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Adsorption Ice making and Water Desalination System Using Metal Organic Frameworks/Water pair

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Abstract

This work describes the development of Metal Organic Frameworks based adsorption system for producing ice, cooling, ice slurry and potable water using a nickel based coordination polymer with open metal sites of organic frameworks and sea water as working pair. In this system, cooling is generated due to the evaporation of the refrigerant caused by the adsorption process. This cooling is used to produce solid pure ice, ice slurry (sea water) and chilled water. The system will also produce desalinated water from the condensation of the water vapour desorbed during the desorption process. The effect of number of cycle, switching time, adsorption/desorption time and salinity of saline water on the performance of the adsorption system in terms of coefficient of performance, specific daily production of ice, slurry mixture and fresh water were investigated. Results showed that with number of cycles, switching time, adsorption/desorption time and salinity were found as up to 3 cycles, 3 min, 15 min and 35000 ppm, the maximum ice production, 8.9 ton/day/ton_ads at generation, chilled antifreeze and ambient temperature of 95˚C, -1 ˚C and 24 ˚C, respectively.

Keywords: Adsorption; MOF; Ice making; Water Desalination.

Nomenclature

AC	Activated carbon, [-]	$SrCl_2$	Strontium chloride
$CaCl_2$	Calcium chloride [-]	T	Temperature, [K]
*C*p	Specific heat, [kJ/kg/K]	t	Time, [sec]
COP	Coefficient of Performance, [-]	**Subscript**	
CO_2	Carbon dioxide [-]	ads	Adsorption
m	mass	AF	Anti-freeze
$\dot{m}$	Mass flow rate [kg/sec]	at	Adsorption time
Q_{evap}	Refrigeration effect, [kW]	ct	Cycle time
Q_{heat}	Consumed heat power, [kW]	des	desorption
MOF	Metal Organic Framework [-]	evap	Evaporator
N	Number [-]	hct	Half cycle time
RTD	resistance temperature detectors	in	inlet
SDIP	Specific Daily Ice Production [ton/day/ton_ads]	out	outlet
SDSP	Specific Daily Ice Slurry Production [ton/day/ton_ads]	w	water
SDWP	Specific Daily Water Production [ton/day/ton_ads]		

1. Introduction

There is a growing demand for fresh water and cooling in many developing countries where access to electricity is limited [1]. The International Institution of Refrigeration (IIR) has reported that about 15% of the entire electrical power generation in the world is consumed for refrigeration and air conditioning applications. Furthermore, the World Health Organization (WHO) has reported that 884 million people have no access to fresh water and more than 2.4 billion have a limited access [2].

There are many applications for ice like preservation of medical products (vaccine), frozen food (fish, meat, vegetables), chemical engineering processes, thermal energy storage and freeze desalination [3]. The use of conventional vapor compression system cooling system for ice making consumes significant amount of electricity leading to high Carbon dioxide (CO_2) emissions. In order to reduce the demand of electricity, the heat driven cooling systems like adsorption and absorption systems are alternative cooling systems [4]. Absorption system has the advantage of higher Coefficient of Performance (COP) compared to the adsorption system [5]. However, there are many disadvantages like contamination, crystallization and corrosion [6]. Therefore, adsorption cooling technology can be used due to its advantages of stability and the use of environmentally friendly working pairs [7].

Adsorption ice making systems were experimentally and theoretically investigated by researchers using various working pairs as shown in Table (1). The majority of researchers used activated carbon as adsorbent with methanol and ammonia as refrigerants. This is due to the potential of such working pairs to achieve the cooling effect for ice making application, as the freezing point of refrigerants are lower than that of water.

Table 1 List of adsorption ice making systems

Ref.	Working pair	$m_{adsorbent}$ /$m_{refrigerant}$ [kg/kg]	SDIP [ton/day/ton_ads]	COP [-]	T_{evap} [°C]	T_{des} [°C]	Heat source
[5]	(CaCl2/AC)/Ammonia	30/_	1.66	0.15	-5	105	solar
[8]	AC/ methanol	44 / 3.23	0.16-0.227	0.452	-1	90-100	solar
[9]	AC NORIT RX3-Extra/ methanol	14/4.3	0.357-0.93	0.42	-4	108	solar
[10]	AC / methanol	20/_	0.35-0.5	0.24	-0.9	115	solar
[11]	AC / methanol	17/_	0.235-0.3	0.12	-6	78	solar
[12]	AC / methanol	22/3.3	0.46	0.38	-2.5	98	solar
[13]	AC /methanol	112/_	0.118	0.086	-11	110	Waste heat
[14]	AC/ Methanol	130/20	0.23-0.26	0.43	-3	N/A	solar
[15]	AC (MD6070)-methanol	N/A	0.6417-0.747	0.6	-3	N/A	solar
[16]	AC/ Methanol	20/_	0.26-0.35	0.12		N/A	solar
[17]	lithium chloride in silica gel pores- methanol	36/_	0.83	0.33	-6	N/A	N/A
[18]	AC–Ammonia	16.99/1.38	0.235	0.25	0	N/A	solar
[19]	$SrCl_2$ – ammonia	22/15	0.527	0.069	-15	93	solar
[20]	AC/ Methanol	19/0.4	0.37-0.473	0.15			
[21]	AC / methanol	20/_	0.2-0.3	0.11	-0.5	N/A	solar
[22]	AC/methanol	29/	0.224	0.122	-2	93	solar
[23]	Zeolite / water	16 / 4	0.3125	0.08	0	180	solar
[24]	Zeolite/Water	75.5 /_	0.09	0.8	-2.8	_	solar
[25]	AC-CaCl2/ water	N/A	N/A	0.39	-20	114	N/A
[26]	Zeolite /water	4.2/_	N/A	0.25	N/A	200-300	N/A

