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# Recent development in thermally activated desalination methods: achieving an energy efficiency less than 2.5 $kWh_{elec}/m^3$

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## ABSTRACT

*Water-Energy-Environment* nexus is a crucial consideration when designing seawater desalination processes, particularly for the water-stressed countries where the annual water availability is less than 250 $m^3$ per capita. Despite the thermodynamics limit for seawater desalination at normal conditions is about 0.78 to 1.09 $kWh_{elec}/m^3$, the specific energy consumption of desalination of real plants is found to operate at several folds higher. Today's technological advancement in membranes, namely the reverse osmosis processes, has set an energy consumption of around 3.5–5 $kWh_{elec}/m^3$, while the conventional perception of thermally activated processes such as MSF and MED tends to be higher. Although the higher energetic specific consumption of MED or MSF processes appeared to be higher at 60–100 $kWh_{thermal}/m^3$, their true electricity equivalent has been converted, hitherto, using the energetic analyses where the work potential of working steam of the processes cannot be captured adequately. Thermally activated processes, such as MED and MSF, form the bottoming cycle of a cogeneration plant where both electricity and desalination processes operate in tandem in a cascaded manner. Only the bled-steam at lower exergy is extracted for the desalination processes. In this presentation, we demonstrate that in a cogen plant with 30% bled-steam for MED processes, the exergy destruction ratio is found to be less than 7% of the total available exergy that emanated from the boilers. By the exergetic approach, the equivalent electricity consumption of an average 75 $kWh_{thermal}/m^3$ would result in an electrical equivalent of less than 2.5 $kWh_{elec}/m^3$. Also in this presentation, the authors will elaborate the latest developments in the use of hybridization concept where the MED and the AD cycles are thermodynamically integrated and enhancing the overall efficiency of desalination.

*Keywords:* Thermal desalination; Adsorption desalination (AD); Exergy analysis; Multi-effect distillation (MED); Hybrid cycles

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## 1. Introduction

All Gulf Cooperation Council (GCC) countries are considered most water stress countries in the World due to highly poor water resources endowment because of extremely arid zone. Water desalination is the major source to meet water requirements in these countries. World highest population growth, more than 3% annually in these countries, is aggravated the water scarcity. Thrust of high gross domestic product (GDP) and food requirement associated with population growth are the major factors of high water requirements. Population of GCC countries in 2002 was 30.3 million, and it is estimated that it will cross 80 million by 2025 with an average growth rate of 3.73%. Population projection for GCC countries over the period 1995–2025 is given in Table 1 [1–5].

In 2002, the total renewable water resources in GCC countries were 82,010 million cubic meter (MCM). The annual per capita of water resources dropped drastically due to higher population growth than water resource development. Most of GCC countries water resources are under 500 $m^3$/cap/year, half the benchmark of chronic water scarcity, 1,000 $m^3$/cap/year. By 2030, the water availability per capita will be worsen to 94 $m^3$/cap/year, caused by the projected population growth and food sufficiency policies. Currently, 85% of available water resources are utilized by agriculture followed by domestic 14% and commercial and industrial 4% as shown in Table 2 [1,2,6–13].

Even though agriculture sector is consuming most of the freshwater, but it has very minimal contribution in GCC countries GDP and employment sectors. In GCC countries GDP, it has only 1–4% share compared to 10–15% share in Egypt and Turkey and 15–20% in India and China. Table 3 shows agriculture sector contribution in GDP and employment of GCC and other water rich countries [14].

In five of six GCC countries, water stress index is crossed 100% and this shows that these countries already drained their renewable water reserves and now depending on non-renewable sources. The current 252% overall water stress index value shows that available water sources cannot fulfill future water demand and these countries need to take positive steps in terms of seawater desalination to meet freshwater demand [15,16].

According to GWI 2010 report, GCC countries own 40% of world total capacities. Current GCC desalination capacity is 9.5 billion $m^3$/year and it is estimated that by 2016, it will reach to 18 billion $m^3$/year as shown in Fig. 1.

It can be seen that in all countries, the contracted capacity is almost double in just six year. This increase in desalination capacities increased energy consumption and corresponding $CO_2$ emission to environment. The income lost from fuel burned by desalination plants has over the recent years become significant; for example, in 2010, the lost income attributed to desalination was 3.5 billion USD and this loss is expected to rise 31 billion USD in 2025 as calculated by considering yearly fuel price in terms of US$/bbl as shown in Table 4 [17].

