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Water Impact statement

We present a low-temperature waste heat driven adsorption desalination (AD) cycle for future sustainable desalination. Through internal heat recovery, it integrates with multi-effect distillation achieving a quantum jump in water production without increasing overall energy input. The "breakthrough" in thermodynamic synergy between processes offers a sustainable and environment-friendly desalination that solves holistically the water-energy-environment nexus, otherwise eluded the desalination industry.

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Future Sustainable Desalination Using Waste Heat: A Kudos to Thermodynamic Synergy.

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There has been a plethora of published literature on the thermally-driven adsorption desalination (AD) cycles for seawater desalination due to its favorable environment-friendly attributes, such as the ability to operate at low-temperature heat sources, from either the renewable or exhaust of prime movers and it has almost no major moving parts. We present an AD cycle for seawater desalination due to its unique ability to integrate for higher water production yields with the existing desalination methods such as the reverse osmosis (RO), the multi-stage flashing (MSF) and the multi-effect distillation (MED), etc. The hybrid cycles exploits the *thermodynamic synergy* between processes, leading to significant enhancement of systems' performance ratio (PR). In this paper, we demonstrate experimentally the synergetic effect between the AD and MED cycles that results in quantum improvement in the water production. The unique feature is in the internal latent heat recovery from the condenser unit of AD to the top-brine stage of MED, resulting in a combined or simply termed as MEAD cycle that requires no additional heat input other than the regeneration of adsorbent. The batch-operated cycles are simple to implement and it has low maintenance when compared with conventional desalination methods. Together, they offer a low energy and environment-friendly desalination solution that addresses the major issues of water-energy-environment nexus.

Key words: Sustainable desalination, Hybrid desalination, Thermodynamic synergy for thermally-driven cycles.

Introduction

The Gulf Co-operation Council (GCC) countries suffer from an acute scarcity in potable water availability due to the region's adverse climatic weather. The daily water availability per capita-day in these countries has, in recent decades, fallen drastically below the UN defined acute water stress (AWS) of 500 m^3, as shown in Table 1.[1-3] The regional water shortage is compounded further by two other factors; Firstly, the exponential increase in the population of GCC countries and secondly, the quest for rapid economic growth of their economies. Confronted by these challenges, the only viable solution for closing the demand-supply water gap of the region is through massive investment into seawater desalination plants. For example, the Kingdom of Saudi Arabia (KSA), United Arab Emirates (UAE) and Kuwait have respectively contracted in new desalination capacities of 15, 10.2 and 3.5 million m^3/day, using conventionally proven but energy intensive processes such as the reverse osmosis (RO), the multi-stage flashing (MSF) and the multi-effect distillation (MED). For energy sustainability, innovative low-energy and environment-friendly desalination methods have to be developed in the near future that can address the holistic targets of water-energy-environment nexus.[4-7]

Table 1: The projected water availability per capita in GCC countries by 2035.

Country	Population (Thousands) 2010	Projected Population (Thousands) 2035	Per capita water availability (m^3) per year by 2035
Kuwait	2,737	4,328	4.6 ±1
UAE	7,512	11,042	13.6 ±2.0
Qatar	1,759	2,451	21.6 ±2.0
KSA	27,448	40,444	59.3 ±2.0
Bahrain	1,262	1,711	67.8 ±3.0
Oman	2,803	4,922	300 ±10

Presently, energy planners of GCC countries have opted to integrate large-scale water desalination plants in-situ with the power plants (PP), e.g., the co-location of PP+MED, PP+MSF, where the processes can be cascaded sequentially to maximize not just energetic but also the exergetic utilization of the working steam. Another

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commonly used but less exergy-efficient scheme is the integration of RO plants operating in remote or tandem with the PP; The latter arrangement shares in-situ the seawater intake and discharge facilities whilst the former operates in remote sites for non-seawater applications. Although a PP+RO configuration squandered the opportunity of maximising steam's exergy for processes but it is compensated by the efficient salt separation process of membranes. In the PP+MED configuration, the co-generation arrangement can optimize the temperatures and pressure levels between the expanding steam of turbines and the bled-off steam that powers the thermally-driven processes. For example, the world's largest co-generation facility available in Jubail (KSA), operated as an independent water and power plant, generating 2,745 MW power and over 800,000 m^3/day desalinated water simultaneously.