The table shows that the values of specific daily ice production (SDIP) ranged from 0.03 to 1.66 ton/day/ton_ads (or kg/day/kg_ads). The maximum value (1.66 ton/day/ton_ads) was experimentally achieved using compound adsorbent Calcium chloride/Active Carbon ($CaCl_2$/ AC) /Ammonia as a working pair with COP of 0.15 using a parabolic trough solar collector to supply the heat energy for the adsorption ice making system [5]. Up to now, only few studies, as shown in the Table 1, have used the zeolite-water as working pair for ice making applications using high generation temperature up to 180˚C to achieve SDIP ranging from 0.09 to 0.3125 ton/day/ton_ads and COP ranging from 0.08 to 0.8. There are many advantages of water to be used as refrigerant like, environment friendly, high latent heat of evaporation and low cost. At vacuum operating pressure, water boils at low temperature reaching freezing point of water about zero ˚C leading to formation of ice. However, the water is commonly recommended to use as refrigerant in air conditioning applications [27]. Many of researchers stated that water cannot be used for freezing application due to the restriction of its freezing point [26]. Adsorbent material is one of the main factors that affect the performance of adsorption ice making system [28]. Many solid sorbents like activated carbon (AC), Chloride strontium (SrCl2), zeolite, Metal hydride (MnCl2), consolidated composite AC, binary salt BaCl2+BaBr2, lithium chloride and compound adsorbent (CaCl2/ AC) have been used in the previously reported adsorption ice making systems (see table 1). The advantage of the stated adsorbents is the high stability; however, there is a drawback in terms of low refrigerant adsorption capabilities, thus affecting the performance of adsorption ice making system in terms of SDIP.

Metal Organic Frameworks (MOFs) are new type of solid sorbent materials, which have high pore volume, high surface area, uniform pore size and robustly tunable structural properties. The MOF materials have been already tested for gas storage, gas separation, sensors catalysis automotive air conditioning, water adsorption applications [28]. Other applications including thermal energy storage, low temperature cooling and water desalination were investigated using the MOF materials [29]. Some researchers have experimentally and numerically investigated a nickel based coordination polymer with open metal sites of organic frameworks (CPO-27(Ni)) with water to use for adsorption desalination application or thermal storage application. They highlighted that CPO-27(Ni) has an advantages in terms of SDWP at low evaporation temperature up to 5˚C compared to other MOFs [30].

Ice slurry is used in many applications like refrigeration systems, food industry and freezing desalination at different temperatures from -5 to -35 ^{0}C with refrigerants used are either organic or non-organic refrigerants like 1,1-Dichloro-1-fluoroethane (R141b) [31]. Regarding the freeze desalination, many researchers used sea water to produce a mixture of ice slurry and brine, then, this mixture is processed through separation and

filter/washing stage to remove any saline solution to obtain potable water [31]. A significant amount of energy was consumed in the cooling and separating processes based on conventional method [32].

Current desalination techniques are: Reverse Osmosis (RO), multi stage flash distillation (MSF) and multi effect distillation [30]. The RO is the most efficient technique in terms of energy consumption but suffer from contamination of chloride, bromide and boron, high maintenance cost and limited validity of membrane life [2]. In addition, the only outcome of such technologies is fresh water and no cooling can be achieved [33]. Adsorption desalination system offers the potential of producing distilled water and cooling as two useful outputs [34] using the same heat source. The sea water is the main refrigerant while silica gel and zeolite are the commonly used adsorbents materials in the adsorption desalination system [34].

In the above literature, the adsorption technique was used for either ice making or desalination and cooling purposes and there is no reported work that combines ice making with desalination and cooling. In addition, there is no published work on using water or saline water as refrigerant in the production of ice, ice slurry or freeze desalination applications. This paper experimentally investigates a new technique (vacuum-direct freezing) of single bed adsorption system to produce four useful outputs; ice, cooling, ice slurry and distilled water using both tap and sea water as refrigerants with CPO-27Ni Metal Organic Framework adsorbent material. In order to find the optimum performance of the adsorption ice making-water desalination, four parameters are investigated, namely, number of cycles, switching time, adsorption - desorption time and salinity effect. The outputs of this system are evaluated in terms of specific daily production of solid ice (SDIP), slurry (SDSP) and fresh water (SDWP), as well as the coefficient of performance based on cooling (COP).

2. Vacuum Direct Freezing

The main difference between this approach and the conventional adsorption cooling system is the production of multi-outputs like ice, ice slurry (flake) and cooling effect compared to the production of only cooling in the conventional system. This is achieved through using the seawater as the main refrigerant in the evaporator and pure water cups for ice production in addition to the cooling coil. Therefore, when adsorption process occurs, evaporation of the pure water in the cups will lead to freezing producing solid ice while the saline water will crystalize producing ice slurry. At the same time, the chilled fluid passing through the coil receives cooling effect. The crystallization phenomenon of solid ice occurs due to the vacuum operating conditions produced by adsorption process during a certain period until the upper surface of fresh water will be frozen. The crystallization phenomenon continues according to the heat transfer with the saline water through the wall's

cups. An external load was applied in the evaporator by circulating antifreeze through the evaporator's coil to be cooled down. The coil was immersed in the refrigerant liquid where a heat transfer will be achieved and the cooling effect of the antifreeze will be produced as a third output.

3. Description of the Test Facility

Fig. 1 and 2 show pictorial and schematic diagrams of the experimental test facility for the adsorption system consisting of adsorber bed, condenser and evaporator. The adsorber bed consists of steel cylinder and pair of finned tube heat exchangers in which 670 grams of CPO-27 (Ni) is packed in the spaces between the fins. Metal mesh was used to cover the heat exchangers to keep the adsorbent material between the fins. The adsorber was connected to heating and cooling systems (liquid side) through four solenoid valves to automatically control the flow direction of water. Two shell and coil heat exchangers were made to work as the condenser and evaporator for the system. The shells are provided with transparent lids to view the condensation and evaporation-freezing processes in which the fresh water and ice, ice slurry could be collected from the condenser and evaporator, respectively. The condenser is cooled using mains water, while the evaporator is heated by circulating chilled antifreeze-water mixture with solenoid valves used to control flow direction of the main water and chilled antifreeze-water mixture, respectively. The solenoid valves are controlled using a control board, which is connected to a computer and controlled using LabView.

