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Pressure Driven Adsorption Cycle Integrated with Thermal Desalination

Muhammad Wakil Shahzad[1*], Doskhan Ybyraiymkul[2], Qian Chen[2], Muhammad Burhan[2], M Kumja[2], Kim Choon Ng[2], Martin Birkett[1], Huijuan Feng[1], Muhammad Ahmad Jamil[1] , Nida Imtiaz[1,3] and Ben Bin Xu[1*]

[1]Department of Mechanical & Construction Engineering, Northumbria University, Newcastle Upon Tyne NE1 8ST, UK
[2]Water Desalination & Reuse Center, King Abdullah University of Science & Technology, Saudi Arabia
[3]School of Mechanical Engineering, Universiti Teknologi Malaysia, 80990, Johor Bahru, Malaysia

[*]Corresponding authors: muhammad.w.shahzad@northumbria.ac.uk ; ben.xu@northumbria.ac.uk

Abstract

The canned food market is growing at an annually average rate of 3.6% due to easy access and awareness of dietary requirements, leading to a surge in water withdrawal and an estimated supply-demand gap of 40% by 2030. The conventional desalination processes are not sustainable due to high energy requirements and chemicals injection. The adsorption cycle is an emerging technology for desalination due to its temperature operation. It has many advantages over conventional desalination processes including integration synergy to improve overall performance. The conventional AD cycle processes, however, have lower performance due to inefficient packing of adsorbent in the beds and heat transfer losses to their massive heat exchangers. In this article, we propose an innovative pressure driven adsorption (PDAD) cycle to overcome conventional AD cycle limitations. In PDAD, firstly, low pressure steam is used to regenerate the adsorbent which eliminates the huge infrastructure requirement of water circulation and secondly, steam selectively extracts water vapours from pores, reducing energy consumption. We have tested the PDAD pilot and showed successful regeneration of silica gel at motive steam pressure of 2-5 bar. We also demonstrate that discharge steam from the PDAD at 65°C can be used as a heat source for a multi effect desalination system when operating in hybrid mode to overcome its operational limitations. Our experiments show that the MED+PDAD cycle increases water production by up to 22% as compared to an earlier hybrid MEDAD cycle. The proposed system has excellent thermodynamic synergy with the combined CCGT power and desalination plant, where low-pressure bleed steam can be utilized more efficiently.

Keywords: Pressure driven AD cycle, hybrid desalination, sustainable water supplies, solar desalination, multi effect desalination.

1. Introduction

Presently, over 4.5 billion people around the world are affected by water shortage and severe drought. During last two decades, freshwater availability per capita has plunged by 20% due to climate breakdown, growing population, industrialization, better life style and inefficient water management and distribution [1]. In addition, over 85% of all diseases and 30% deaths worldwide are caused by poor water quality [2]. The United Nations (UN) sustainable development goals need more efforts to manage resources equitably around the world. Recent urbanization and healthy diet trends promote a requirement for water-intensive food, as shown in Table 1, which make water resources even more crucial [3]. The processed canned food market is growing at a CAGR 3.6% due to easy preparation and consumption coupled with awareness of plastic packaging ills and sustainable recycling solutions. However, the processing of canned food needs more water as compared to simple fresh food and it has a severe impact on the food-water nexus [4].

Table 1: Water footprint of food & drink items [3]

Food item	Quantity	Water consumption in litres
Chocolate	1 kg	24,000
Beef	1 kg	15,500
Lamb	1 kg	10,412
Pork	1 kg	4,800
Butter	1 kg	5,553
Chicken	1 kg	2,900
Cheese	1 kg	3,178
Olives	1 kg	3,025
Rice	1 kg	2,497
Pasta (dry)	1 kg	1,849
Bread	1 kg	1,608
Pizza	1 unit	1,239
Apple	1 kg	822
Banana	1 kg	790
Potatoes	1 kg	287
Milk	250ml	200
Cabbage	1 kg	237
Tomato	1 kg	214
Egg	1	135
Wine	250ml	109
Beer	250ml	74
Tea	250 ml	27

Current, development activities are boosting the annual water withdrawal up to 4,500 billion cubic meter (bcm) and it is expected to surge to 6900 bcm by 2030, creating a 40% supply-demand gap. This global figure is a aggregation of a large number of regional gaps, some of which are in a significantly worse situation than others [5]. Desalination processes appear to be the most feasible and practical solution to bridge this water supply-demand gap. However, the conventional technologies such as reverse osmosis (RO), multi effect distillation (MED) and multi stage flash (MSF) are not sustainable due to high energy demand. [6]. The also require extensive chemicals those create marine pollution [7]. Extensive literature is available on

Presently, over 19,000 desalination plants are operating in 158 countries worldwide to produce 38 bcm per year, as shown in Figure 1 [8]. These energy intensive and non-eco-friendly desalination plants are currently consuming 75.3 TWh of electricity and contribute 76.2 million tons (Mt) of CO_2 per year [9].