In 2014, the installed co-generation plants in KSA is reported to consume approximately 1.5 million barrels of oil daily for both the water and electricity production;- Equivalently, this is about 15% of the total daily oil production of Saudi Arabia. Given the KSA's projected GDP and population growth in the coming decades, the predicted domestic oil consumption is expected to exceed its oil production capacity by 2040 in a business-as-usual scenario, as shown in Figure 1. If such a domestic consumption rate remains unabated, the balance of payments for the Kingdom's economic situation will then be untenable, and moreover, the increase in energy consumption leads to severe environmental pollution.[8,9]

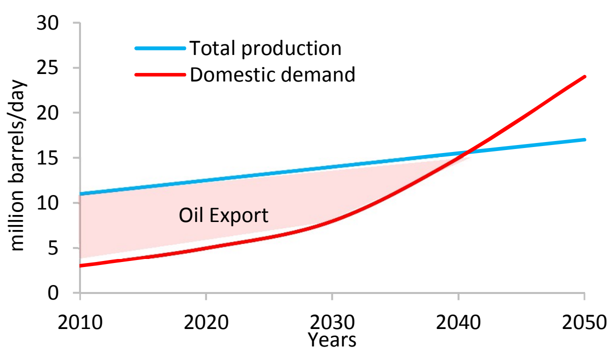

Figure 1: Oil production and domestic use in Saudi Arabia [9].

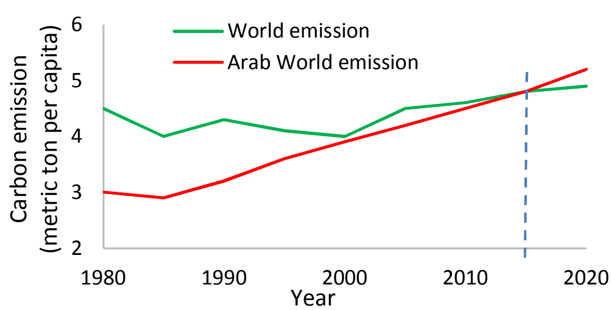

Figure 2: Carbon emission in Arab countries as compared to the World's emissions [10].

Within the GCC countries, with their share of 65% of world's installed desalination capacities, they emit 140-180 million tons of CO_2 annually from the desalination plants. At these rates of consumption of electricity and water production, the carbon emission per capita of Middle East and North Africa (MENA) countries will supersede the World's average CO_2 emission, as shown in Figure 2.[10, 11]

In view of the looming energy consumption and pollution increase of KSA, the King Abdul-Aziz City of Science and Technology (KACST) has recently announced the first low-carbon desalination initiative where a utility scale solar-powered desalination plant of 60,000 m^3/day of seawater (carried by pipelines from the Gulf) is to be built at the north eastern city of Al Khafji. The proposed project is an integrated solar concentrated photo-voltaic (CPV) of 40 MW_{elec}, to be built adjacent to a RO plant for potable water. The proposed RO plant needs only half of power generated, 20 MW_{elec} , and extra half will be added to grid during diurnal period that will be utilized for nocturnal operation. This initiative by KACST demonstrates the Kingdom's longer term goal of achieving sustainable desalination using the renewable solar energy which is available in abundance in the Kingdom. The design comprises many two-axes sun tracking CPV panels, spread over 90 hectares land, concentrating solar irradiance up to 1000 suns onto homogenizer-mounted multi-junction cells (MJC). They produce electricity that power the RO plant in the day time and excess electricity is up-loaded to the grid. Several accompanying hybrid technologies may have to be developed and tested for reliability. One probable approach is a heat-driven multi-effect adsorption (MEAD) cycle that treats the retentate of RO, increasing the water recovery ratio by 45% to 85%. It is a positive step towards achieving a low-carbon, sustainable desalination solution because the processes are energy efficient. In addition to CPV electricity, the harnessing of the rejected heat, from the MJC (CPV) cells at 65°C to 80°C, is a heat source for the MEAD cycle. The hybridization results in all the more environment-friendly seawater desalination.[12, 13]