Seawater desalination processes have significant impact on energy and environment. Water-Energy-Environment nexus encouraged the engineers and scientists to improve the desalination processes to save energy and environment. Despite the high share and low energy consumption, reverse osmosis processes may face challenges such as (1) frequent occurrence of hazards algae blooms (HABs) such as algae and red tides in sea water, (2) high salt concentration in feed (>42,000 ppm), (3) high maintenance cost of membrane replacement, and (4) residuals of boron, chlorides, and bromides [18–22]. Thermal processes, on the other hand, are preferred options for desalination in severe feed conditions such as GCC region. Only thermal

Table 1
Past and projected GCC countries population (1995–2025)

| Country | Past and projected population in GCC countries (×1,000) | | | | | | | Percent 2025/1995 |
|---|---|---|---|---|---|---|---|---|
| | 1995 | 2000 | 2005 | 2010 | 2015 | 2020 | 2025 | |
| Bahrain | 557 | 618 | 671 | 717 | 766 | 897 | 1,049 | 188 |
| Kuwait | 1,691 | 1,966 | 2,192 | 2,390 | 2,576 | 3,076 | 3,673 | 217 |
| Oman | 2,027 | 2,717 | 3,302 | 3,986 | 4,752 | 7,002 | 10,316 | 509 |
| Qatar | 548 | 599 | 648 | 693 | 734 | 842 | 967 | 176 |
| KSA | 18,255 | 21,661 | 25,255 | 29,222 | 33,483 | 45,580 | 62,048 | 340 |
| UAE | 2,210 | 2,410 | 2,660 | 2,869 | 3,049 | 3,520 | 4,078 | 185 |
| Total | 25,288 | 29,597 | 34,728 | 39,877 | 45,360 | 60,828 | 81,570 | 323 |

Table 2
Water utilization by different sectors in GCC countries (1995–2025)

| | 1995 (MCM) | | | 2000 (MCM) | | | 2025 (MCM) | | |
|---|---|---|---|---|---|---|---|---|---|
| Country | Domestic | Agriculture | Industrial | Domestic | Agriculture | Industrial | Domestic | Agriculture | Industrial |
| Bahrain | 86 | 120 | 17 | 117 | 124 | 26 | 169 | 271 | 169 |
| Kuwait | 295 | 80 | 8 | 375 | 110 | 105 | 1,100 | 140 | 160 |
| Oman | 75 | 1,150 | 5 | 151 | 1,270 | 85 | 630 | 1,500 | 350 |
| Qatar | 76 | 109 | 9 | 190 | 185 | 15 | 230 | 205 | 50 |
| KSA | 1,508 | 14,600 | 192 | 2,350 | 15,000 | 415 | 6,450 | 16,300 | 1,450 |
| UAE | 513 | 950 | 27 | 750 | 1,400 | 30 | 1,100 | 2,050 | 50 |
| Total | 2,553 | 17,009 | 258 | 3,833 | 18,089 | 676 | 9,679 | 20,466 | 2,229 |

Table 3
The economic importance of agriculture in the GCC countries (1997–2010)

| Countries | Average (1997–2010) contribution to GDP (%) | Average (1997–2010) contribution to employment (%) |
|---|---|---|
| Bahrain | 0.9 | 1.0 |
| Kuwait | 0.5 | 1.1 |
| KSA | 4.4 | 9.1 |
| Oman | 2.2 | 35.4 |
| UAE | 2.9 | 4.6 |
| Turkey | 12.3 | 41.9 |
| China | 14.4 | 63.2 |
| Egypt | 15.5 | 29.4 |
| India | 21.6 | 56.9 |