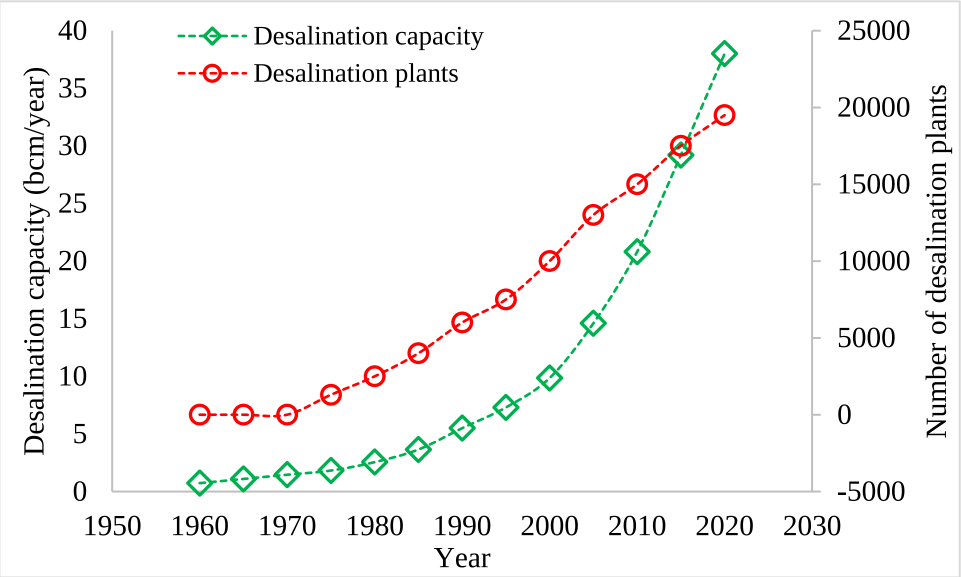

Figure 1: Global desalination capacity and number of plants

For future sustainable water supplies, three solutions have been proposed. Firstly, new and efficient processes such as membrane distillation (MD) [10] and its improvement [11] forward osmosis (FO) [12] and its advancements [13], humidification dehumidification (HDH) [14] and ultra/nano filtration (UF/NF/IF)[15,16]. These emerging technologies are still at the R&D stage and require more time for reasonable size pilot demonstration to attract investor and utilities operators. Secondly, hybridization of processes to improve overall performance due to processes synergy. For example, commercial processes hybridization such as MSF+MED [17] and RO+MSF [18] and their optimization for energy savings [19]. These hybrids successfully tested and showed great improvement in terms of energy efficiency and CO_2 reduction [20]. Lastly, renewable energy application for desalination processes. In this case it can be either electricity generation (from solar PV or wind) to operate RO processes or direct thermal energy (solar thermal or geothermal) application to power MED and MSF processes. The latter solution is more feasible due to higher efficiency as compared to electricity production. The solar evacuated tube collectors showed 60-70% conversion efficiency [21] and flat plat collectors also showed good conversion performance [22] compared to 15-20% practical PV panels [23]. Based on the above arguments, it can be concluded that solar thermal desalination processes can be one of the most sustainable solutions for future water supplies. In cogeneration power plants, where power and water are produced simultaneously, thermal desalination processes have excellent capabilities to operate with low pressure bleed steam, improving the overall performance of plant.

Extensive literature is available on MED theoretical modelling [24] and economic analysis [25]. However, recently, the adsorption (AD) cycle has emerged as a low-cost seawater desalination process [26] and has ability to operate with different configurations [27]. In addition to its low temperature heat requirement (55-85°C), it has the ability to achieve over 85% recovery due to sub-ambient evaporator operation. Moreover, its hybridization synergy makes it a leading technology for future water supplies. In this article, we present an innovative pressure driven AD cycle (PDAD) and their hybridization with commercial MED processes to overcome its operational limitations. Three pilot demonstrations show that the proposed hybridization can achieve a thermodynamic efficiency of 20% as compared to 10-13% for conventional RO, MED and MSF processes.

2. Conventional Adsorption Cycle Operation

The conventional heat driven adsorption (AD) cycle consists of four major components, namely; (i) evaporator, (ii) condenser, (iii) adsorbent beds and (iv) auxiliary system for heat supply. The AD cycle operates in a cyclic manner, adsorption and desorption of the adsorbent beds. For a continuous operation, it is always designed with a pair of adsorbent beds in which one bed undergoes the adsorption process and the second bed performs the desorption process, and after a specific time they switch their duties to continue the cycle. The adsorber bed receives the vapour from the evaporator and the desorber bed transfers the regenerated vapours to the condenser for condensation. The heat of regeneration is supplied from evacuated tube solar thermal collectors and the heat of adsorption is recovered by circulating cooling water through the adsorbent bed heat exchanger. The system can be used as an AD chiller or a desalination machine and the output can be easily switched from condenser to evaporator by only one recirculation valve operation. The conventional AD cycle has many advantages such as (i) low maintenance due to no moving parts, (ii) compatibility with solar energy or low grade heat because of low temperature operation, 55-85°C, (iii) robust and reliable operation and (iv) high quality water production, total dissolved solids (TDS) <50ppm [27].

In this work we have designed, fabricated, installed, commissioned and tested an AD cycle to evaluate its performance at assorted operating conditions. It is designed as a 4-bed system and silica gel is packed in the form of cake in each bed. The AD cycle is designed to operate with rooftop mounted solar thermal evacuated tube collectors of 352m^2 area with an external radiator (100kW capacity) to ensure safe operation of the collectors, especially in summer. This radiator helps to reject the heat to ambient if the temperature increases from the set limit of plant operation. The evacuated tube collectors and AD pilot installed at King Abdullah University of Science and Technology (KAUST), Saudi Arabia is shown in Figure 2.