In addition to solar powered cycle example, the other waste heat driven and yet highly efficient cycles can be explored by the desalination industry. Low temperature heat sources are abundantly available, either from the exhaust of prime movers or from oil and gas refineries. Recent published literature shows a major shift in the process design of conventional heat-driven cycles, particularly those that utilizes low temperature heat input for seawater desalination. In this paper, we demonstrate the thermodynamic synergy of MEAD cycle, leading to a quantum increase in water production. Therefore, there is a great motivation to incorporate hybrid technologies for sustainable desalination in GCC countries.

MED-AD Cycle

We present the MEAD cycle that combines a multiple reuse of latent energy within evaporators of a AD cycle:- It is akin to having the MED system designed as an integral AD evaporator, exploiting a wider range of temperature differentials across the MED stages. The key innovations are as follows; - Firstly, the recovery of condensed vapour energy, from the re-generation of AD adsorbent, is delivered to the top-brine stage of MED. The re-use of this latent energy reduces eventually the need of an external cooling tower that reduces the foot print of an AD design. Secondly, the bottom-brine stage of MED is operated at a low evaporative temperature, typically less than 5°C. It reduces the risk of scaling and fouling because the solubility of sulphate ions SO_4^{--} increases with decreasing solution temperatures. Detailed process flow schematic of new cycle is shown in Figure 3(a).

Being batch-operated, the AD half-cycle time interval varies from 3 to 10 minutes depending on the low-grade heat source temperatures. The heat source from 55° to 80°C is used for re-generating the silica gel adsorbent during the desorption half-cycle. However, the top-brine stage of MED recovers the heat emanating from the condenser that increases the vapour uptake of AD adsorbent due to higher evaporator pressures. For the MED stages, seawater is sprayed in parallel onto the tube surfaces. The vapour produced in the top-brine stage is channelled into the subsequent stages to reuse for seawater evaporation. This process is repeated to the final stage of the MED cycle. The vapour from the last stage is hybridized with the AD cycle.

The distillate (potable water) from all stages and AD condenser is collected to a tank whilst the local pressure differences of the stages are accommodated via differential liquid columns of u-tubes. Similarly, the collected brine is re-circulated for more water recovery depending on the local salt concentration. As only recovered energy is used by the hybrid cycle, the electricity consumed is less than 1.3 kWh/m³. The thermal input to the MEAD cycle is deemed to be non-payable because if it is unused, it will be purged into the ambient.

MED-AD Pilot

We conducted experiments on a 3-stage MEAD hybrid pilot plant to demonstrate the thermodynamic synergy between the cycles, as shown in Figure 3(b). Each MED vessel has a volume of 0.25 m³ and the heat transfer area of cuprous-nickel tubes is 4 m² and they are instrumented with pressure, temperature and flow sensors. The top-brine stage of MED is solely powered by the condensed vapour latent energy, recovered from the AD condenser. The cascading condensation and evaporation processes of the MEAD cycle, coupled with the extraction of vapour by the adsorption half-cycle boost the water production up to 2 to 3 folds over the conventional MED, and detailed of these results are presented in the next section.

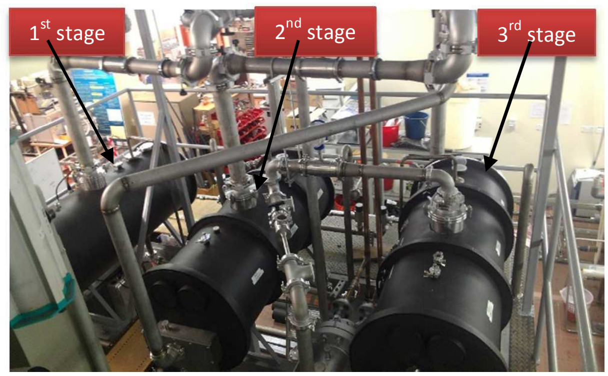

Figure 3(b): A 3-stage ME-AD experimental facility at NUS's adsorption desalination laboratory.