Many measuring instruments are fixed in the test facility for measuring the temperatures, flow rate and pressures. Five thermocouples (type T) with an accuracy of ±0.5˚C are fitted on the adsorber bed to measure the adsorbent temperature at different positions. The inlet and outlet temperatures of hot/cold water flow to the adsorber are measured using two resistance temperature detectors (RTDs) with an accuracy of ±0.3˚C. Another pair of thermocouples (type T) is fitted in the evaporator to measure the vapor and liquid temperatures of refrigerant, while the inlet and outlet temperatures of chilled antifreeze are measured using two RTDs. The condenser is provided with two thermocouples (type K) to measure the refrigerant vapor and liquid temperatures. The inlet and outlet temperatures of cooling water in the condenser were measured using two RTDs. The inlet mass flow rate of heating/cooling water to the adsorber bed is measured using FLC-H14 flow meter from Omega with the range of 0-57 LPM and accuracy of ±1LPM. The inlet mass flow rate of the chilled antifreeze is measured using EFW.0302 flowmeter from Parker with range of 2-30 LPM and accuracy of ±5%. The pressure in the adsorber bed, condenser and evaporator are measured using three pressure transducers with range of 0 to 350 mbar (absolute pressure) and an accuracy of ±0.01kPa and current output signal ranging from

four to 20 mAmp. A data taker is used to log the output signals of measuring instruments every 4 seconds, which are monitored using personal computer.

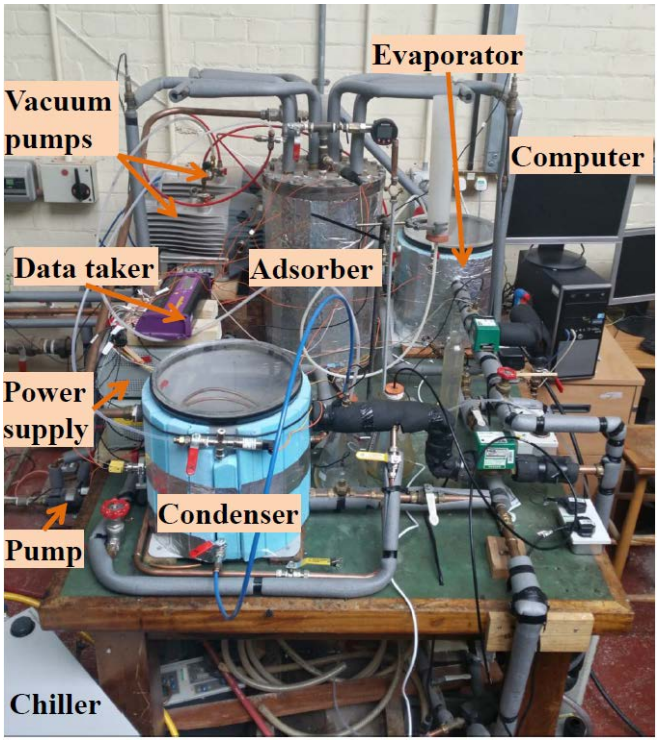

Fig. 1. Pictorial view of adsorption ice making and water desalination system

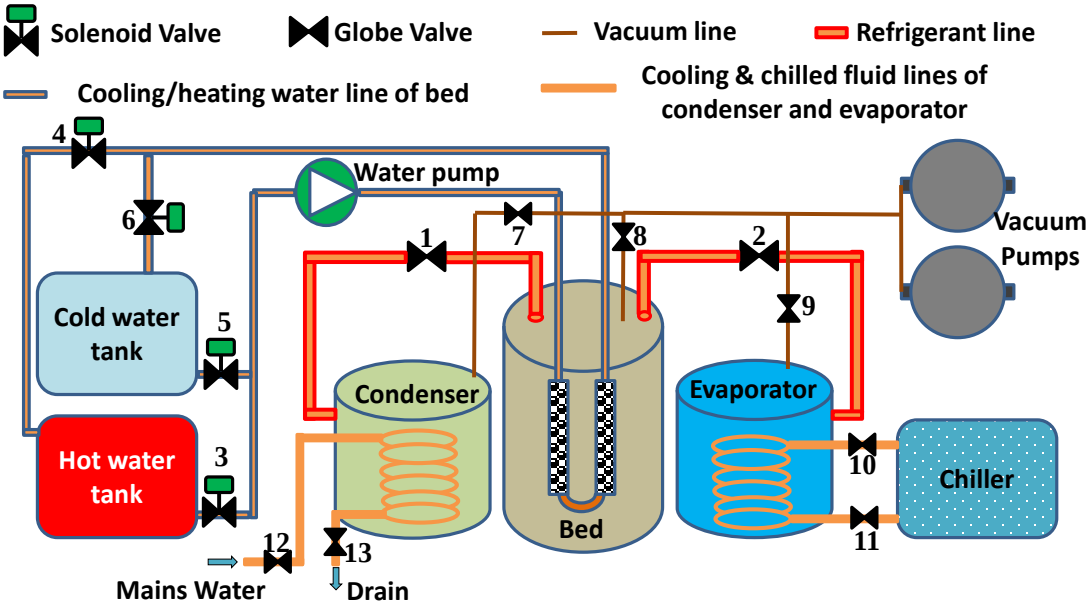

Fig. 2. The schematic diagram of adsorption ice making and water desalination system

4. Experimental Procedure

The following steps explain the practical procedure in details, including preparing and operation.

4.1 Preparing Procedures:

There are many preliminary procedures, which are required to prepare the current system before each run to be operated at same initial conditions (see Table 2) and obtained reliable results. Firstly, connect the adsorber bed to the heating water system and a vacuum pump by opening valves 3, 4 and 8, as shown in table 3, to remove any refrigerant from the adsorbent material. This task was finished when the pressure and temperature of adsrber bed reaches to certain values of 7 mbar and 85℃, respectively. Secondly, connect the condenser to the vacuum pump by opening valve 7 until the pressure and temperature in the condenser reaches to certain values of 2 mbar and 23℃, respectively. Thirdly, dissolve a required mass of a real sea salt with two liters of deionized water to obtain the required value of total dissolved solids of sea water (i.e. 35000 ppm based on 70grams of real sea salt). Fourthly, pour the two liters of sea water (as refrigerant) in the evaporator's shell for the purpose of ice slurry producing, and then immerse 16 of stainless steel cups (480 mL) [3] by filling them with fresh water for the purpose of ice making. Finally, the vacuum pumps were connected to the evaporator by opening valve 9 for a period of 5min, thus, pressure inside the evaporator reach to 6mbar based on the liquid temperature of refrigerant of 1^0C.