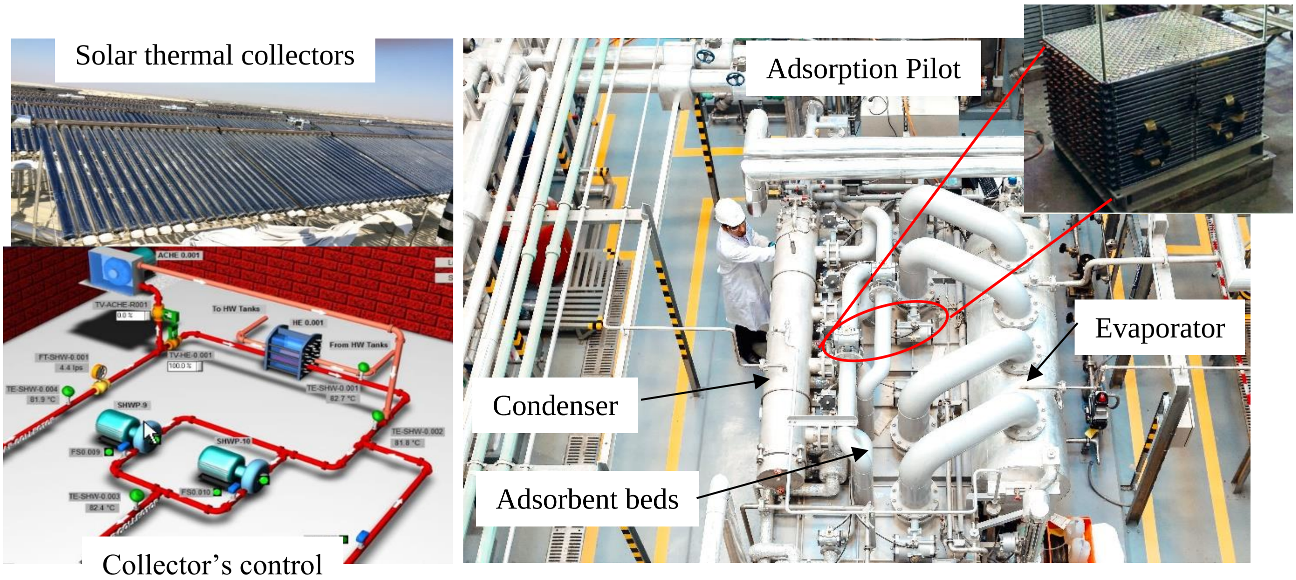

Figure 2: Solar driven AD pilot at KAUST

Detailed experiments were conducted at assorted operational parameters (T &P) to evaluate the specific cooling capacity and coefficient of performance of the AD cycle. The temporal profiles of all component temperatures are shown in Figure 3. It can be noticed that the evaporator temperature is maintained at 10°C by supplying building cooling load. The AD cycle evaporator can be operated at any temperature depending on cooling application requirements. This specific experiment was conducted at a heat source temperature of 85°C and condenser cooling water temperature of 25°C. The half cycle time was maintained at 300 seconds.

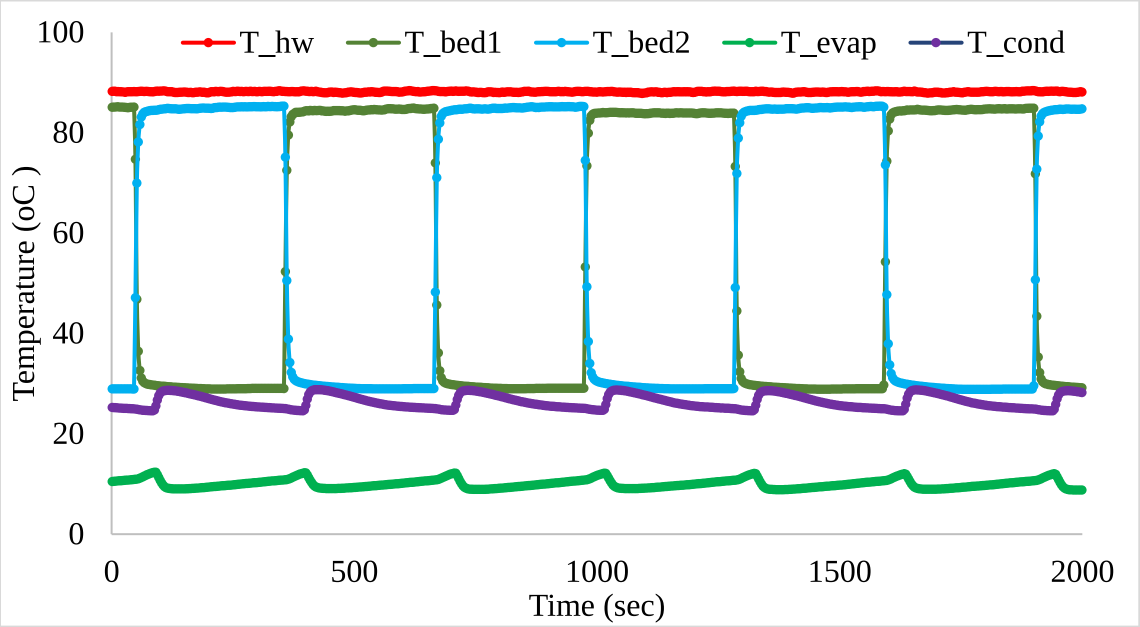

Figure 3: Temperature profiles of AD beds, evaporator and condenser.