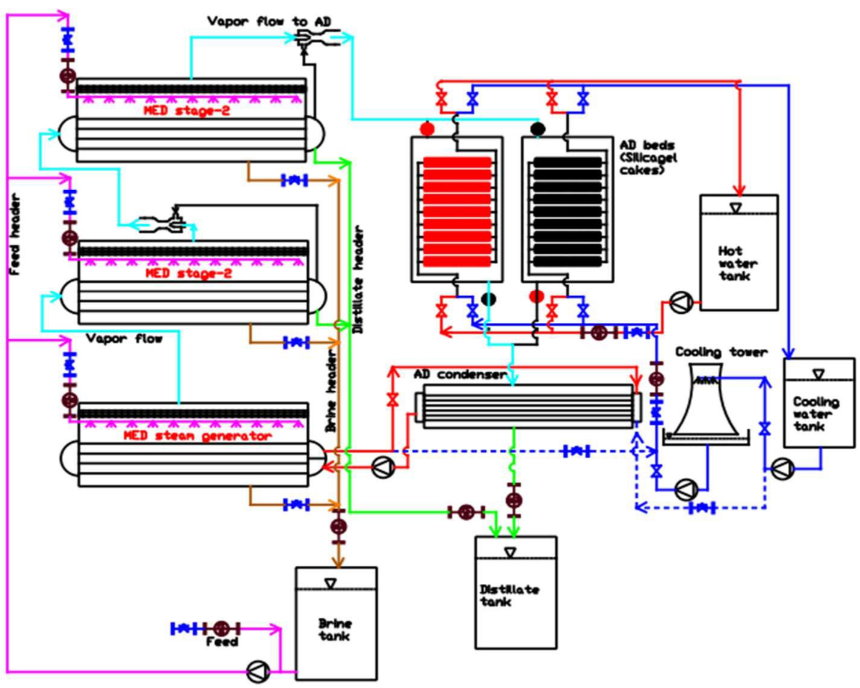

Figure 3(a): Detailed flow schematic of a 3-stages ME-AD cycle with AD heat recovery loop

Results and Discussion

Figure 4 shows the measured temperature profiles of key components of MEAD cycle over the first 9000s to reach cyclic steady state after starting from cold. The top two lines (denoted in red and brown) depict the supply and return hot water temperatures of the top-brine stage of MED. This heat input is derived from the run-around coolant circuit of the condenser-evaporator where latent energy is recovered from desorbed vapour emanating from AD beds during the desorption processes. The third line (shown in blue) denotes the temperature of generated vapour in the top-brine or steam generator (SG). The bottom two temperatures (shown in green and black) are the vapour temperatures of the 2nd and 3rd stages.

It can be observed that MED inter-stages temperature difference (ΔT) varies 4°C to 5°C, indicating the successful operation of the 3-segment evaporator unit. The high ΔT across each MED stage increases the evaporative heat flux of feed water resulting in a higher water production. The oscillating heat inputs (as depicted by the water inlet and outlet traces) are caused by the batched-operated operations of AD beds; One bed is undergoing the adsorption process with vapour drawn from evaporator, and the other bed is undergoing desorption process where desorbed vapour communicates with the water-cooled condenser. Bed switching interval between the adsorption to desorption is 30 sec where both beds are isolated from evaporator and condenser. Consequently, the vapour generation profiles of the MED stages follow the same temperature trends of the steam generator (SG) but with diminishing magnitude of fluctuations at each subsequent stages.