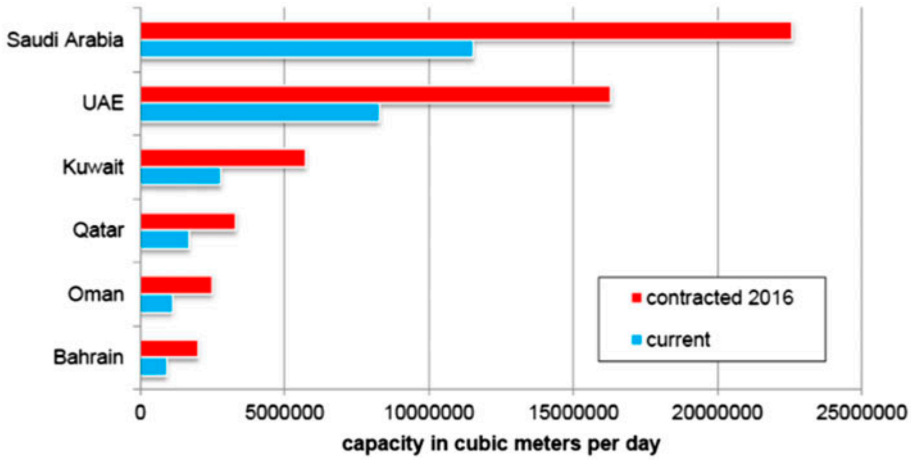


Fig. 1. Current and contracted desalination capacities in GCC countries.

desalination methods could handle the HABs where the impact on health (illnesses such as neurotoxins, amnesic toxin, etc.) can be minimized. Hence, there is a motivation for improving thermal desalination processes, making them more energy efficient, robust, and less maintenance required.

An innovative thermal hybrid desalination system called MEDAD is introduced. In this new cycle, a thermally driven robust multi-effect desalination (MED) is integrated with waste heat-driven adsorption desalination (AD) cycle. AD cycle can operate at a temperature ranges from 55 to 85°C, and this low

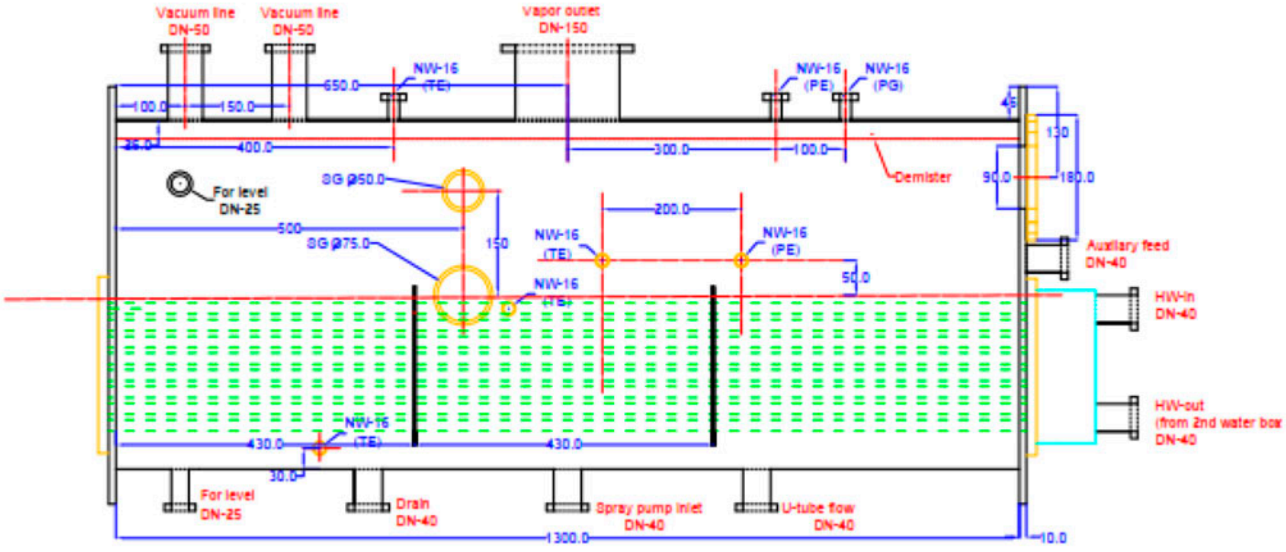


Fig. 2. A model of MED-SG design.

