economic growth and human prosperity. In every part of daily life cycle such as power generation, feedstock crops production and fossil fuel processing, water is ubiquitous source. Similarly, energy is vital to power water cycle that include, collection, treatment and distribution to end users. The mutual vulnerability of water and energy is amplifying due to rising demand as a consequence of exponential gross domestic product (GDP) growth, population bourgeoning and climate change.

Global water demand is projected to increase more than 55% by 2050 mainly due to high GDP growth rate that will increase water demand for manufacturing, power generation and domestic sector use by 400%, 140% and 130%, respectively. This current demand trend will push 40% of the World population below water scarcity level by 2050. Presently, more than 19,500 desalination plants in 150 countries producing roughly 38 billion m^3/y as shown in Fig. 1. It is projected to increase to 54 billion m^3/y

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by 2030, 40% more compared to 2016. Desalination is the most energy-intensive water treatment process that consume 75.2 TWh/y, about 0.4% of global electricity [1,2].

Conventionally, three major desalination processes employed at large scale are; (i) seawater reverse osmosis, (ii) multi-stage flashing and (iii) multi-effect desalination. Application of these processes depends on size of plant and feed water quality and accordingly they have some limitations. For example, seawater reverse osmosis (SWRO), even though are famous around the world, have operational limitations in terms of feed water quality. They are leading in overall desalination market where mostly processes are installed on brackish or river water treatment. In terms of seawater desalination, in the Gulf region, other two desalination processes hold over 60% market. Frequent occurrence of hazardous algae bloom, red tides and sea foams are the major hinderance of SWRO applications in most of the Gulf region as shown in Fig. 2. Slight variation in seawater quality in terms of silt density index is another example of SWRO process complication and it require large pre-treatment system. The longer-term effects of discharge concentrate has not been documented but it is possible that small traces of toxic substances used in the cleaning of RO membranes may be harmful to marine life and ecosystem [4].

On the other hand, thermal desalination processes such as multi-stage flashing (MSF) and multi-effect desalination (MED) are not only robust but also can handle variation in feed water quality without effecting the overall plant operation. Even though they are leading in the Gulf regions, but they also have limitations in terms of operational temperatures that cause sacking and fouling at high temperature and salt concentration as shown in Fig. 3. For example, MED processes operates between 65°C to 40°C and MSF 130°C to 40°C. These inherent operational limitations limit the overall performance of conventional desalination processes from 10%–13% of thermodynamic limits [6,7].

The desalination industry learned the lesson from the past that a paradigm shift in separation processes is the only hope to achieve high jump in the performance. Otherwise, processes improvement or material development can only help in gradual improvement that is not sustainable for future water supplies. One of the possible solutions is to hybridize the conventional systems to improve overall performance [9]. For example, in the past some hybridizations were proposed such as SWRO+MSF and SWRO+MED and MSF+MED but there was no significant performance improvement. This is because of no thermodynamic synergy between processes and they were operating as independent systems. Recently MED hybridization with adsorption (AD) system was proposed to overcome the lower temperature limitations of MED. The hybrid MED-AD system demonstrated extended operational temperature range, 65°C to 5°C, and hence improved the performance to 20% of thermodynamic limit by booting water production to over two-fold. Many other processes are proposed such as membrane distillation (MD), forward osmosis (FO) and their hybrid for sustainable water production. There is no real

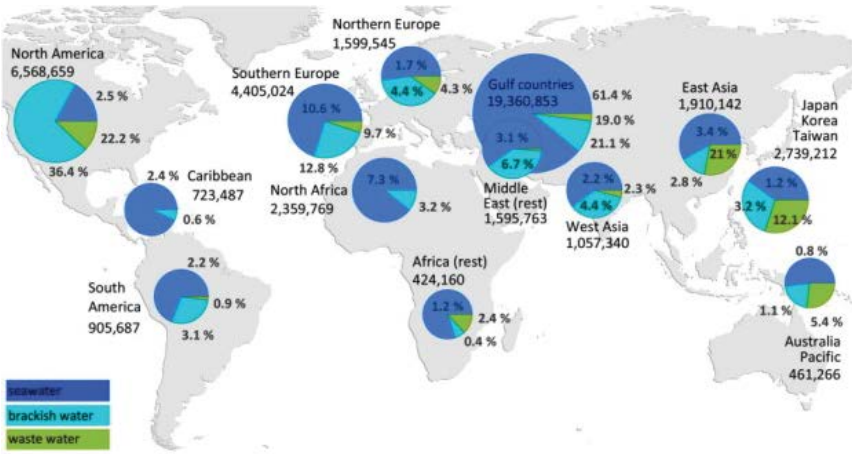

Fig. 1. World desalination capacities map with different feed sources [3].