Evacuated tube collectors heat source temperature and AD pilot cooling capacity variation during a whole day is presented in Figure 4. The coefficient of performance was calculated from 0.43 at a chilled water temperature of 7°C to 0.5 at a chilled water temperature of 20°C.

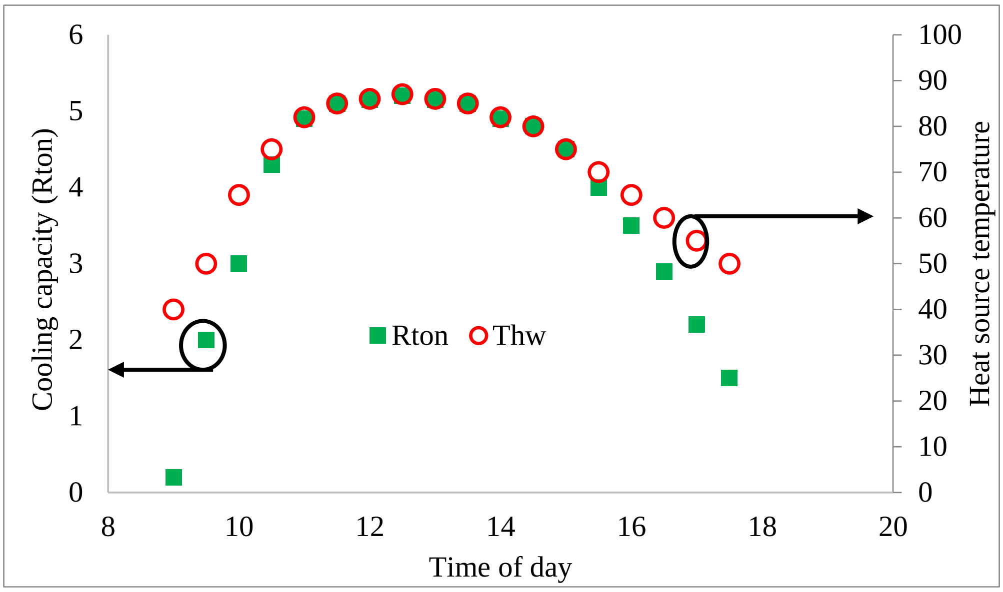

Figure 4. Full day trend of 352 m^2 of evacuated tube collectors and effect of hot water temperature on cooling capacity.

After successful demonstration of the solar driven AD cycle, we attempted to integrate it with a Multi Effect Desalination (MED) system. The MED method is known for its robustness and yet low operating cost. However, its operation is constrained by two practical temperature limits namely, top-brine temperature (TBT) of 65^{o}C due to the fear of salts scaling from ions such as Ca^{2+}, Mg^{2+}, SO_4^{2-} etc., and the bottom-brine temperature (BBT) that is restricted by heat rejection to the ambient, as well as the temperature difference required for a finite heat transfer rate. Consequently, the allowable stages are usually designed to a mean temperature difference of 5 to 6 °C. Given these operating limits, the possible number of effects are 6 to8 and consequently, the water production rate per unit heat input is constrained. The AD cycle integration enables the MED to overcome the bottom brine temperature limitation by bypassing the seawater cooled condenser. We have successfully demonstrated the hybrid MED+AD cycle operation from 65^{o}C to as low as 7^{o}C, doubling the number of effects and hence water production. The hybrid MEDAD pilot was build and tested to show thermodynamic synergy of the two thermally driven cycles. The overall water production was boosted over two-fold for a fixed top brine temperature, as compared to the conventional MED cycle. The detailed experimentation of the hybrid MEDAD was published early by the authors [28]. They also presented detailed exergetic analysis [29] and theoretical simulation [30] of hybrid desalination cycle as summarised in Table 2.

Table 2: Theoretical modelling of hybrid MEDAD cycle

Evaporator energy balance $[(M_b.Cp_{Tb}) + (M_{HX}.Cp_{HX})]\frac{dT_1}{dt} = \left(\dot{m}_f h_{f,Tf}\right) - \left(\dot{m}_b h_{f,Tb}\right) - \left(\dot{m}_v h_{g,Tv}\right) + Q_{in}$
Heat source outlet temperature $T_{hw,out} = T_v + \left(T_{hw,in} - T_v\right) exp\left\{\frac{U_1 A_1}{\dot{m}_{hw} Cp_{hw}}\right\}$
Material balance $M_b \frac{dX_b}{dt} = \left(\dot{m}_f X_f\right) + \left(\dot{m}_b X_b\right) - \left(\dot{m}_v X_v\right)$
Heat transfer coefficient $U_i A_i = \frac{1}{\frac{1}{h_{in,i} A_{in,i}} + R_{wall,i} + \frac{1}{h_{out,i} A_{out,i}}}$ $Nu = \frac{h_{in,i} d_{in,i}}{K_{tube,i}} = 0.023\, Re_l^{0.80}\, Pr_l^{0.40}$ $R_{wall,i} = \frac{ln\left(\frac{d_{out,i}}{d_{in,i}}\right)}{2.\pi.K_{tube,i}.L_{tube,i}}$
MED stage linked with AD cycle $\left[\left(M_{b,n}.Cp_b\right) + \left(M_{HX,n}.Cp_{HX,n}\right)\right]\frac{dT_n}{dt} = \left(\dot{m}_{f,n} h_{f,Tf}\right) - \left(\dot{m}_{b,n} h_{f,Tb}\right) - \left(M_{sg} h_{g,Tv}\right)\frac{dq_{ads}}{dt} + Q_{in,n}$
Adsorption cycle uptake $\frac{dq}{dt} = \frac{15 D_{so}\, exp\left(\frac{-E_a}{RT}\right)}{R_P^2}(q^* - q)$

