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An Emerging Hybrid Multi-Effect Adsorption Desalination System

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This paper presents an advanced desalination cycle called "MEDAD" desalination which is a hybrid of the traditional multi-effect distillation (MED) and the adsorption cycle (AD). The combined cycles break the operating regime of conventional MED system and allow some stages to operate below ambient temperature, as low as 5°C in contrast to the conventional MED: The MEDAD cycle results in a quantum increase of distillate production at the same top-brine condition. Being lower than the ambient temperature for the bottom stages of hybrid, ambient energy can now be scavenged by the MED processes whilst the AD cycle is powered by low temperature waste heat from exhaust or renewable sources. In this paper, we present the experiments of a 3-stage MED and MEDAD plants that were fabricated and installed in the air-conditioning laboratory of the National University of Singapore. These plants have been tested at assorted heat source temperatures ranging from 15°C to 70°C. All system states are monitored including the stages temperature and distillate production. It is observed that the synergetic matching of MEDAD cycle led to a quantum increase in distillate production, up to 2.5 to 3 folds vis-a-vis to a conventional MED of the same rating.

Keywords: Thermal Desalination, Adsorption desalination (AD), Multi-effect distillation (MED), hybrid cycles, MEDAD cycle.

1. Introduction

The supply of fresh water is an emerging critical issue faced by many nations of the World[1)], as it is limited whilst its demand continues to increase rapidly because of (i) urbanization, (ii) economic development, and (iii) improved living standards[2,3)]. In the last two decades, water withdrawal increased up to eight percent annually in developing countries due to higher population growth as well as per capita requirements[4)]. Lack of fresh water in developing countries due to (a) economy growth and (b) limited water sources likely to be the major factor limiting the development of these countries in next decades as World Bank has warned[5)].

The natural hydrological cycle extracts 505,000 km3 of renewable water from sea to land annually via rain or snow and only about 44,000 km^3 is considered accessible for normal use[6)]. The availability of fresh water per capita per year in most of the part of the World fallen from 17,000 cubic meters per person in 1950 to 7,044 cubic meters in 2000[7)]. The countries with water supply less than 1000 cubic meter per capita per year (cm/ca/y) are deemed as "water-scare" countries, whilst those below 500 cm/ca/y is considered as acute poverty level.

Table 1 shows the fresh water by renewable sources, its withdrawals and per capita availability in different regions of the World. It can be seen that other than North America, all nations are living under water scarcity and most of the countries are under acute poverty level[8)].

Table 1. Fresh water sources and per capita availability in the World.

	Renewable resources (km3/year)	Withdrawals		
		Total (km^3/year)	% of renewable resources	Per capita (m^3)
Asia	13,297	2,404	18.1	644
Africa	3,956	217	5.6	265
Europe	6,603	418	6.4	574
North America	6,253	525	8.4	1,664
Latin America	13,570	265	2	507
World	43,659	3,829	8.8	626

Recent literature on water needs of the world[9-15] has predicted an annual growth rate of 2% for potable water demand, typically from a present water demand of 4500 million m^3 per day (mcm/d) to 6900 mcm/d in 2030. By 2050, the World population is expected to be 9 billion, of which 8 billion live in developing countries. This rate of population increase alone will push most of the developing countries below acute water poverty level (UN Population Division, 2001). The available fresh water sources cannot be stretched to accommodate the high growth rate of population and economic development which makes a water crisis nearly inevitable. To prevent this projection to be happen in reality, desalination technologies need to be developed to convert seawater into fresh water to fulfill the World water demand.

Over the past three decades, the advent of desalination for supplying fresh water has led to a rapid development of commercially-reliable desalination methods, both thermally and work-driven or membrane-based processes of varying energetic efficiencies. In the past decade, the world's production capacity of RO has exceeded that of the thermal desalination processes, namely the multi-stage flashing (MSF) and the multi-effect distillation (MED)[16,17]. The key reasons for rapid increase in deployment of RO plants are (i) the high energetic efficiency of desalting at 3.5 to 5 kWhe/m^3 of water production[18-20], (ii) the portability of the RO plants and (iii) more importantly, a rapid advancement in the membrane technology via R&D efforts[21]. Although superior energetically, the RO method has some limitations that may be location related; For example, the membrane performances are susceptible to high saline feed (salinity > 43,000 ppm) in the Gulf and Red sea regions, and the surface pores of membranes are equally passable to toxins (such as neuro-, paralytic-, diarrhetic-toxins) of HAB that are carried by the water molecules when the feed are contaminated by algae blooms.