Table 2 Operating and initial conditions for the parametric study of the test facility.

Parameter	***Value***	***Unit***
Ambient temperature	23	˚C
Mass flow rate of heating/cooling water system	7.3	L/min
Mass flow rate of chilled anti-freeze	5	L/min
Mass flow rate of tap water in condenser	5	L/min
Specific heat of water	4.18	kJ/kg/K
Specific heat of anti-freeze	4.1	kJ/kg/K
Preparing time	8	min
Total adsorbent mass	670	gram
Average temperature of inlet tap water	15	˚C
Average temperature of inlet chilled antifreeze	-1	˚C
Average temperature of heating water	95	˚C
Average temperature of cooling water	20	˚C
Volume of sea water in evaporator	2	L

4.2 Operation Procedures

At the end of preparing procedures, the system is ready to be operated and four steps were required to run the system and obtain the results. Firstly, the evaporator and condenser were connected to the chiller and main water line by opening valves 10, 11, 12 and 13 to circulate the antifreeze and cooling water at certain temperatures, respectively. Secondly, the adsorber was connected with the cold water system (liquid side) by opening valves 5 and 6 to achieve a pre-cooling process during a required switching time. Thirdly, the adsorber was connected to the evaporator (refrigerant side) by opening valve 2 to start the adsorption process during the half cycle time, by continuing the circulation of cooling water with the adsorber to shed a heat, which is generated during the adsorption process. At the end of this task, close the valves 5, 6 and 2 to isolate the generator from the evaporator and cooling water system. Fourthly, the adsorber was connected to the heating water system (liquid side) by opening valves 3 and 4 to prepare it for a next mode which is desorption phase at the same switching time. Fifthly, the adsorber was connected with the condenser (refrigerant side) by opening valve 1 to start a desorption-condensation process during the same half cycle time of adsorption process. Finally, the solid ice and ice slurry were collected from the evaporator to calculate the specific daily production of ice (SDIP) and slurry (SDSP), respectively. In addition, the fresh (distilled) water was collected from condenser to calculate the specific daily water production (SDWP) of the system.

Table 3 Control sequence and valves operation for the test facility.

	Description	Time (min)	Valve 1	Valve 2	Valve 3	Valve 4	Valve 5	Valve 6	Valve 7	Valve 8	Valve 9	Valve 10	Valve 11	Valve 12	Valve 13
Preparing Period	Bed-vacuum pump	_	M	M	A	A	A	A	M	M	M	M	M	M	M
	Condenser-vacuum pump	_	M	M	A	A	A	A	M	M	M	M	M	M	M
	Evaporator-vacuum pump	_	M	M	A	A	A	A	M	M	M	M	M	M	M
Operation period	Switching time-precooling	3	M	M	A	A	A	A	M	M	M	M	M	M	M
	Adsorption-evaporation	16	M	M	A	A	A	A	M	M	M	M	M	M	M
	Switching time-preheating	3	M	M	A	A	A	A	M	M	M	M	M	M	M
	Desorption-condensation	16	M	M	A	A	A	A	M	M	M	M	M	M	M

A	Closed valve/Automated control (LabView)	M	Closed valve/ manually control
A	Opened valve/Automated control (LabView)	M	Opened valve/ manually control

5. SYSTEM PERFORMANCE ANALYSIS

The coefficient of performance (COP) of adsorption ice making and freeze desalination system was defined as the ratio of effective cooling capacity in the evaporator and the regeneration heat in adsorber The calculation was based on the temperatures of liquid and antifreeze side as given by,

$$COP = \frac{Q_{evap}}{Q_{heat}} \qquad (1)$$

In equation (1), Q_{evap} was the refrigeration effect during the adsorption time. Q_{heat} was the consumed heat for the preheating and desorption process. They were evaluated using equations (2) and (3) as follows,

$$Q_{evap} = \frac{\dot{m}_{AF} C_{p_{AF}}}{t_{at}} \int_0^{t_{at}} \left(T_{AF,in} - T_{AF,out}\right) dt \qquad (2)$$

$$Q_{heat} = \frac{\dot{m}_{w,hot} C_{p_{w,hot}}}{t_{hct}} \int_0^{t_{hct}} \left(T_{hot,w,in} - T_{hot,w,out}\right) dt \qquad (3)$$

The Specific Daily Ice Production (SDIP) was calculated using equation (4) based on the collected mass of solid ice from the evaporator (fresh water in the cups). The required time between two batches was taken in to account as 8 min for collecting the ice and evacuating process in task (e) of preparing procedures as follows:

$$SDIP = \frac{m_{ice,batch} \times 60 \times 24}{\left(t_{ct} \times N_{cycle/batch} + t_{preparing}\right) \times m_{ads.}} \qquad (4)$$

The Specific Daily Ice Slurry Production (SDSP) was calculated using equation (5) based on the collected mass of ice slurry from the evaporator (seawater side). The required time between two batches was also taken in to account as follows:

$$SDSP = \frac{m_{ice\_slurry,batch} \times 60 \times 24}{\left(t_{ct} \times N_{cycle/batch} + t_{preparing}\right) \times m_{ads.}} \qquad (5)$$

The Specific Daily Fresh Water Production (SDWP) was calculated based on the collected mass of fresh water from the condenser as given in equation (6). The required time between two batches was also taken in to account as follows:

$$SDWP = \frac{m_{water,batch} \times 60 \times 24}{\left(t_{ct} \times N_{cycle/batch} + t_{preparing}\right) \times m_{ads.}} \quad (6)$$

6. RESULTS

In this section, parametric studies of the test facility are experimentally analyzed and discussed based on four parameters by investigating the performance of the adsorption ice making-water desalination system and finding the optimum conditions. Regardless the studied parameters, the parametric studies were conducted at same initial and operating conditions (see Table 2). For each experiment of the parametric studies, the uncertainties were assessed based on the calibrations of the measurement instruments. The uncertainty in the SDIP, SDSP, SDWP were estimated based on the calibration of a scale and a beaker which were used to measure the outputs, while for the COP, it was assessed based on the calibration of the thermocouples and flow meter, as follows:

6.1 Salinity Effect of Sea Water

Fig. 3 (A), (B), (C) and (D) show the salinity effect of water as the refrigerant in evaporator on the performance of the adsorption ice making-water desalination system. As shown in Fig. 3(A), it is clear that the optimum SDIP was at 35 ppm based on maximum mass of the produced ice in cups per batch. There was a slight increase in the SDIP by 7.7% when the salinity was increased from 20 to 35 ppm. This is due to the potential of water to evaporate for longer time before starting frozen in the evaporator. Then the SDIP started to slightly drop to 1.3% per 15×10^3 ppm by increasing the salinity from 35 to 65 ppm. Fig. 3(B) shows that there were sharp increases in the SDSP and SDWP up to 60% and 6.3% by increasing the salinity from 20 to 35 ppm, respectively. The same trend was shown in Fig. 3 (C) but with slight effect on the COP. The reason for this is because the period of evaporation-adsorption processes is relatively increased by lowering the freezing point of water. In contrast, the SDSP, SDWP and COP are moderately decreased by increasing the salinity of water from 35 to 65 ppm. This is may be caused by changing the physical properties of water which leads to drop in SDSP, SDWP and COP.

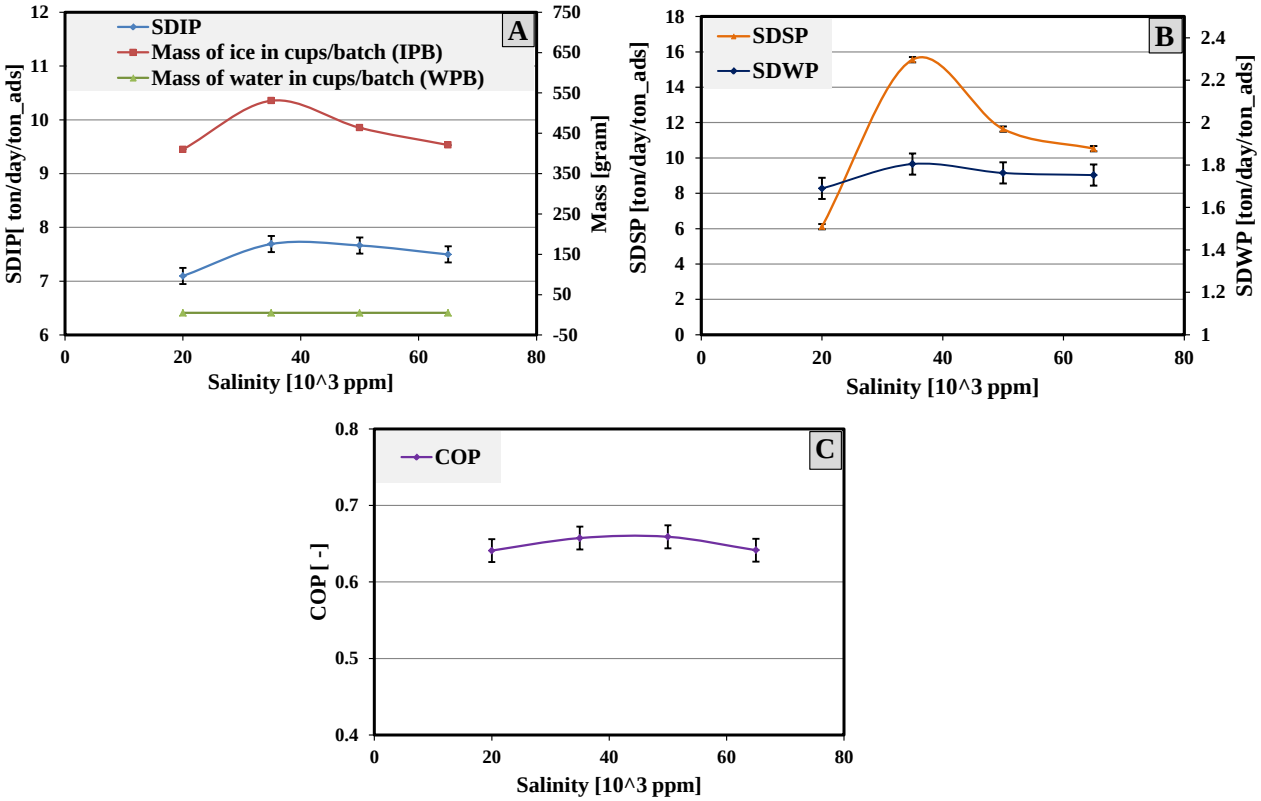

Fig. 3. Effect of water salinity on each of (A) SDIP, mass of solid ice and fresh water in the evaporator, (B) SDSP in the evaporator and SDWP in the condenser, and (C) COP of cooling.

6.2 Effect of cycle's number

Fig. 4 shows the effect of cycle's number on the performance of adsorption ice making – water desalination system in terms of the COP, SDIP, SDSP and SDWP. It can be seen in Fig. 4(A) that the overall trend of the SDIP shows fluctuation between 8.4 to 7.5 ton/day/ton_ads by increasing the cycle's numbers from 1 to 4. Despite this trend, the mass of solid ice in stainless steel cups per batch increased considerably by increasing the cycle's numbers. This is because the batch/run time, as by increasing the number of cycles, the batch time will be increased, in turn; the increase in mass of solid ice may not be noticed according to the operating time during the whole day period. For example the batch/run time of one and four cycles is up to 34 and 112 mins (including the preparing time) where the same number of the cups was used in the both tests, in which the ice formed at different run times. Fig. 1 shows that there was water in the stainless steel cups after 1st, 2nd and 3rd cycles while the all water in the cups is crystallized to solid ice at the 4th cycles. This is due to the improvement in ice production per batch, as the solidity of ice is directly proportional with the number of cycles according to the longer time of cooling effect based on the same amount of fresh water in the16 cups.

Fig. 4(B) shows that the SDSP is significantly decreased by 30.4%, 15.3% and 12.8% per one cycle by increasing the number of cycles from one to four cycles, respectively. In spite of this drop in SDSP the mass of ice slurry is considerably increased by 30.9%, 26.6% and 11.8% per one batch by increasing the cycle's number from 1 to 4, respectively. This is due to the day time, where the rate of increase in ice slurry per batch dose not overcomes the increase in run time itself which has inversely effect on the SDSP during a period of whole day. The increase in ice slurry mass per batch is due to the highly potential of sea water (as refrigerant) to freeze in evaporator, according to the evaporation process will be increased which leads to increase the amount of ice slurry per batch.