$q^* = \frac{k_0\, exp\{\Delta H_{ads}/(RT)\}\, P}{\left[1+\left\{\frac{k_0}{q_\infty}\, exp\{\Delta H_{ads}/(RT)\}\, P\right\}^t\right]^{1/t}}$
Beds energy balance $\left(M_{sg}C_{P,sg}+M_{HX}C_{P,HX}\right)\frac{dT_{ads}}{dt} = \Delta H_{ads}(T_{ads},P_{ads}).M_{sg}\frac{dq_{ads}}{dt} + \dot{m}_{cw}C_{P_{cw}}(T_{ads},P_{ads})\left(T_{cw,in}-T_{cw,out}\right)$ $\left(M_{sg}C_{P,sg}+M_{HX}C_{P,HX}\right)\frac{dT_{des}}{dt} = -\Delta H_{des}(T_{des},P_{des}).M_{sg}\frac{dq_{des}}{dt} + \dot{m}_{hw}C_{P_{hw}}(T_{des},P_{des})\left(T_{hw,in}-T_{hw,out}\right)$

Overall, it is concluded that this hybrid MEDAD cycle is an excellent approach if heat is supplied from solar, geothermal or industrial waste heat processes. In cogeneration plant settings where power and water are produced simultaneously, usually steam is available at 3 to 5 bars, tapped from the last stage of the low pressure steam turbine. In conventional processes, this steam is throttled down to 65^{o}C to operate MED systems. The exergy destruction across the throttling valve also charged to the MED and that makes it energy intensive process. In the next section we propose an innovative pressure driven adsorption cycle (PDAD) that can be integrated with an MED cycle to improve overall system performance in cogeneration arrangement. In this hybrid MED+PDAD cycle, the bleed steam at 3 to5 bar can be effectively used for adsorbent regeneration instead of throttling, before introducing it into the MED steam generator at 60 to 65^{o}C. The proposed cycle will not only utilize bleed steam more efficiently but also help to overcome bottom brine temperature limitations of conventional MED cycles by extracting vapours and bypassing the condenser. Full details of the PDAD and hybrid cycle are provided in following sections.

3. Pressure Driven AD cycle (PDAD)

The pressure driven adsorption cycle is an innovative process for adsorbent regeneration using low pressure steam, unlike the thermally driven conventional AD cycle. Figure 5 shows the flow schematic of the PDAD cycle. The working steam is produced by an electric boiler to simulate the bleed steam conditions in a practical cogeneration power plant. The working steam is supplied to a thermal vapour compressor (TVC) to achieve the desired low pressure at its throat. The secondary intake of the TVC is connected to the adsorbent beds that draw water vapour from the silica gel pores. It has many advantages over conventional thermally driven AD cycles such as; (i) smaller overall footprint, (ii) eliminates heating and cooling water circulation infrastructure, (iii) reduces bed mass and hence reduces substantial heating requirement (iv) eliminates heat exchanger requirement for adsorbent packing, silica gel can be dumped in a tank and (v) low capital and operating expenditure.

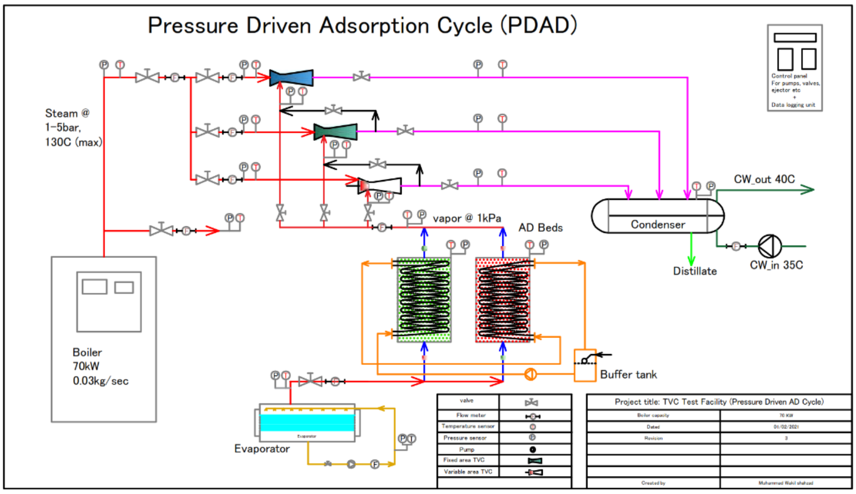

Figure 5: Schematic of pressure driven adsorption cycle.

