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Adsorption ice making and water desalination system using metal organic frameworks/water pair

Hassan J. Dakkama [a,b,*], Peter G. Youssef [a], Raya K. Al-Dadah [a], Saad Mahmoud [a]

[a] Department of Mechanical Engineering, School of Engineering, University of Birmingham, Birmingham B15 2TT, UK
[b] Engineering Technical College-Baghdad, Middle Technical University, Baghdad, Iraq

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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 35,000 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.

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 vapour 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.

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 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

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[*] Corresponding author at: Department of Mechanical Engineering, School of Engineering, University of Birmingham, Birmingham B15 2TT, UK.

E-mail address: hassan_jfsd@yahoo.com (H.J. Dakkama).

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Nomenclature

AC	activated carbon [–]
$CaCl_2$	calcium chloride [–]
Cp	specific heat [kJ/kg/K]
COP	coefficient of performance [–]
CO_2	carbon dioxide [–]
m	mass
$\dot{m}$	mass flow rate [kg/s]
Q_{evap}	refrigeration effect [kW]
Q_{heat}	consumed heat power [kW]
MOF	metal organic framework [–]
N	number [–]
RTD	resistance temperature detectors
SDIP	Specific Daily Ice Production [ton/day/ton_ads]
SDSP	Specific Daily Ice Slurry Production [ton/day/ton_ads]
SDWP	Specific Daily Water Production [ton/day/ton_ads]
$SrCl_2$	strontium chloride
T	temperature [K]
t	time [sec]

Subscript

ads	adsorption
AF	anti-freeze
at	adsorption time
ct	cycle time
des	desorption
evap	evaporator
hct	half cycle time
in	inlet
out	outlet
w	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-$CaCl_2$/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

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 $BaCl_2 + BaBr_2$, 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 °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