For the mentioned reasons, the dominant method of desalination in GCC countries, hitherto, is the thermally-driven methods: About 80% of the total daily 36 million m3 of production remains thermally-driven, either by the MSF or the MED processes. Other reasons for adopting thermal desalination, but mainly peculiar to the GCC countries, are (i) the desalination plants are well integrated to thermal power plants where the low enthalpy steam (lower work potential) is bled-off from work producing turbines, easing the foot-print of expanding steam and, (ii) most of the thermal power plants in GCC countries are powered by heavy crude/fuel oil; - A distillation reject from refineries which is deemed to have low commercial value other than for it to be burned in co-generation plants[22-24].

The tri-factor nexus of water, energy and environment has prompted scientists and engineers to innovate for better desalination processes that are both energetic efficient and environment friendly. In this paper, the authors present an emerging and yet energy efficient hybrid MED+AD desalination cycle. A 3-stage MED system is designed, fabricated and installed in NUS. Experiments are performed at assorted heat source temperature to investigate conventional MED system and hybrid MEDAD cycle performance. The detail of experimental facility is provided in following sections. The detail of AD cycle can be found in literature[25-40].

2. MED system design

A MED system, comprising 3-stage of evaporators, is fed with parallel feed for the seawater through an array of nozzle sprays. Spray of feed brine is introduced to the horizontally-finned tubing are known to have a better evaporation rates. A special magnetically-driven pump for vacuum application is installed to feed brine at relatively high pressures onto tube surfaces via nozzles. 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. Figure-1 & 2 shows the detail design of SG and MED effects. Falling film heat transfer coefficient is developed to design heat exchangers[41].

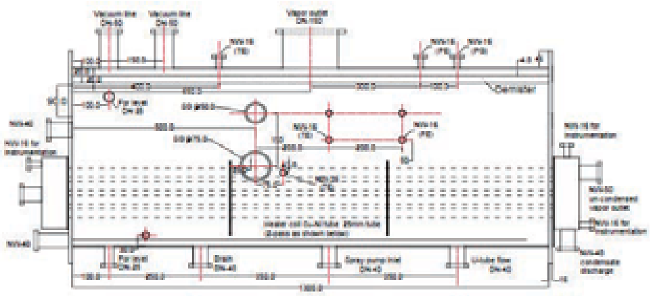

Fig. 1. Detail design of MED steam generator.

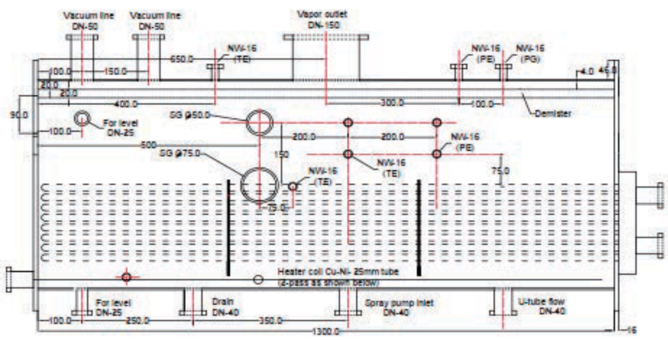

Fig. 2. Detail design of MED stage/effect.

The steam generator (SG) consists of 8-passes specially fabricated "end-crossed" tubes. The heat source circulated internally through the tubes whilst the vapor is generated from the external surface of tubes. The vapor is then condensed inside the tubes of the successive MED stages.

3. MED system operation

There are four main components of MED system namely; 1) evaporators, 2) collection tanks, 3) jet pumps and 4) circulation pumps. The operation of MED system can be subdivided into 1) feed flow, 2) vapor flow, 3) distillate flow and 4) brine flow. The schematic diagram of MED operation is shown in Figure 3 and installed setup rig is shown in Figure 4.

3.1. Feed flow

MED evaporators are parallel feed horizontal tubes evaporators. Spray nozzle header is installed in each evaporator to spray the feed on the outer surfaces of the tubes. The preheating of the feed is achieved using the preheater (U-tube bundle type) immersed in the brine pool of each effect. Thus sensible heat of the brine is recovered to preheat the feed. The feed supply to the system is attained using a vacuum-sealed feed pump that utilized magnetic-coupling.

3.2. Vapor flow

The initial vapors are produced in steam generator. Heat source is circulated through the tubes of steam generator and at the same time the brine is sprayed outside the tube through nozzles. The vapors produced due to heat transfer from hot water to brine are directed toward to the tubes side of next stage (2nd stage). These vapors are condensed inside the tubes due to heat transfer to the brine sprayed outside the tubes. The heat of condensation evaporates the outside brine and these vapors directed toward the 3rd stage and condensed inside the tubes. The vapors produced in last stage are condensed in a condenser where cooling water is supplied from cooling tower. Low pressure jet pump are introduced to pull the non-condensable from each evaporators.

3.3. Distillate flow

The U-tubes are used to collect the distillate from each stage distillate box. All U-tubes are connected to a distillate header. This header is connected to a distillate collection tank. A high accuracy turbine flow meter is installed on header to record the distillate production.

