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Recent developments in thermally-driven seawater desalination: Energy efficiency improvement by hybridization of the MED and AD cycles

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HIGHLIGHTS

- Recent development in adsorption desalination
- A new isotherm model based on energy distribution function (EDF) for all types
- An exergy-based method for fuel cost apportionment in cogeneration plants

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ABSTRACT

The energy, water and environment nexus is a crucial factor when considering the future development of desalination plants or industry in the water-stressed economies. New generation of desalination processes or plants has to meet the stringent environment discharge requirements and yet the industry remains highly energy efficient and sustainable when producing good potable water. Water sources, either brackish or seawater, have become more contaminated as feed while the demand for desalination capacities increase around the world. One immediate solution for energy efficiency improvement comes from the hybridization of the proven desalination processes to the newer processes of desalination: For example, the integration of the available thermally-driven to adsorption desalination (AD) cycles where significant thermodynamic synergy can be attained when cycles are combined. For these hybrid cycles, a quantum improvement in energy efficiency as well as in increase in water production can be expected. The advent of MED with AD cycles, or simply called the MEDAD cycles, is one such example where seawater desalination can be pursued and operated in cogeneration with the electricity production plants: The hybrid desalination cycles utilize only the low exergy bled-steam at low temperatures, complemented with waste exhaust or renewable solar thermal heat at temperatures between 60 and 80 °C. In this paper, the authors have reported their pioneered research on aspects of AD and related hybrid MEDAD cycles, both at theoretical models and experimental pilots. Using the cogeneration of electricity and desalination concept, the authors examined the cost apportionment of fuel cost by the quality or exergy of working steam for such cogeneration configurations.

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1. Introduction

Fresh water is a key resource that is necessary for the economic development of every country of the world, and it is consumed by all economic sectors such as agriculture, industrial, commercial and dwellings. Annually, the growth of water demand in the world is estimated to be around 3–4% [1–12], and two factors contributed to this growth, namely, (i) the continued economic growth of all countries and (ii) the exponential increase in the world's population, have imposed increasing demand for potable or drinkable water. Despite the fact that more than 70% of the earth is covered by water, much of it is not directly available for consumption or usage in all sectors due to the high water salinity, either in the form of brackish, waste or seawater, as shown in Table 1 [13–18]. In many water-stressed countries of the world, the annual water availability is less than 250 m^3 per capita per year [19], risking the health of population due to poor water quality and sub-standard sanitation. Also, there is a clear disparity of water consumption levels amongst the economic sectors of developed and developing countries, as shown in Fig. 1(a): The water consumption is most dominant in the agriculture sector of developing countries while the developed countries would have higher water consumption in the industrial sectors [20]. It is predicted that future potable-water demand of the world will be led by the East Asia and Asian developing countries, contributing to more than 50% of the world's water requirement and the remaining water demand trend would come from the America, Europe etc. [21–25].

With the increasing trend of water consumption, it is foreseeable that the future water demand will exceed the existing level of sustainable water supply: In 2030, the estimated demand for fresh water is 6900 billion cubic meters (Bm^3), however, total available water from the natural water cycle remains only at 4500 Bm^3 [26–29], as shown in Fig. 1(b). Hence, the sustainable natural water cycle is unable to meet future water demand of the world. To bridge this water demand–availability gap in the years to come, new solutions to water supply must be sought. Improvements in desalination efficiency of processes alone can only alleviate partially the projected water shortage gap, leaving a large portion of water deficit to be met by further increase in desalination capacity offered by engineering solutions [30].

From 2010 to 2016, the desalinated water production capacities of many water stressed countries have been collated by the International Desalination Association (IDA), as shown in Fig. 2. Over the past 5 years, the increase in the installed capacities has been rising at 9 to 10% per annum [31], with the total global installed desalination capacity increasing from 44 million cubic meters per day (Mm^3/day) in 2006 [32] to 75 Mm^3/day in 2010. This increasing trend is expected to double by 2015 [33,34]. Owing to the dry climate of GCC (Gulf Cooperation Council) countries, it is understandable that the growth rate for desalination capacity is higher in this region than the rest part of the world. It is noted that the GCC countries suffer a rapid depletion of ground water due to high extraction rates from agriculture while the population growth rates of these countries are increasing exponentially [35–41]. Despite the higher installed desalination capacities in recent years, the annual water availability per capita in GCC countries is deemed to remain at an acute level as they are having less than 300 m^3/year per capita.

In order to meet the future water demand, GCC countries have to pursue energy efficient desalination methods. Owing to the ease of fuel oil supply, higher salinity of seawater feed and the frequent occurrences of the harmful algae blooms, the majority of desalination methods found in the region is designed to have the thermally-activated type [42–46] to be collocated together with power (electricity) plants: Electricity is produced by high exergy steam that emanates from the boilers at high pressures and temperatures while the thermally-activated desalination processes form the bottoming cycles, powered by low temperature and pressures bled-steam of low exergy, such as the multi-stage flash (MSF) or the multi-effect distillation (MED). The energetic analysis of thermal system is presented in literature [47–55] in detail and operating fuel cost of MSF or MED cycles, hitherto, has been computed based only on the energetic analysis [55–64], omiting the role of the quality or exergy of expanding steam. Thermal system exergy analysis is conducted by many researchers [65–80] for overall system performance investigation.

Table 1
Distribution of earth surface water.

Source	Volume (cubic kilometer)	
	Fresh water	Salt water
Oceans	0	1,338,000,000
Ice sheets, glaciers	24,364,000	0
Ground water	10,530,000	12,870,000
Surface water	122,210	85,400
Atmosphere	12,900	0
Total	35,029,110	1,350,955,400
Grand total	1,386,000,000 (estimated)	

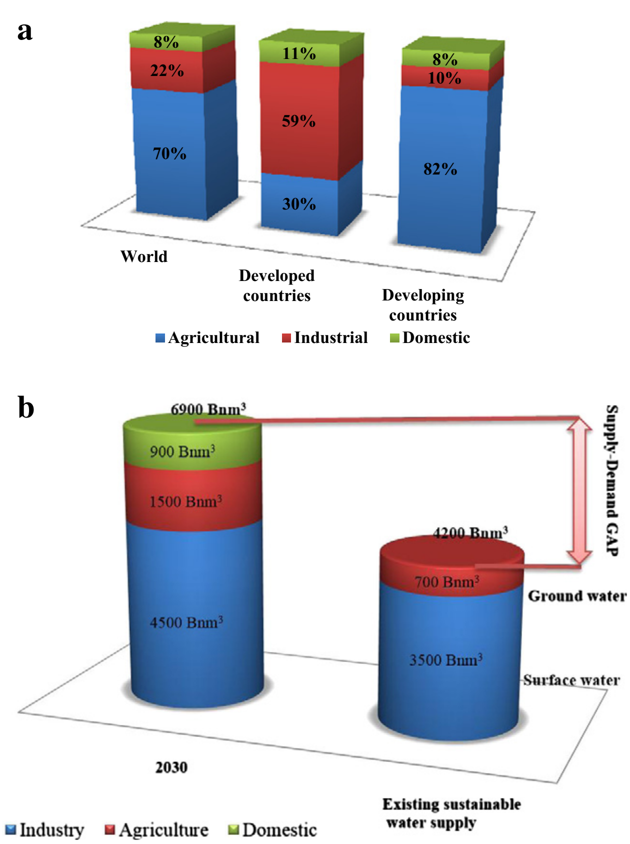

Fig. 1. (a): Share of different sectors (by percentage) in water consumption in different parts of the world and total Global water consumption [20]. (b): Fresh water supply demand gap: current and future estimates.