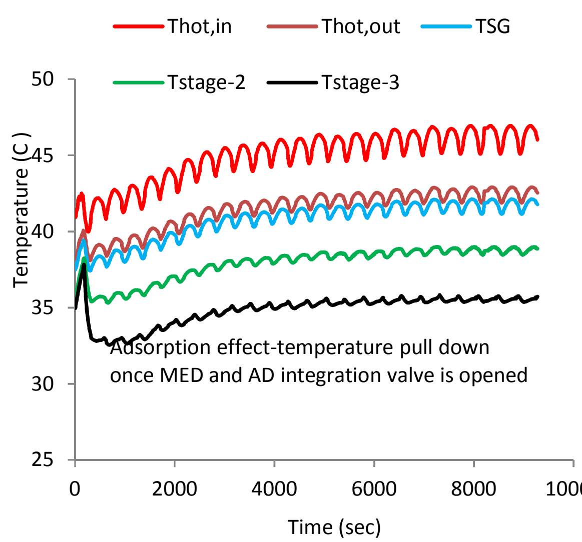

Figure 4: Measured temperature profiles of key components of an MEAD cycle.

The pressure profiles of MEAD stages are shown in Figure 5 and correspondingly, they depict similar fluctuations to those observed in the temperature profiles and the top, mid and the bottom traces are the pressures of steam generator, the 2nd and 3rd stages of MED, respectively. The magnitude of fluctuations decreases also with each subsequent stage but the pressure drop across the stages is about 1.5 kPa in the first pair, and reduces to about 1 kPa in the next pair, indicating excellent synergetic operation of MED stages.

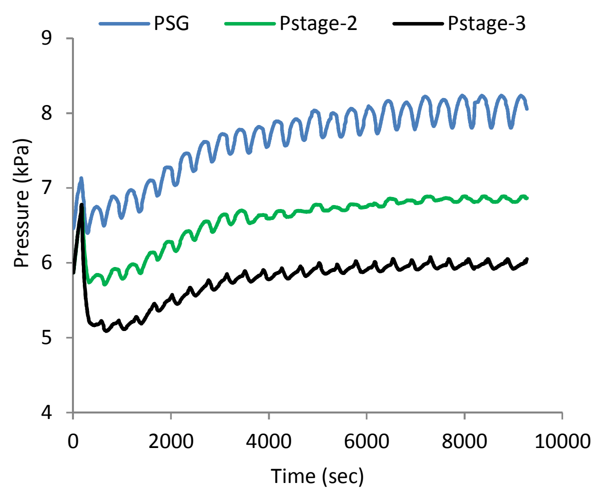

Figure 5: Measured pressure profiles of the key components of MEAD cycle.

Figure 6 shows the water production profiles of both the MED stages and the AD condenser. The blue line water indicates the water production from 3 MED stages whilst the green trace is the water production from the AD condenser. The combined distillate production is shown by the dark-orange colour traces and the dotted-red line is the time-average total water production, achieving about 1.15 LPM from the small pilot unit. The cyclic nature of water production of MED stages is also a consequence of the batch operation of AD cycle. The hybridization of MEAD cycles has boosted the water production by two-fold (0.56 LPM to 1.15 LPM) of the basic AD cycle which is achieved solely by the recovered heat of condenser. The other aspect of the cycle is that all major components are stationary except liquid circulation by pumps and thus, it has a specific power consumption of less than 1.3 kWh/m^3. The MEAD stages operate with decreasing brine temperatures with increasing concentrations of brine. Therefore, the tendency for scaling on tube surfaces, from the known soft salts such as the SO_4^{-2}, is significantly mitigated due to the inverse characteristics of solubility limits at lower brine temperatures. In the MEAD pilot, the seawater desalination reached a high concentration of up to 240,000 mg/l without scaling. Such is high concentration application of MEAD cycle is suited for the treatment of produced water of oil wells where environmental regulations have stringent levels for re-charging of water into the reservoirs.