The system can be designed with multi TVCs to achieve desorption and recompression conditions and process optimization. In 3 TVC system, in parallel operation, higher desorption rate can be achieved. On the other hand, if they operate in series, lower pressure can be achieved at the throat of the last TVC for a fast desorption process. So, the operational scheme of TVCs depends on the specific facility requirements. In a practical system, the bleed steam from 3 to 5 bars of pressure will be used for adsorbent regeneration in the PDAD cycle and recompressed steam after the TVC will be supplied to a multi effect desalination system as a heat source.

4. PDAD Pilot and Experimentation

A pilot test facility was designed, fabricated and built at KAUST to evaluate the performance of the PDAD cycle. The PDAD pilot deign is based on the schematic presented in Figure 5, with 3 TVCs and primary steam produced by an electric boiler. The system is fully instrumented to observe operation and to calculate performance. The pilot facility is presented in Figure 6.

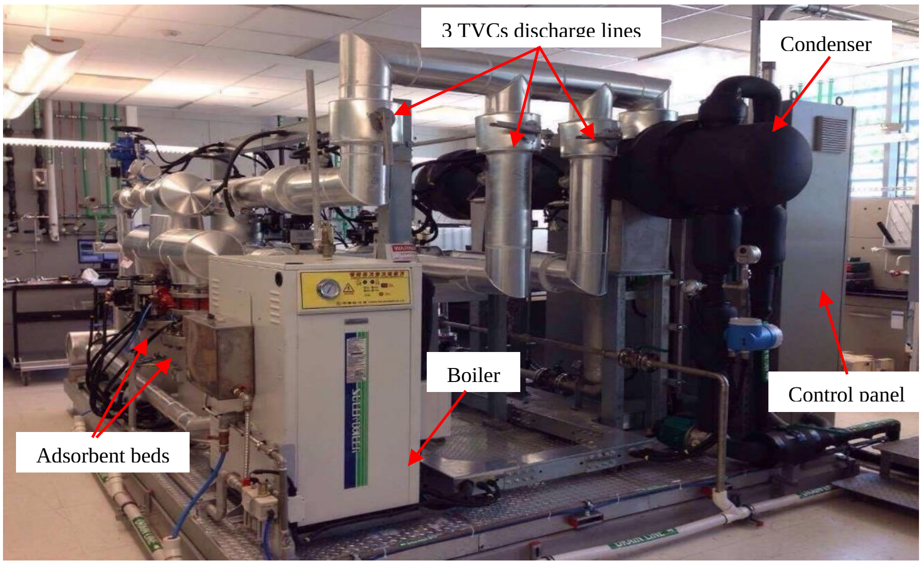

Figure 6: Pressure driven adsorption cycle pilot facility at KAUST.

The first pilot facility experiment was conducted at a steam temperature 130°C (2 bar) and temperature profiles of assorted components are presented in Figure 7. It can be seen clearly that TVC recompression steam temperature is 65°C and it can be used as a heat source for the MED steam generator. The entrainment ratio was measured as 0.45 and clearly demonstrates successful proof of concept of the PDAD cycle operating with low pressure steam.

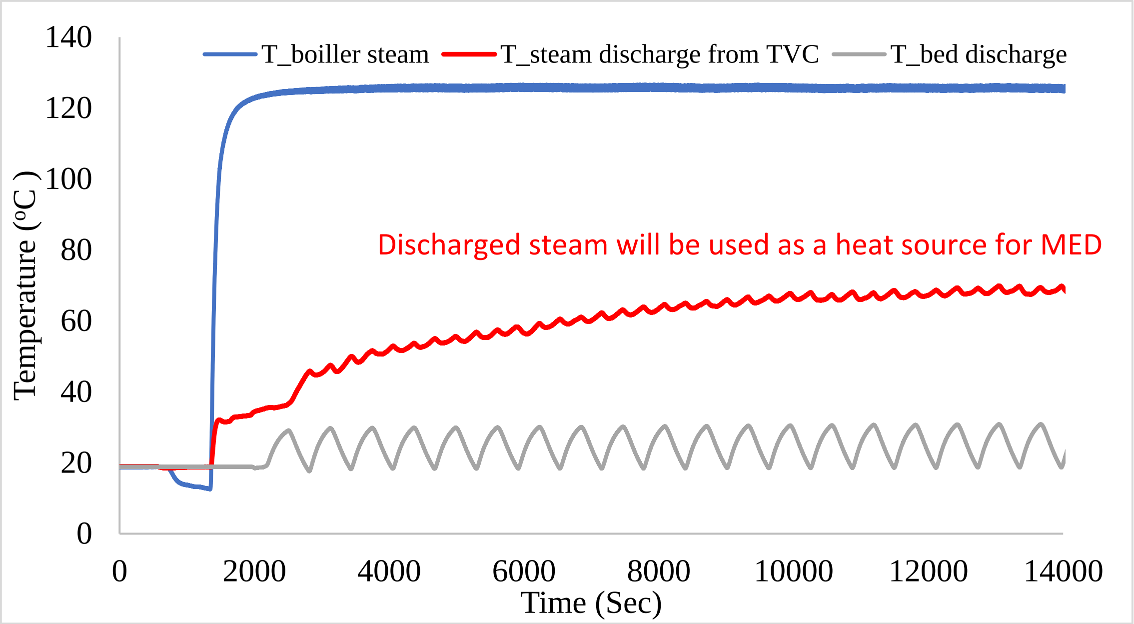

Figure 7: Temperature profiles of motive steam, discharge steam, and bed of the PDAD cycle.