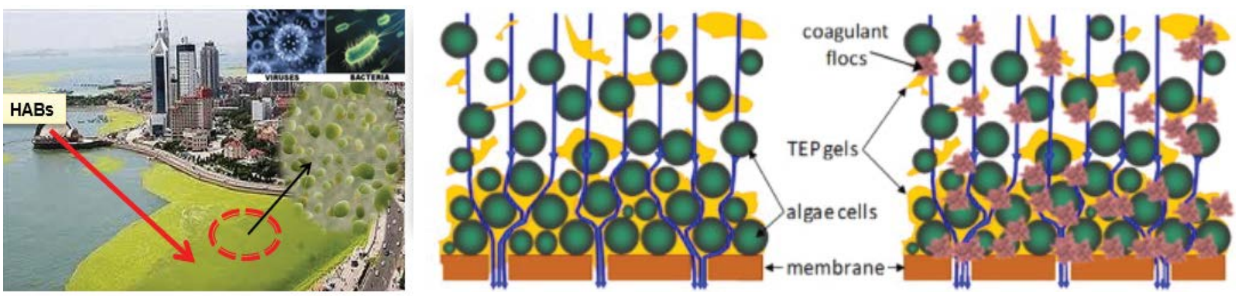

Fig. 2. HABs impact on SWRO operation [5].

experimental demonstration is available in the literature of these hybrids and they are still at lower TRL level of 2–3.

We proposed a hybrid cycle to overcome the operational limitations of conventional MED to boost performance to 2–3 times [10,11]. The innovative pressure swing adsorption cycle (PSAD) integration with last effect of MED can help to lower the temperature to as low as 5°C–7°C that can boost water production to more than two folds at same heat source temperature as shown in Fig. 4. After successful pilot demonstration, the adsorption cycle is commercialized to the industry. First commercial plant of 100 m^3/d is installed at Riyadh, Saudi Arabia that is successfully commissioned and tested at various operational parameters. The second hybrid plant of 5,000 m^3/d is awarded and will be installed in Saudi Arabia. This successful commercialization shows the game-changer potential of hybrid MED-PSAD cycle.

2. Methodology: MED-PSAD cycle

The combined or hybrid MED-PSAD has been demonstrated in a laboratory-scaled pilot, enhancing the overall water production rates of the conventional cycles by two

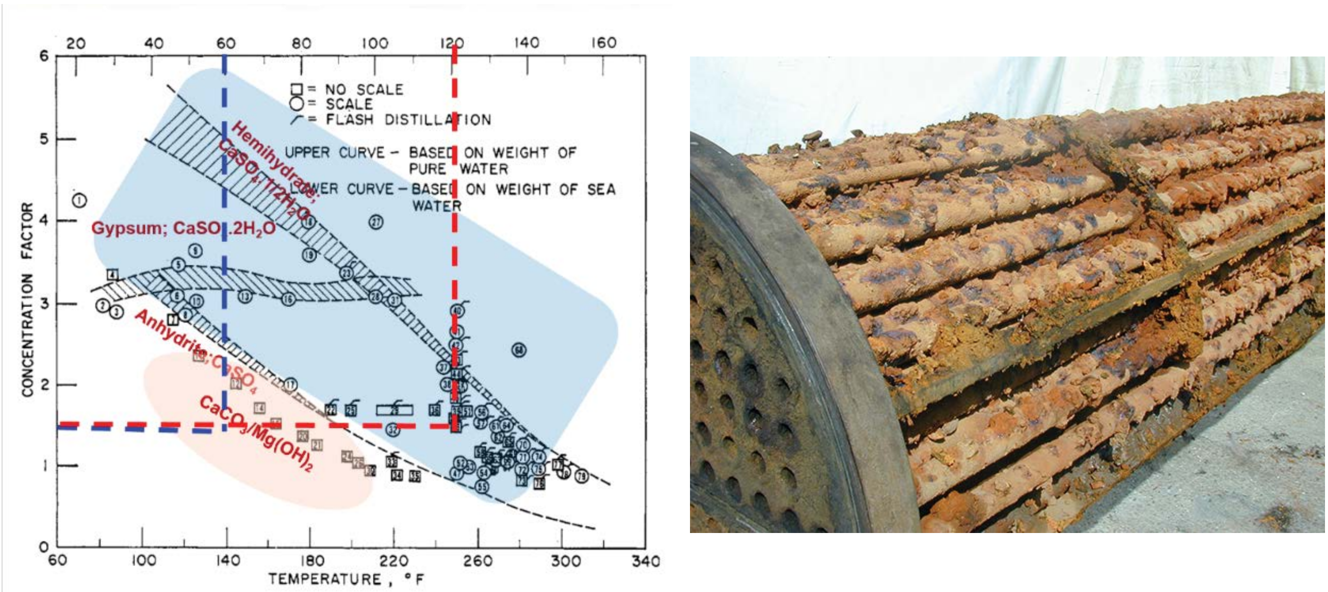

Fig. 3. High temperature scaling and fouling on thermal desalination internals [8].