As shown in Fig. 4(C), the cycle's numbers effects on the cooling COP as it is clear to notice that the COP of one and two cycles is up to 0.3, and based on this value, the COP drops down by about 60% and 73% with three and four cycles, respectively. The reason of this drop belongs to the potential of the ice slurry to be formed on the exposure surface in the evaporator is higher than the one and two cycles. Accordingly, the evaporation-adsorption process between the evaporator and bed will be weaker than in case of one and two cycles.

Fig. 4(D) shows that there were an enhancement in the SDWP up to 78% and 24 % per one cycle by increasing the cycle's number from one to three cycles, respectively. In the same figure, there was a drop in the SDWP after the third cycle. However, despite this drop, the mass of distilled water in condenser is significantly increased per one batch by increasing the number of cycles. The main cause of this drop is the day time as it will be affected on the water production in condenser per day. The figure also shows that the one cycle per batch produced small amount of water (4 grams) in condenser due to the adsorbent in the bed has low potential to release the vapour to the condenser as some of refrigerant stuck in the adsorbent which needs longer time to release the vapour to the condenser.

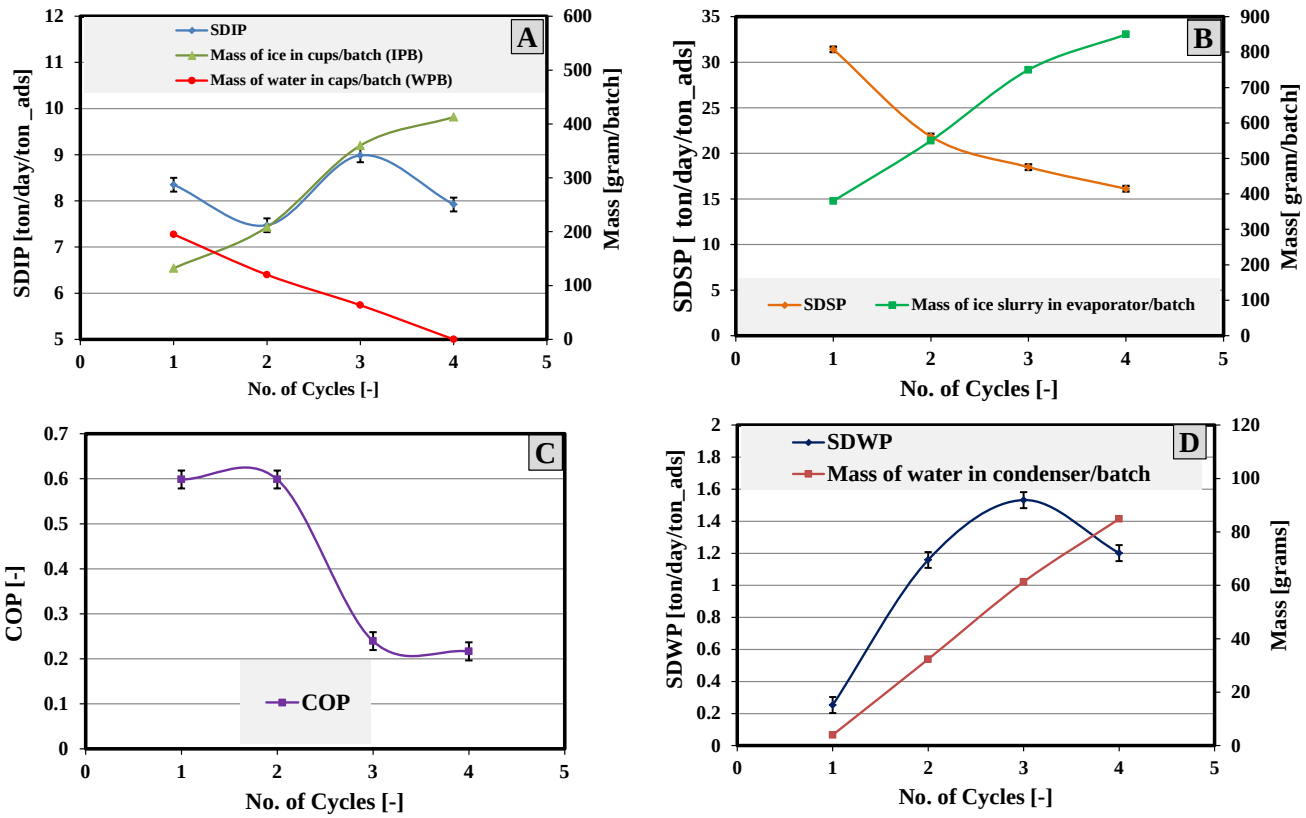

Fig. 4. Effect of cycles number on the each of (A) SDIP, mass of solid ice and fresh water in the evaporator,(B) SDSP and mass of ice slurry in the evaporator ,(C) SDWP and mass of fresh water in the condenser and (D) COP of cooling.

6.3 Effect of Switching Time

Fig. 5 shows that the impact of switching time on the SDIP, SDSP, SDWP, and COP based on the selected cycles number of 3 cycles per batch as shown in the previous section. As shown in Fig. 5(A), there were small enhancements on the SDIP up to 7.6% 1.7% and 1% per one min by increasing the switching time from one to four, respectively. This is because that the adsorbent (at high switching time) will take a longer time for pre-cooling and pre-heating, in turn, the bed will be prepared to absorb and release high amount of refrigerant vapour from evaporator and to condenser during the adsorption and desorption times, respectively. It is clear to mention that the rate of enhancement in SDIP is decreased by increasing the switching time due to the decrease in cycle's number per day. Fig. 5 also shows that there were decrease in the amount of water in cups inside the evaporator up to 39%, 25% and 0% per one minute by increasing the switching time from one to four minutes, respectively.