Experiments were continued to evaluate the performance of the PDAD cycle at assorted motive steam pressures. The discharge steam pressure varies linearly with motive steam pressure. TVC recompression achieved a 65-75°C dischareg temperaure at all motive steam conditions and shows its ability to integrate with the MED system while operating in a cogeneration arrangement.

Lastly, the experimental points were marked on the design and operation chart of the TVC to ensure its operation is within range at all motive steam pressures. Figure 8 shows that all data points for motive steam pressures of 2 to 5 bar are within operational range, which means that the PDAD pilot is performing as per design conditions. At low motive steam pressure, the entrainment ratio is lower due to relatively lower pressure differential at TVC throat. However, at higher motive steam pressure, high pressure differential at throat allow more regenerated vapor to enter and hence high entrainment ratio was observed.

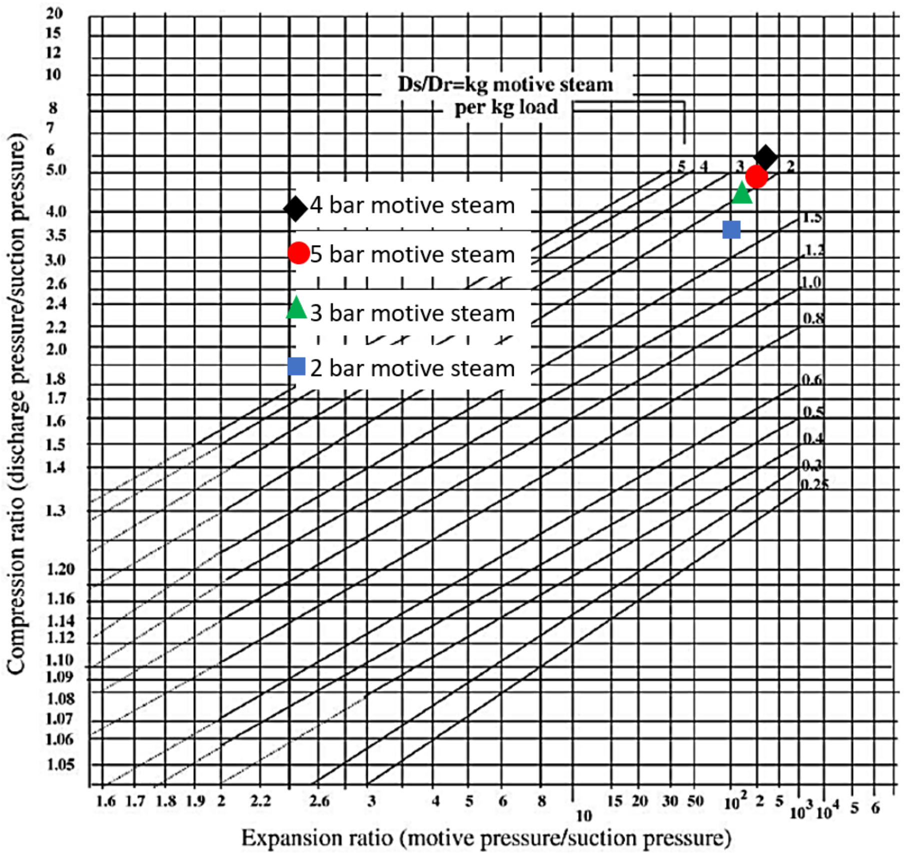

Figure 8: PDAD pilot's thermal vapor compressor operational point on design chart.

This successful pilot demonstration of PDAD cycle led to its integration with a conventional MED system to overcome its lower brine temperature limitations.

5. PDAD+MED Hybrid System

The authors proposed an innovative PDAD cycle integration with MED to achieve two major objectives; Firstly, the exergy of the low pressure bleed steam can be exploited to regenerate the saturated adsorbent of the AD cycle, which otherwise is throttled in the conventional design to supply steam at the TBT of 65°C. This has been demonstrated in section 4 where the PDAD cycle is powered with low pressure steam of 2 to 5 bar to develop less than 2 kPa pressure at the throat of the TVC for the regeneration of saturated adsorbent. Secondly, it allows more than double the number of stages of the MED and hence boosts water production by over two-fold at the same energy input due to double heat recoveries. The schematic of MED+PDAD cycle is shown in Figure 9.