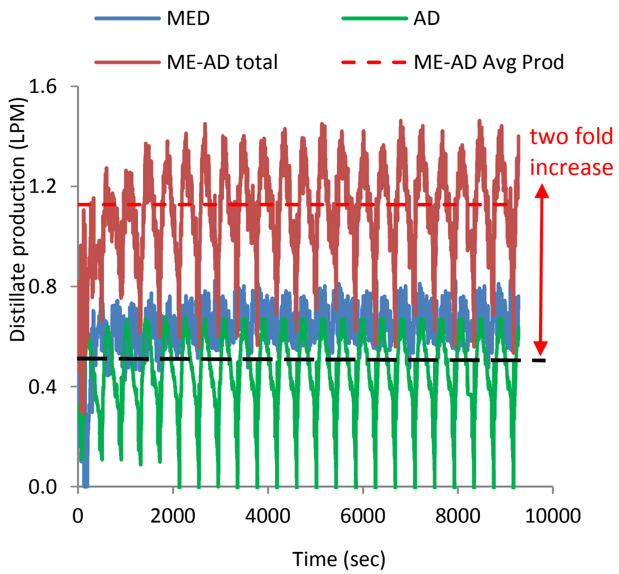

Figure 6: The combined and individual distillate production of the MEAD cycle.

In the basic AD, about 42 kW heat input is supplied to re-generate the adsorbent at 80C. The lowest evaporator temperature was maintained about 10°C, caused by the continued vapour uptake adsorption of the AD cycle, leading to a lower pressure ratio (PR) of 0.5 and the water production rate is 0.56 LPM. However, under the hybrid operation, the water production rate of MEAD has increased from 0.56 to 1.15 LPM. The synergetic operation has increased the PR to 0.96 even though its energy input remains almost same. We believe that the concept of hybridization of MEAD cycle has a great potential for large-scale implementation in seawater desalination. Details of the basic AD cycle operation and adsorbent characterises can be found in published literature[14-25]. Advanced AD cycle and its hybrid detail can be found in published articles [26-33].

We conduct a simulation of exploiting the latent of condenser of AD cycle. The simulation is conducted on a FORTRAN platform using the international math and state libraries (IMSL) along with the steam-water properties as a function of the pressure and temperature of seawater. A list of the governing differential equations is provided in the ESI. At 47°C heat source temperature, a total of 8 MED stages can be inserted to attain a bottom brine temperature of about 4°C. Figure 7 shows the temperature profiles of all stages. The simulation is in good agreement when compared with experiments: The inter-stage temperature differential is within the same magnitude of experiments of 4° to 5°K. It is also noted that the oscillations, induced by the AD cycle batch operation and connected to the bottom brine stage, diminishes at the higher stages. Figure 8 indicates the respective water production rates of MEAD cycle and the total average production rate is 5.5 LPM.

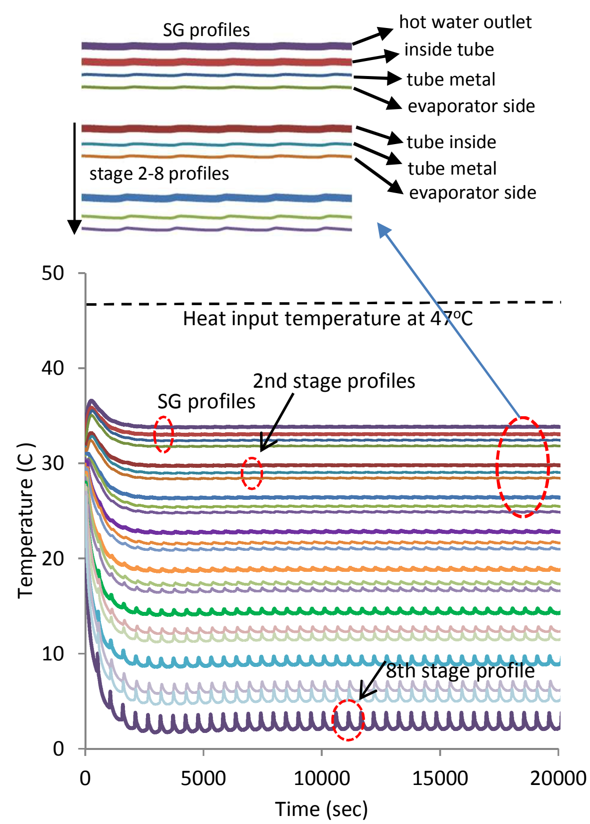

Figure 7: A projected 8-stages MEAD temperature profiles for a full exploitation of the recovered energy of condenser.