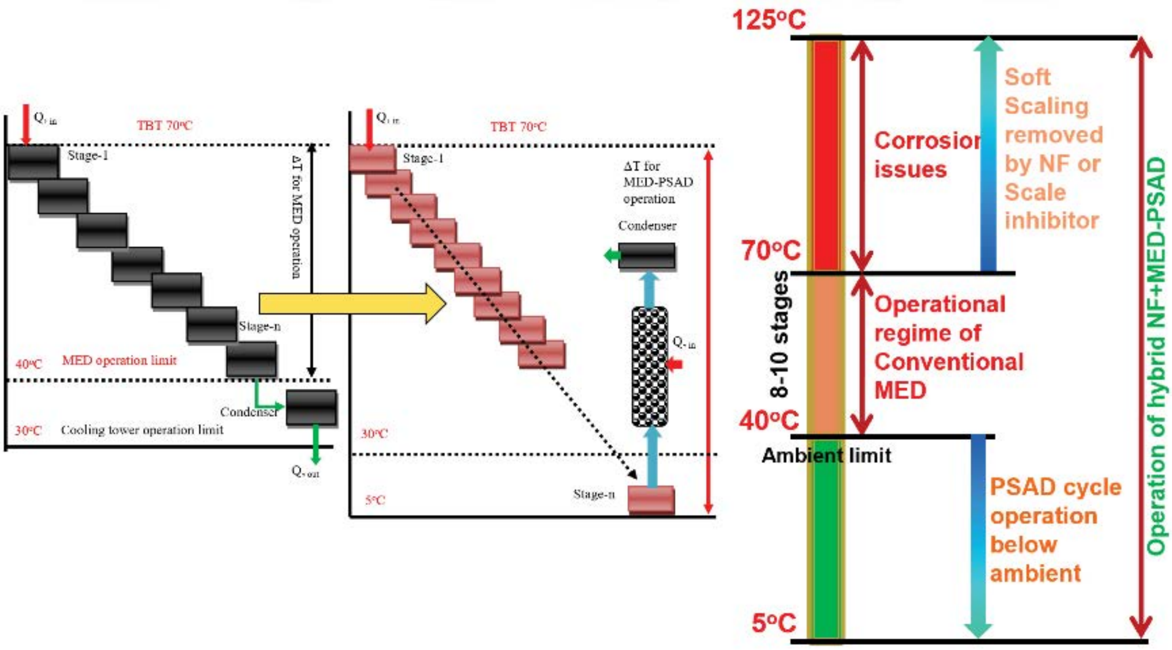

Fig. 4. Hybrid MED and PSAD cycle to overcome operational limitations.

or more folds through greater thermodynamic synergy, yet the heat input to the top-bine stage of the hybrid cycle is increased marginally. Fig. 5 shows the hybrid pilot plant installed at KAUST. The pilot consists of 4-effect parallel feed MED integrated with pressure swing adsorption cycle. The pilot is operated with 352 m^2 evacuated tube solar thermal collectors installed at one building rooftop. In practical combined power and water plants, bleed steam exergy will be utilized to regenerate adsorbent of PSAD cycle before introducing into MED as a heat source. The low pressure steam creates around 2 kPa pressure at the throat of the thermal vapor compressor and helps to regenerate saturated adsorbent. The bleed steam together with regenerated vapors are then supplied to MED first effect as a heat source. This excellent thermodynamic synergy between two cycles maximize the exergy utilization of bleed steam. It can be noticed that there is no additional energy is required for adsorbent regeneration, the same bleed steam perform two important task that boot the performance of cycle to over two folds [9–15].

Fig. 6a shows the temperature profiles of conventional 4-effect MED and hybrid MED-PSAD cycle. It can be clearly seen that once MED was linked with PSAD, the temperature was dropped due to high affinity of silica gel for water vapors. It can be observed that hybrid cycle can extend last effect temperature to below ambient condition; first time in the history of MED systems. It can also be noticed that this excellent thermodynamic synergy between two cycle booted the water production to two folds at same heat source temperature as shown in Fig. 6b. This higher water production is due to evaporation and flashing effect in effect due to silica gel adsorption.

Experiments were conducted at assorted heat source to cover the full range of operation. It can be seen from Fig. 6c, hybridization of PSAD with MED boosted water production to over two-fold at same heat source temperature as compared to conventional MED system. In addition, hybrid cycle has no last stage operational temperature limitations, and it can operate as low as 5C. Lastly, additional cooling effect can be extracted from last stage operating below ambient temperature for control room cooling.