Table 4
$CO_2$ emission and income displaced for desalination in GCC countries

| Year | Specific energy utilization for desalination (GWh_pe) | $CO_2$ production on the basis of fuel (0.527 tonne/MWh) (million tonne/year) | Displaced income due to desalination (1 bbl = 1628 kWh) (million USD) |
|---|---|---|---|
| 1950 | 0 | 0 | 0 |
| 1955 | 0 | 0 | 0 |
| 1960 | 0 | 0 | 0 |
| 1965 | 0 | 0 | 0 |
| 1970 | 8117.04 | 1.5 | 408.8 |
| 1975 | 32264.02 | 6.0 | 1625.1 |
| 1980 | 79193.47 | 14.6 | 3988.9 |
| 1985 | 117436.73 | 21.7 | 3967.5 |
| 1990 | 123776.38 | 22.8 | 3041.2 |
| 1995 | 137928.51 | 25.4 | 2118.1 |
| 2000 | 140024.78 | 25.8 | 2752.3 |
| 2005 | 163931.43 | 30.2 | 5538.2 |
| 2010 | 202905.26 | 37.4 | 9970.8 |
| 2015 | 234686.92 | 43.3 | 16578.0 |
| 2020 | 270998.80 | 50.0 | 19975.3 |
| 2025 | 310183.46 | 57.2 | 23244.7 |

Notes: GWh = Gigawatt hours, MWh = Megawatt hours, pe = Primary energy, and bbl = Barrel of oil.

temperature can be achieved from industrial waste heat or solar energy. AD cycle detail can be found in the literature [23–39].

This synergetic hybridization of two thermal systems extends the operational range of conventional MED system toward downstream from 40 to 5˚C. Additional number of stages because of higher overall operational range and high inter-stage temperature difference increase the water production two- to three fold as compared to conventional MED system at same top brine temperature. The other advantage includes the following: (i) It scavenged the ambient energy in part of the MED stages operating below ambient temperatures where the latent energy is further recycled, (ii) waste heat is utilized for the AD cycle operation, (iii) all hybrid cycle equipments are almost stationary so very less maintenance cost, (iv) it reduces the chances of corrosion and fouling due to high concentration exposed to low temperature (5˚C) in last stages, (v) additional cooling effect from last stages of MED operating below ambient temperature, and (vi) significant increase in system performance.

Hybrid MEDAD cycle simulation is conducted by Shahzad et al. [40], Thu et al. [41], and Ng et al. [42] and the results show two- to three fold production improvement as compared to conventional MED system. To investigate hybrid system performance experimentally, a 3 stage MED system is designed [43], fabricated, installed, and tested. This study presents the experimental investigation of hybrid MEDAD system at assorted heat source temperatures. Exergy analysis is also conducted for economic comparison with available desalination technologies. The detail of experimental setup, experimentation, and analysis is provided in following sections.

## 2. MED system overview

A three stage parallel feed MED system is designed, fabricated, and installed for performance investigation. The evaporator tubes are arranged horizontally because of their high wetting rate that eliminates the dry patches formation. Each evaporator is equipped with spray header to spray the feed onto the tube bundle. Special magnetic feed pump is used to work in vacuum environment. A vacuum pump is installed to pull the non-condensable from system.

The first stage is called the steam generator (SG) which feeds vapor to the subsequent stage by exploiting the latent heat of condensation that occurs within the tube surfaces. The last stage vapors directed to AD adsorption bed and desorbed vapors are than condensed in condenser. Fig. 2 shows the detail design of SG of MED. The design of other two MED stages is also similar to SG; only difference is the tubes are single pass with vapor condensation inside.

The brine from each stage is collected to brine tank, and it can be mixed with feed according to concentration of salt. The distillate from each tank is collected via u-tubes to a collection header and then to collection tank. The schematic diagram of the process is shown in Fig. 3. The system is fully instrumented to