Fig. 5(B) shows that the SDWP increased by increasing the switching time to reach a maximum value at 2.5 minutes and then decreased. After this point, the mass production of water in condenser per batch reached

steady state while the SDWP dropped down by increasing the switching time. This can be attributed to the disproportion between the water production and run time per day.

Fig. 5(C) shows that by increasing the switching time of the system from one to four minutes, the rate of enhancement in the COP per one minute is up to 15.4%, 24% and 8%, respectively. This is due to the longer pre-cooling and pre-heating processes which leads to prepare the adsorber to enhance the adsorption and desorption processes, respectively, in turn, a large amount of refrigerant vapour will be evaporated and desorbed from evaporator and bed respectively.

As shown in Fig. 5(D), the SDSP is slightly decreased with maximum rate of 6.3% by increasing one minute of switching time. Despite this decrease in SDSP, there was a small increase in the mass of ice slurry per one minute up to 1.7%, 6.6% and 0.3% with range of switching time from one to four minute, respectively. This conflict is caused by disproportion between the increases in run time per day against the mass in of slurry ice in the evaporator.

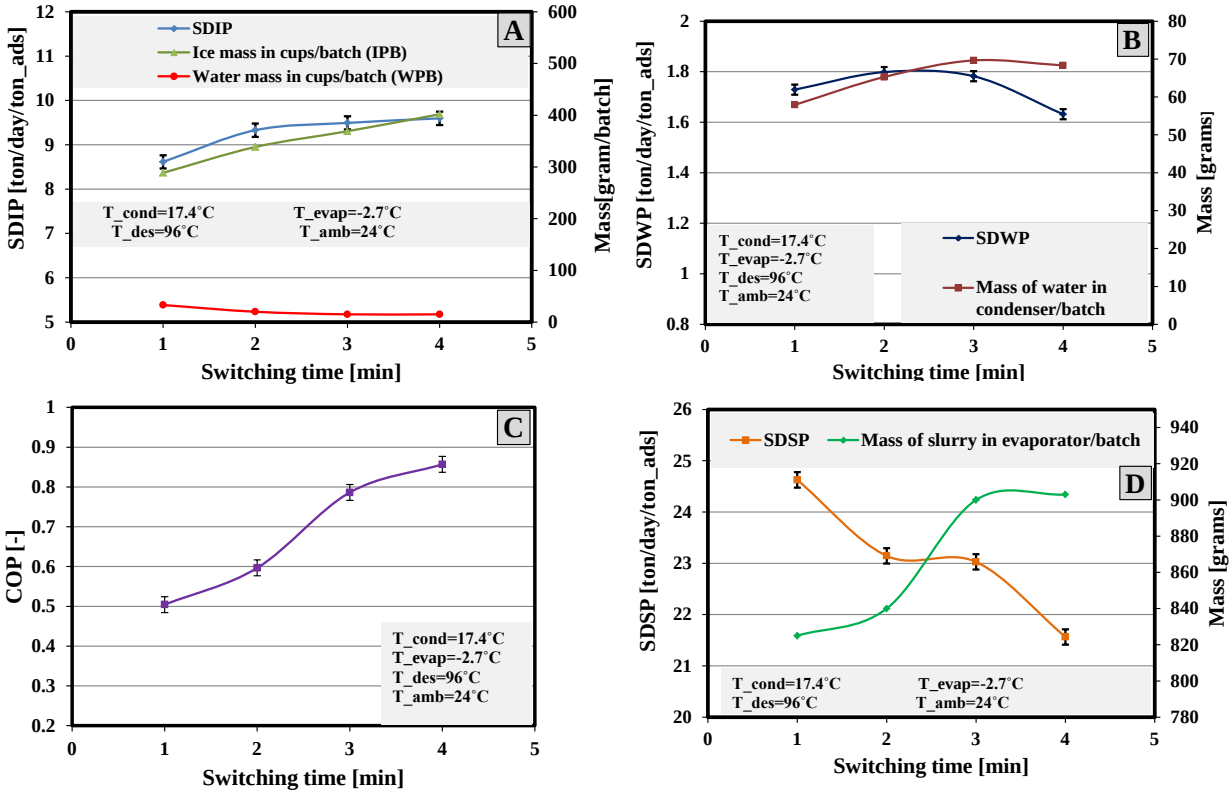

Fig. 5. Effect of switching time on the each of (A) SDIP, mass of solid ice and fresh water in evaporator, (B) SDSP and mass of ice slurry in evaporator, (C) COP of cooling and (D) SDSP and mass of ice slurry in the evaporator.

6.4 Effect of adsorption/desorption time

Fig. 6 shows the effect of adsorption and desorption time (ADT) on the SDIP, SDSP, SDWP and COP based on the selected switching time of 3 second as stated above. In can be seen from Fig. 6(A) that the SDIP was increased significantly up to 14.7% by increasing the ADT from nine until 11 minutes; however, there were a drop in the SDIP of 2%, 4.9% and 3.4% per two minutes during the ADT from 11 to 17 minutes, respectively. Despite this drop in SDIP, the mass of solid ice increased by up to 25 %, 9.7%, 5.7% and 0.8% per two minutes by increasing of the ADT from nine to 11 minutes, respectively. The main reason of this increase is due to longer time of adsorption and desorption which leads to absorb and release more amount of refrigerant vapour, respectively. Accordingly, the formed ice increased by increasing the ADT. It is worth to mention that there was no water in the cups at ADT of 15 and 17 minutes.

Fig. 6(B) shows that the SDWP increased by up to 35% by increasing in the ADT from nine to 11 minutes this can be attributed to the higher amount of desorbed vapour from bed to condenser at the ADT of 11 minutes. The SDWP was continued to increase but with fewer rates until the ADT of 15 min. After the latter ADT, SDWP was dropped by 6% by increasing the ADT to 17 min. This is because the adsorption and desorption processes will be weaker at certain ADT based on the characterization of adsorbent material.

Fig. 6(C) shows a significant increase in the COP of the system based on cooling effect up to 10% per two minutes for the ADT from nine to 15 minutes, respectively. This is attributed to that by increasing the ADT from nine to 15 minutes would increase in average drops of antifreeze temperatures up to 2.25, 2.6, 2.7 and 2.85 K per two minutes, respectively. After the 15 min, the COP was slightly dropped to 3.4 % due to decrease in the average drop of antifreeze temperature from 2.85 to 2.2 K.