3.4. Brine flow

Although the feed is supplied parallel to all evaporators, the brine is cascaded through u-tubes to the successive stages to get the additional flash effect due to pressure difference between stages. From last stage of MED, brine is collected to a brine collection tank. The feed tank and brine tank are installed in a manner so that a small amount of brine can mix with feed depending upon salt concentration to get higher recovery ratio.

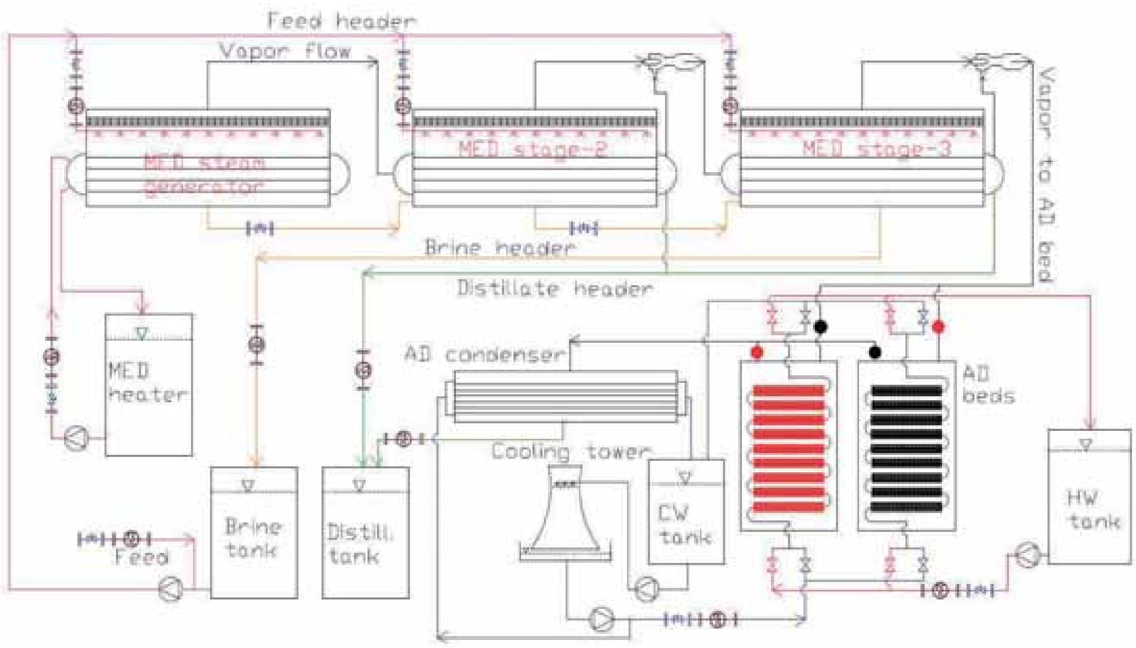

Fig 3. MEDAD system process flow schematic.

Fig. 4. MEDAD system installed in NUS.

4. Results and discussion

Experiments are conducted in two steps. In first part, system is operated as a conventional MED at assorted heat source temperature ranges from 38°C to 70°C. In second part, experiments are conducted as a hybrid MEDAD system at assorted heat source temperature ranges from 15°C to 70°C and results are compared with conventional MED system.

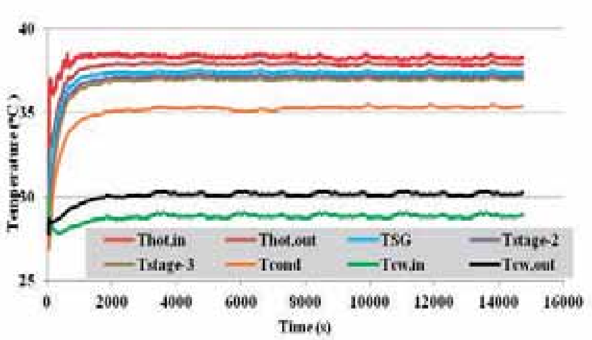

Fig. 5. MED components temperature profiles at 38°C heat source temperature.

MED components temperature profiles at heat source temperature 38°C are shown in Figure 5. Experiments were conducted for 4 to 5 hours for steady state results. It can be seen that inter stage temperature is varies 0.8-1°C. Similar trend is observed for all heat source temperatures.

MEDAD components temperature profiles at heat source temperature 38°C are shown in Figure 6. It can be seen clearly that inter stage temperature is varies 3-4°C as compared to 1°C in case of conventional MED. This higher inter stage temperature difference increase the evaporation rate and hence water production.