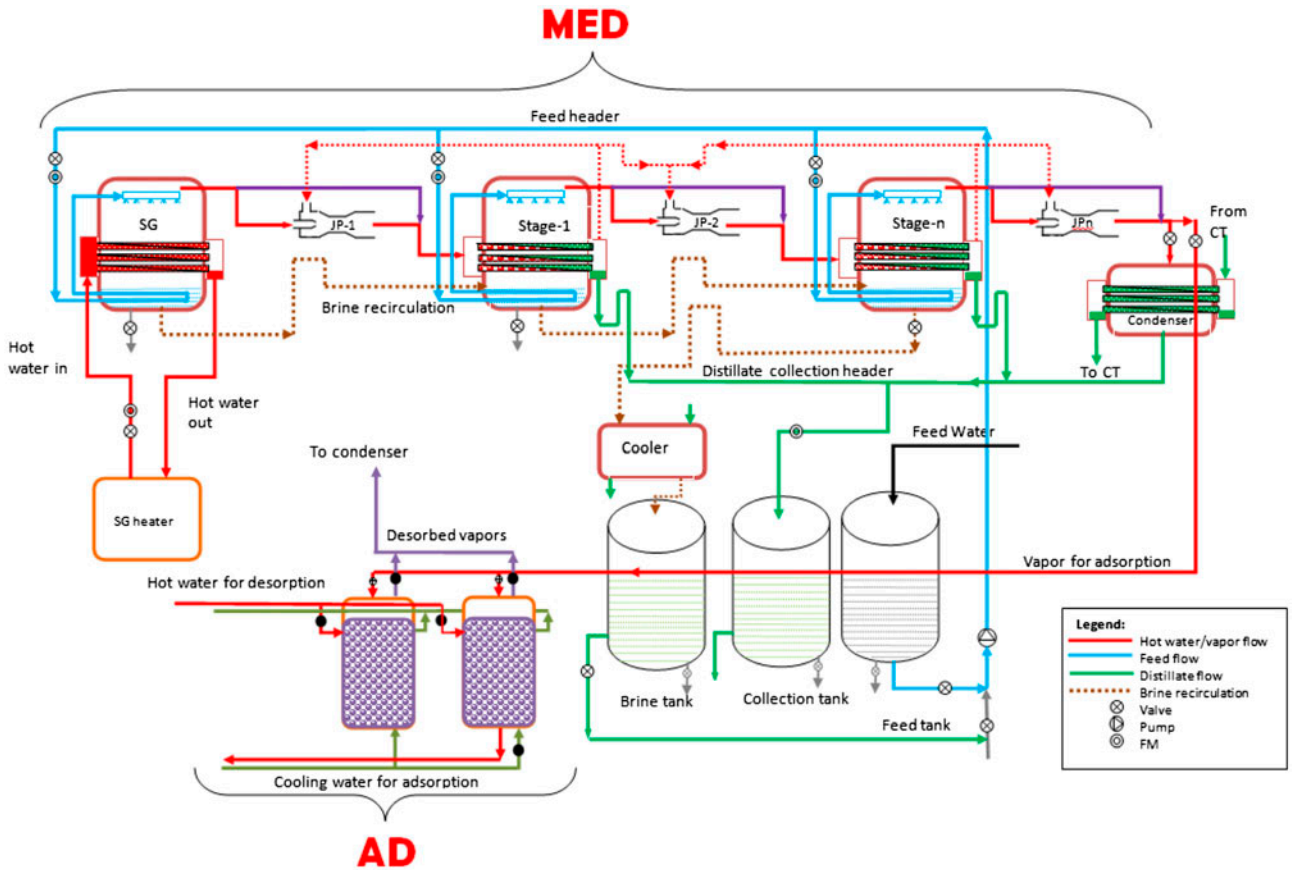


Fig. 3. Hybrid MEDAD detailed flow schematic.