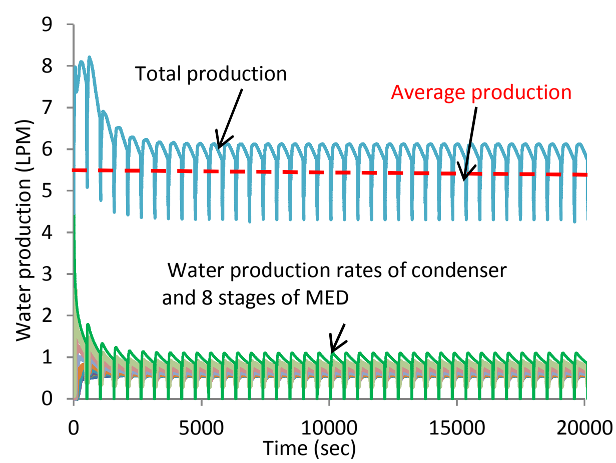

Figure 8: Water production profiles of MEAD by exploiting the total recovered latent energy of condenser.

The comparison between the basic AD, the 3-stage ME-AD experiments and the simulated 8-stage MEAD are summarized in Table 2: Three parameters are presented, namely, the water production (in LPM), power input (in kW) and the performance ratio (PR). The PR is defined here as the energy of the distillate produced to the power input [34].

The simulation demonstrates the maximum possible number of MED stages powered solely by using the recovered heat of condenser at 47°C. The kudos effect of thermodynamic synergies in between the stages and the AD cycle have yielded a high water production and hence the performance ratio. A sustainable solution for seawater desalination using the highly-efficient MEAD cycle is achievable and it can address the key issues of water-energy-environment nexus.

Table 2: Comparison of the conventional AD and the hybrid MEAD cycle performance.

Type of pilot plant	Average water production (LPM)	Energy input (kW_th)	PR = $\frac{(\sum_1^m m_d)2350}{Q_{in}}$
Basic AD Cycle	0.56	42 ±0.5	0.52±0.05
ME-AD (3 stage-Experiment)	1.15	45.0 ± 0.5	1.0±0.05
MEAD (simulation at 8 stages)	5.5	45.0 ± 0.5	4.8±0.05

Conclusions

We have successfully demonstrated the efficacy of a hybrid MEAD desalination cycle that can be operated with a low temperature waste heat or renewable energy source. The experiments confirmed the efficacy of thermodynamic synergy between AD and MED cycles. At the same heat source input, the simulation indicates that a maximum PR of 4.8 can be reached. These investigations demonstrate the kudos of innovative technology for a cost-competitive and sustainable desalination of seawater.

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Nomenclature

MED Multi-effect desalination
AD Adsorption desalination
RO Reverse osmosis
MSF Multi stage flash
PR Performance ratio
GCC Gulf Cooperation Council
GDP Gross national product
PP Power plant
KACST King Abdul-Aziz City of Science and Technology
MJC Multi junction cell
CPV Concentrated photo-voltaic
ΔT Temperature differential
SG Steam generator
LPM Litre per minute
KWh Kilo-watt hour
mg/l Milligram per litre
$\dot{m}$ Mass flow rate
Cp Specific heat capacity
h Enthalpy/heat transfer coefficient
A Area of heat transfer
T Temperature
Q Heat input
X Brine concentration
d Tube diameter
K Conductivity
Nu Nusselt number
Re Reynold number
Pr Prandtl number
R Tube wall resistance
L Tube length
U Overall heat transfer coefficient
h_{fg} Latent heat
q Adsorbent uptake
t Time
μ Viscosity
ρ Density
S Feed water salinity
S_o Reference salinity (30000ppm)
v Vapor specific volume (v_{ref} =52.65m3/kg at 295K)
ΔT Temperature difference

Subscripts

hw Hot water
in Inside/tube side
v Vapor/gas
out Outside/ vapor space
f Liquid/feed
g Gas
b Brine
HX Heat exchanger
sat Saturation
ref Reference
$cond$ Condenser
ads Adsorption

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