Detailed thermodynamic and life cycle costing analysis was also conducted for proposed hybrid MED+PSAD cycle. It was found that hybrid cycle water production cost is \$0.47/m^3, one of the lowest as compared to all conventional desalination systems. In addition, it achieved 20% of thermodynamic limit, as compared to 10%–13% of conventional systems performance.

3. Conclusion

In conclusion, they paradigm shift in desalination processes is the only choice for future sustainable water supplies. The proposed hybrid MED-PSAD cycle is one of the best choices for future water supplies, achieving highest performance with lowest cost, 20% of thermodynamic limit at \$0.47/m^3, as reported up till now in desalination industry. This will not only help to save energy but also environment by reducing emission rates.

3.1. Data collection and presentation

All data is presented with the permission of designers of hybrid system and authors of earlier publications.

Fig. 5. Solar operated hybrid MED+PSAD pilot at KAUST, Saudi Arabia.

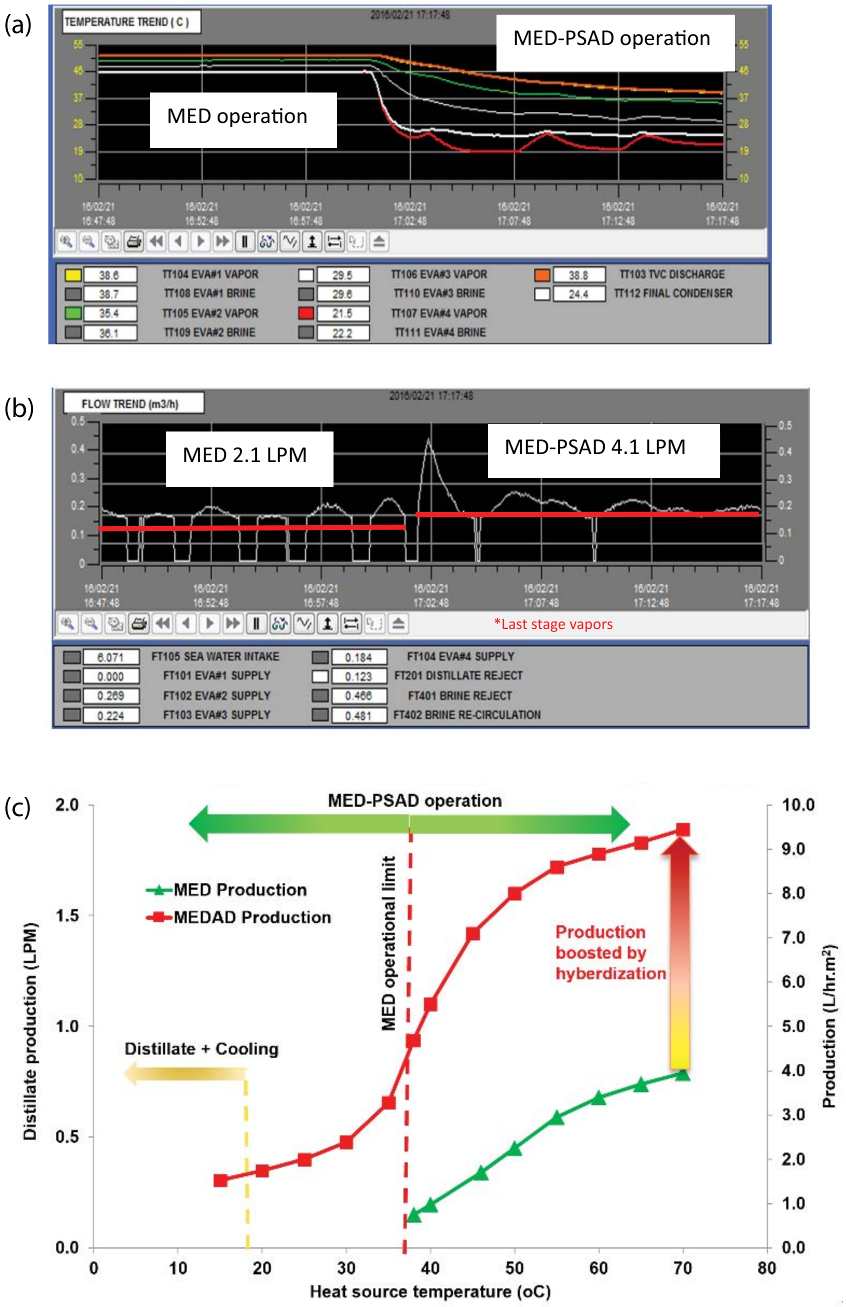

Fig. 6. (a) Conventional MED and hybrid MED+PSAD components temperature profiles during experiment. (b) Conventional MED and hybrid MED+PSAD water production profiles during experiment. (c) Conventional MED and hybrid MED+PSAD water production at assorted heat source.

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