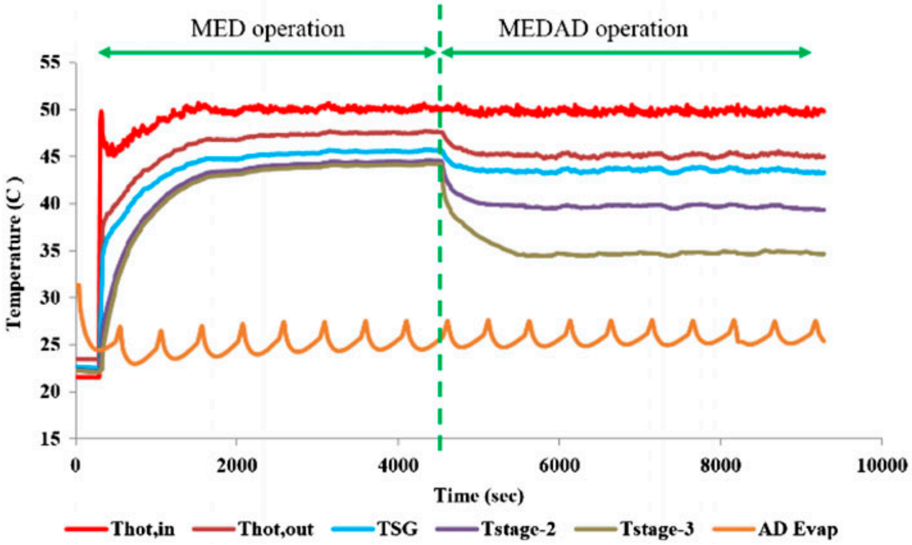


Fig. 4. Temperature profile of MEDAD components at heat source 50°C.

capture all required parameters to investigate the system performance.

## 3. Results and discussion

Fig. 4 shows the temperature profiles of system components at heat source 50°C. Initially, system is started as conventional MED and it can be seen that inter-stage temperature difference varies 0.8–1°C. After steady state operation, MED condenser is bypassed and last stage vapor valve is opened to adsorption beds. Once the valve is opened, all stages pressure is dropped due to silica gel pulling effect and corresponding saturation temperature also dropped as it can be seen clearly.

During hybrid MEDAD operation, inter-stage temperature difference increased to 3–4°C. This higher inter-stage temperature difference increases the heat flux and hence the evaporation rate and production from the system. It can also be seen that at heat source 50°C, the last stage temperature observed is 30°C and it is because of only 3 stages. In real practical plant with 6–8 stages, the last stage temperature can be as low as 5°C.

Fig. 5 shows the water production profile for conventional MED system and hybrid MEDAD cycle at

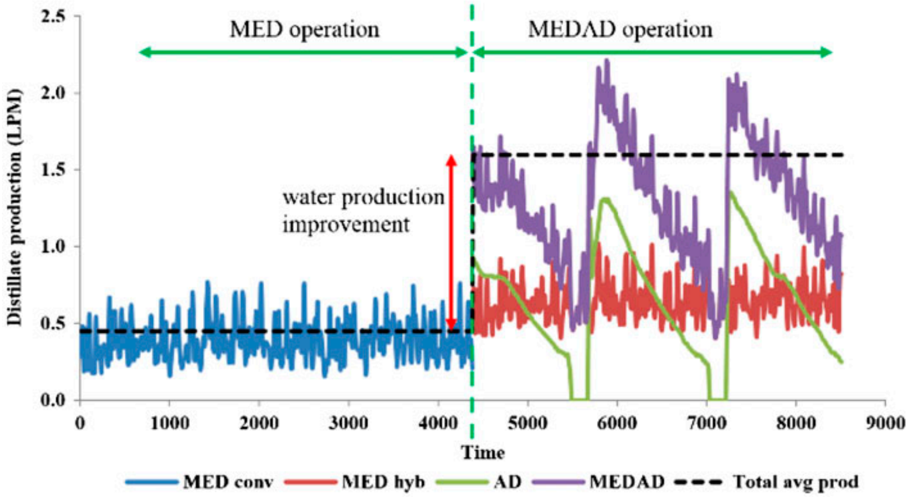


Fig. 5. Distillate production from MED and MEDAD at heat source 50°C.

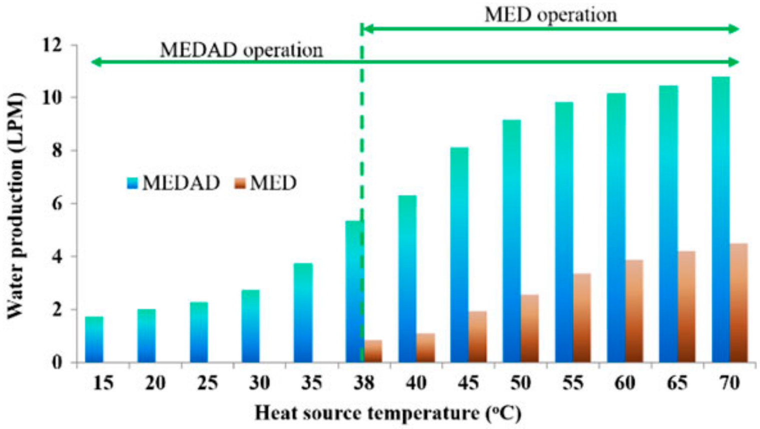


Fig. 6. Total distillate production from MED and MEDAD at assorted heat source temperatures.

heat source temperature 50˚C. The response of system at the time of last MED stage vapor valve open to AD beds can be seen clearly. It can be observed that once the MED system combined with AD system, the production is boosted almost double. It is because of increase in inter-stage temperature difference that increases the heat flux and hence the evaporation rate.