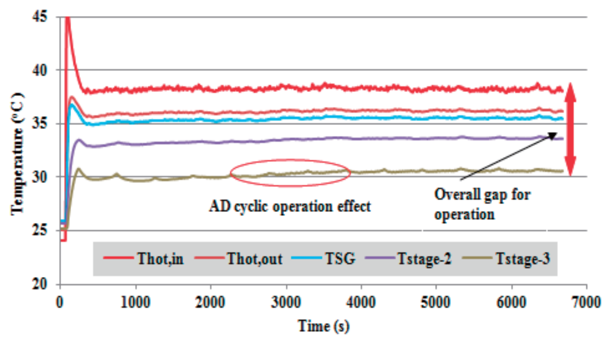

Fig. 6. MEDAD components temperature profiles at 38°C heat source temperature.

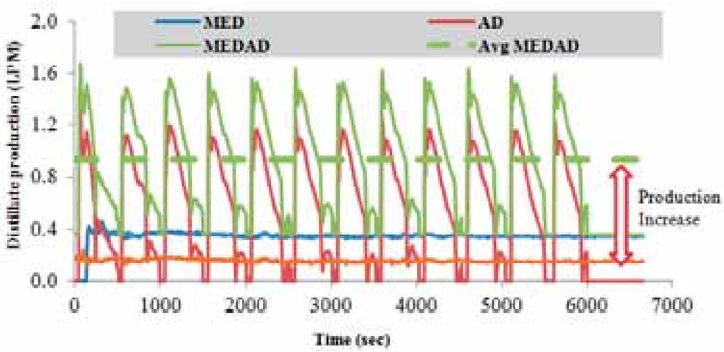

Fig. 7. Conventional MED and hybrid MEDAD cycle water production profiles at 38°C heat source temperature.

Figure 7 shows the transient water production profiles of conventional MED and MEDAD systems. The average productions are estimated and it is seen that there is quantum increase in the water production as a consequence of hybridization. This synergetic increase in water production is attributed to the higher temperature differences of the MED stages that provide a larger potential for evaporative film boiling on the tube surfaces. Should the MED stages were to be optimally designed with higher number of stages, there will be better performances expected from the combined MEDAD cycle. The merits of MEDAD hybrids are fully realized even with a 3-stage pilot plant.

Figure 8 shows the comparison of water production of MED and hybrid MEDAD cycles at assorted heat source temperatures. Quantum increase in water production (2-3 folds) can be observed at all heat source temperatures. These results have good agreement with simulation results published by Wakil et al.[42]. It can also be seen that in conventional MED system last stage temperature is limited to 38°C due to condenser operating with cooling water from cooling tower. While in the case of hybrid MEDAD, the last stage temperature can be as low as 5°C because there is no condenser and last stage is connected to AD beds for vapor adsorption. This higher overall operational gap in proposed hybrid MEDAD cycle helps to insert more number of stages (up to 19 stages) as compared to conventional MED system (about 4-6 stages). More number of stages increases the vapor condensation heat recoveries and hence the water production at same top brine temperatures.

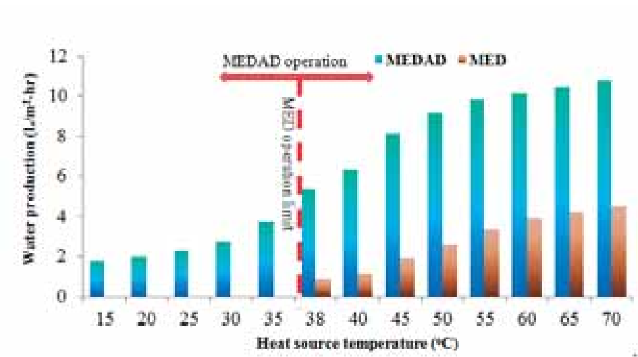

Fig. 8. MED and MEDAD steady state water production at different heat source temperatures.

5. Conclusions

A 3-stage MEDAD plant is designed and installed in NUS. In the light of the data and above discussions, the following points can be concluded:

1-MEDAD system is tested at different heat source temperatures and it is found that ΔT between the stages varies from 3 - 4°C as compared to 0.8 - 1.0°C in conventional MED system.

2-Higher inter stage temperature difference increase the evaporation rate and hence the water production from 2-3 folds as compared to conventional MED system.

3-Hybridization increases the overall operational temperature gap from 5 - 70°C as compared to 40 - 70°C in case of conventional MED system.

4- Larger operational gap helps to insert more number of stages that increase the vapor heat recoveries.

5-Ambient energy can be harnessed in last stage of MED due to below ambient temperature in case of MEDAD cycle.

6-Low grade waste heat or renewable energy can be utilized to operate the system due to lower top brine temperature (70°C).

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Abbreviation

MED	Multi Effect Distillation
AD	Adsorption Desalination
TBT	Top Brine Temperature
SG	Steam Generator
MSF	Multi Stage Flash Evaporation
TVC	Thermal Vapor Compression
RO	Reverse Osmosis
HAB	Hazards Algae Blooms

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