Fig. 6(D) shows that the mass of ice slurry was sharply increased up to 22 % by increasing the ADT from nine to 11 minutes. In contrast, the SDSP was decreased by 9.6% at the same period. This is because more heat is absorbed by the antifreeze at longer ADT, in turn; the evaporation process will be increased which leads to produce more ice slurry per batch. But the increase in the ADT has an inversely proportional on the SDSP as the longer ADT leads to decrease the runs number per one day. After the 11 minutes of ADT, the SDSP and mass of slurry ice are fluctuated according to the capacity of adsorbent to absorb the refrigerant vapour will be reduced after certain time. Therefore, the adsorbent material keeps absorbing/desorbing the refrigerant vapour but with insignificant effect.

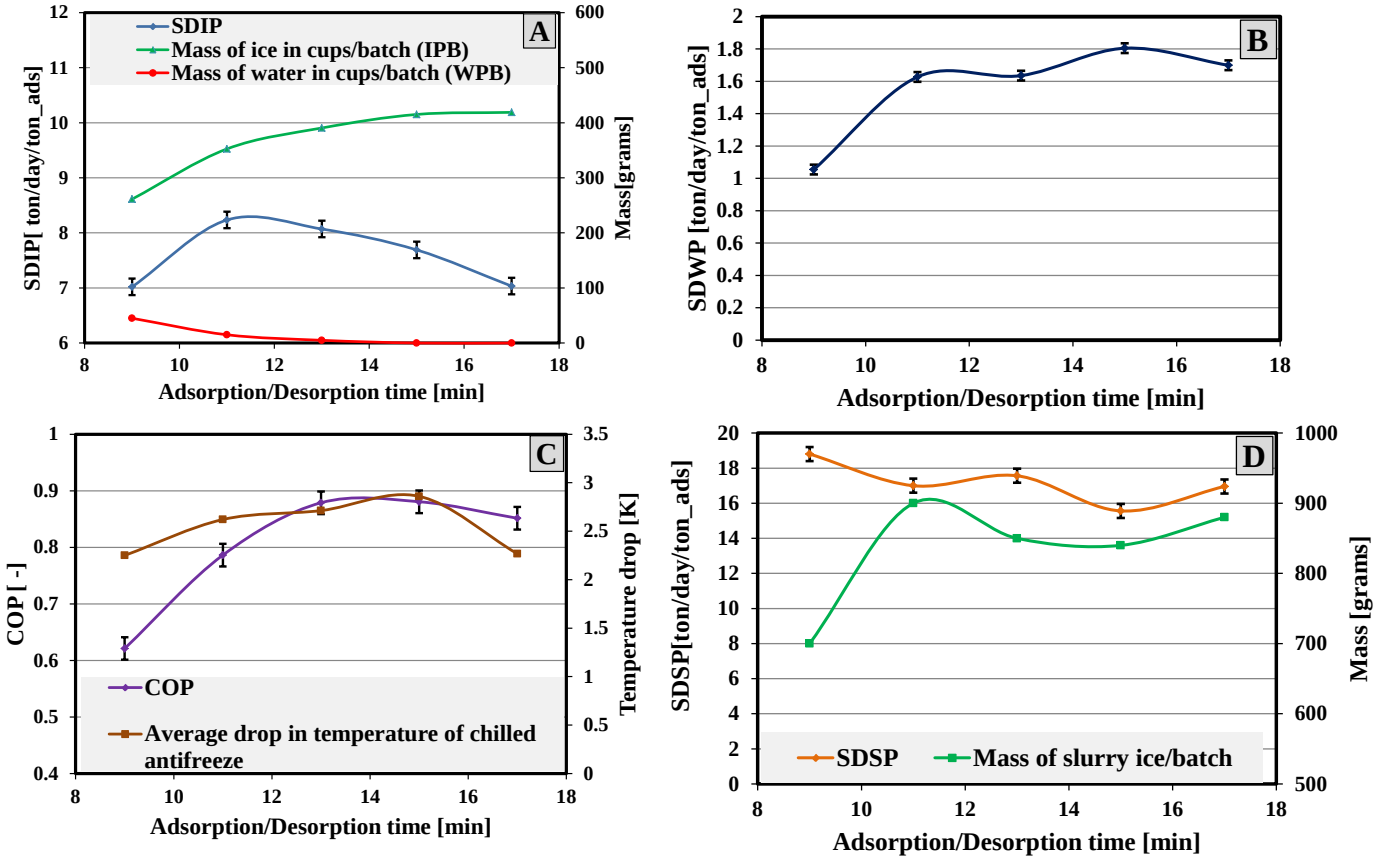

Fig. 6. Effect of adsorption/desorption time on the each of (A) SDIP, mass of solid ice and fresh water in the evaporator, (B) SDWP in the evaporator, (C) COP of cooling and temperature drop in the evaporator, and (D) SDSP and mass of ice slurry in the evaporator.

7. CONCLUSION

In this work, an advanced technique for adsorption ice making integrated with vacuum direct freeze desalination is developed. The effect of numbers of cycle, switching time, adsorption-desorption time and salinity on the performance of single bed adsorption based on ice making, cooling, ice slurry and desalination using CPO-27 (Ni) MOF-water as working pair was experimentally investigated. Results showed that:

- CPO-27 (Ni) MOF-water working pair shows the potential to be used for ice making application.
- The fresh and sea water can be used as refrigerant in adsorption systems to achieve low evaporation temperature <0˚C thus reducing dependence on CFCs and HFCs refrigerants for ice making applications.
- Based on ice production of current system, the optimum number of cycles is three cycles per batch.
- The optimum switching time and adsorption/desorption time are 3 and 15 minutes respectively for producing all outputs.

- There is an enhancement in SDIP up to 5.4 times with a maximum value up to 8.9 ton/day/ton_ads using fresh and sea water as refrigerants compared to the maximum value reported in the literature using adsorption technique with ammonia as refrigerant [5].
- With this technique, the optimum salinity is 35000 ppm for maximum production of ice up to 8.3 ton/day/ton_ads, COP cooling up to 0.9 and water desalination up to 1.8 ton/day/ton_ads.

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