Distillate production comparison of MED and MEDAD system at assorted heat source temperature can be seen in Fig. 6. At each SG temperature, a marked improvement to the water production is observed with two- to three fold quantum jump. These experiments have good agreement with author's simulation results.

## 4. Exergy analysis

Exergetic analysis is conducted for fuel cost apportionment in dual-purpose plants (power and desalination). It is found that at 20% bled-steam from the low pressure turbine, the ratios of power-to-water for exergy and energetic analyses are 95.7:4.3% (exergy) and 72.2:27.8% (energetic) methods, respectively. This ratio of energy-to-exergy shares of the total working

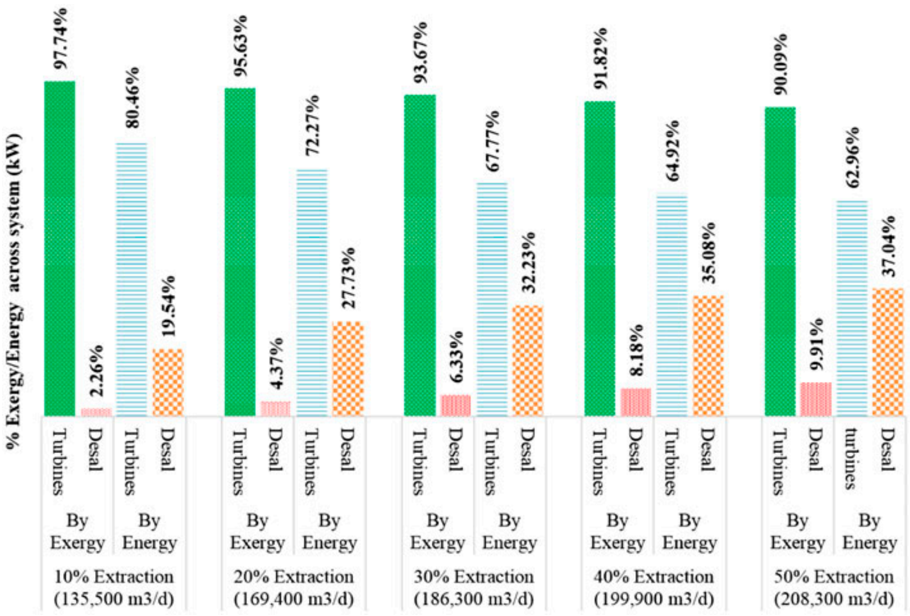
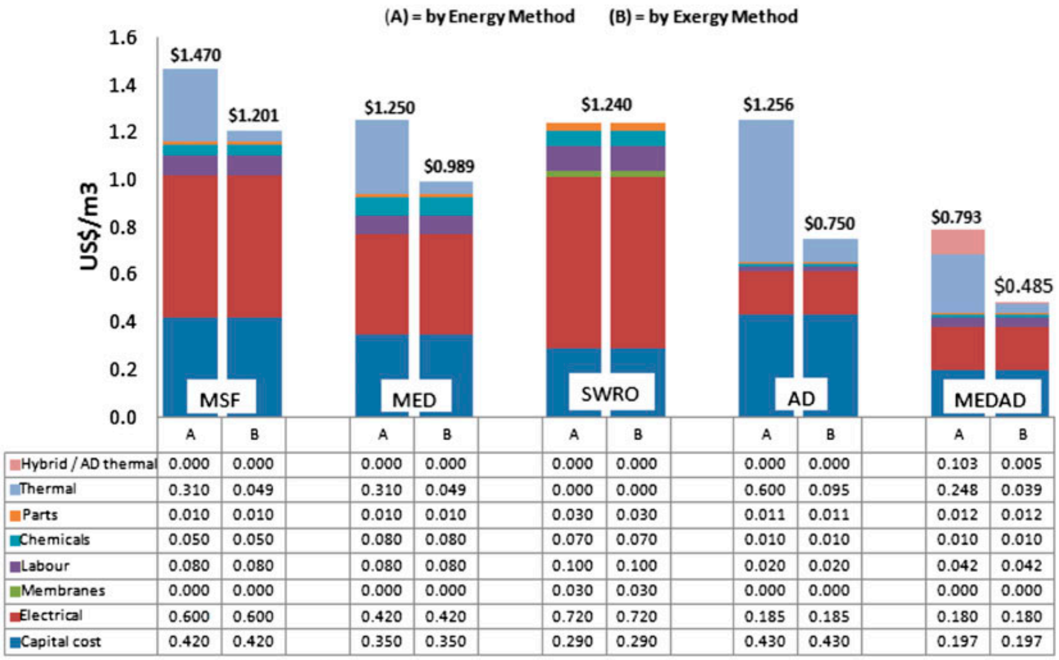