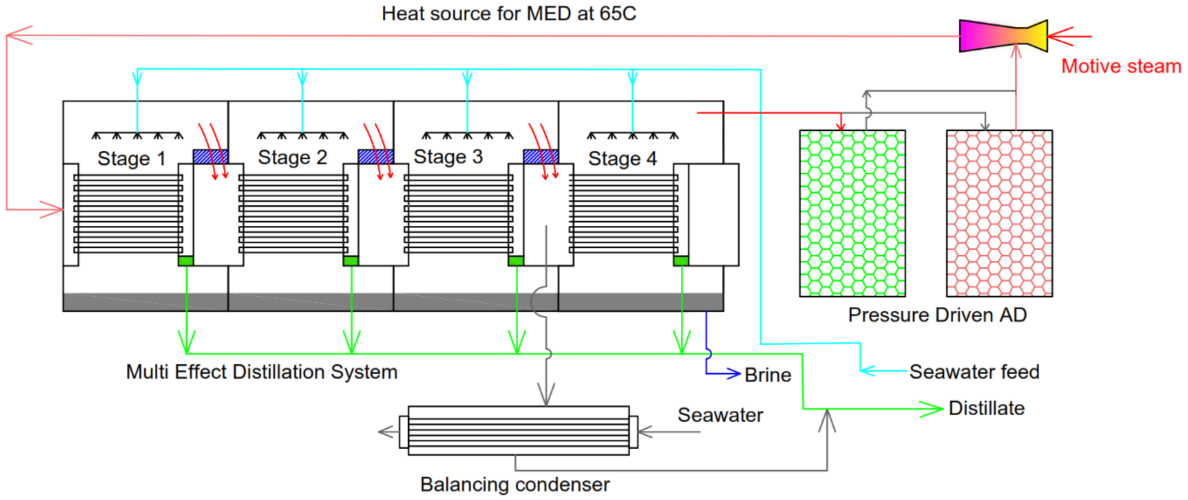

Figure 9: Hybrid MED+PDAD cycle operational schematic.

The 4-stage MED system that was tested earlier with a thermally driven AD is now integrated with the PDAD cycle to evaluate overall system performance. The experimental results of three pilots, conventional MED (4 stages), the MEDAD, and the proposed MED+PDAD are presented in Figure 10.

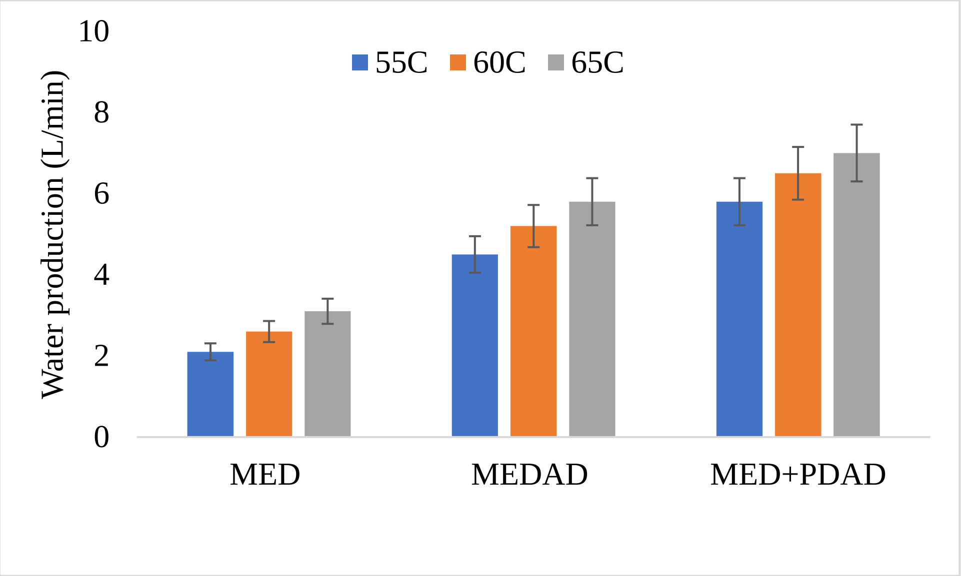

Figure 10: Summary of water production comparison of MED, hybrid MEDAD and MED+PDAD cycles at assorted heat source temperatures.

It can be clearly seen that the proposed MED+PDAD hybridization improved water production by 17 to 22% as compared to the MEDAD cycle at heat source temperatures of 55 to 65°C. This improved water production is due to better regeneration of adsorbent due to the pressure driven as compared to thermally operated AD cycle. It is also worth mentioning that only the last stage of the MED or BBT is communicating with the AD adsorbent (silica gel type RD with pore surface area > 755 m^2/g) so the size of the adsorbent beds is significantly smaller and yet it allows the MED cycle to operate far below the ambient temperature. The uncertainty bars are also drawn at 10% error.

The high degree of thermodynamic synergy embedded in these hybrid processes maintains high energy efficiency, where the increase in water production has a quantum jump vis-a-vis over the conventional MED. The overall universal performance ratio for the hybrid processes is approaching more than 20% of the thermodynamic limit as compared to 10 to13% for conventional processes [31–33].

6. Conclusion

An innovative pressure driven adsorption cycle integrated MED system has been designed, fabricated, and tested at assorted motive steam pressures. The major outcomes are:

- PDAD cycle can operate at motive steam pressures as low as 2 bar and still produce discharge steam at 65°C to operate the MED cycle in hybrid operation.
- PDAD integrated MED cycle no need additional heat input for operation, regenerated steam can initiate MED process.
- PDAD hybridization improved water production by 17 to 22% as compared to conventional AD cycle.
- The overall universal performance ratio improved to over 20% of the thermodynamic limit.

In summary the MED+PDAD hybrid system can be one of the most feasible solutions to achieve the United Nations sustainable development goals 2 and 6 to supply the worlds future food and water supplies.

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Abbreviations

AD	Adsorption
PDAD	Pressure driven adsorption
CAGR	Compound annual growth rate
SDG	Sustainable development goals
MED	Multi effect desalination
TVC	Thermal vapor compressor
MSF	Multi stage flash

RO	Reverse osmosis
BCM	Billion cubic meter
MD	Membrane distillation
HDH	Humidification and dehumidification
UF	Ultra filtration
NF	Nanofiltration
SCC	Specific cooling capacity
TBT	Top brine temperature
BBT	Bottom brine temperature

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