Fig. 7. Primary fuel apportionment for power and desalination at different % steam extraction (energetic and exergetic analysis).



| | A | B | | A | B | | A | B | | A | B | | A | B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hybrid / AD thermal | 0.000 | 0.000 | | 0.000 | 0.000 | | 0.000 | 0.000 | | 0.000 | 0.000 | | 0.103 | 0.005 |
| Thermal | 0.310 | 0.049 | | 0.310 | 0.049 | | 0.000 | 0.000 | | 0.600 | 0.095 | | 0.248 | 0.039 |
| Parts | 0.010 | 0.010 | | 0.010 | 0.010 | | 0.030 | 0.030 | | 0.011 | 0.011 | | 0.012 | 0.012 |
| Chemicals | 0.050 | 0.050 | | 0.080 | 0.080 | | 0.070 | 0.070 | | 0.010 | 0.010 | | 0.010 | 0.010 |
| Labour | 0.080 | 0.080 | | 0.080 | 0.080 | | 0.100 | 0.100 | | 0.020 | 0.020 | | 0.042 | 0.042 |
| Membranes | 0.000 | 0.000 | | 0.000 | 0.000 | | 0.030 | 0.030 | | 0.000 | 0.000 | | 0.000 | 0.000 |
| Electrical | 0.600 | 0.600 | | 0.420 | 0.420 | | 0.720 | 0.720 | | 0.185 | 0.185 | | 0.180 | 0.180 |
| Capital cost | 0.420 | 0.420 | | 0.350 | 0.350 | | 0.290 | 0.290 | | 0.430 | 0.430 | | 0.197 | 0.197 |

Cost of electricity is taken at US$0.15 /kWh, the exergy ratio for Turbine to MED is 0.9563 to 0.0437,
Increase in water production by MEDAD is 2 folds of the conventional MED.

Fig. 8. A comparison of life-cycle unit water cost for various desalination methods.

steam is found to be four- to seven fold higher, descending with the larger amount of bled-steam as shown in Fig. 7.

The higher effectiveness of working steam incurred at the MED cycle is attributed to the better thermodynamic matching of steam's latent energy. The work production from turbines requires higher exergy destruction of the expanding steam. On the basis of above analysis for primary fuel cost and with data from the published literature [44–46], the life-cycle cost (LCC) of water production is compared for all capital expenditure (Capex) and operation expenditure (Opex), across all proven industrial processes, as shown in Fig. 8.

## 5. Conclusion

The experimental investigation of a thermally driven MEDAD hybrid desalination system has been presented: A significant increase in water production (two- to three fold) has been observed which is attributed to the synergetic operation of the conventional MED and the AD systems. In a practical dual-purpose plants (power + desalination) configuration where the bled-steam is about 20%, the ratio of exergy to energy consumption of the cogeneration plant is 4–7 times lower than the energetic method. Hence, the fuel cost of steam consumed water production can be lower by the same ratios. It has been demonstrated here that with greater thermodynamic synergy, the LCC water production cost of the PP + MEDAD cycle is found to be the lowest at \$0.485/m$^3$: the lowest ever reported for seawater desalination in the literature.

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