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# Experimental investigation of an adsorption refrigeration prototype with the working pair of composite adsorbent-ammonia

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## HIGHLIGHTS

- A 4-valve adsorption refrigeration prototype is developed and tested.
- Reliability is improved by the design of adsorber and heating/cooling circuit.
- The optimal cycle time and mass recovery time are 50 min and 120 s, respectively.
- COP and SCP of typical conditions are 0.197and 205.2 W $kg^{-1}$, respectively.

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## ABSTRACT

A 4-valve adsorption refrigeration prototype, which utilizes the composite adsorbent of calcium chloride/activated carbon and the refrigerant of ammonia, is developed and tested. System reliability is significantly improved because the integrated adsorbers are adopted, the closed circulation for heating and cooling processes is designed, and the system operation is optimized. Experiments showed that the prototype can start quickly, and the operation of the system is very stable. The influences of mass recovery time, cycle time, heating temperature, evaporating temperature and cooling water temperature on system performance have been studied. Experimental results indicate that for the −5 °C evaporating temperature, 130 °C heating temperature, 25 °C cooling water temperature, the optimized cycle time is 50 min with a mass recovery time of 120 s. The optimal coefficient of performance (COP), specific cooling power (SCP) and cooling capacity of this prototype are 0.197, 205.2 W $kg^{-1}$ and 1.64 kW, respectively.



## 1. Introduction

Nowadays, the energy crisis and environmental damages are two main challenges for the development of the society. As a thermal-driven refrigeration technology, adsorption refrigeration has advantages for the utilization of low-temperature thermal energy (i.e. solar energy and waste heat) [1–5]. Besides, adsorption refrigeration is environmentally benign since it uses green refrigerants. In addition, adsorption refrigeration has many benefits including simple structure, easy control, low maintenance and less noise [6,7] which make it very suitable for vehicles air conditioning or fishing boats ice making. Thereby the research and product developments of adsorption refrigeration have been paid more and more attention in recent years [8,9].

Silica gel–water adsorption chillers have been commercialized successfully. Nishiyodo Kuchouki Company, Mycom Company and Shanghai Jiao Tong University developed their silica gel–water adsorption refrigeration products in 1986, 2003 and 2004, respectively [10]. Small scale adsorption chillers have been commercialized by SorTech, Solar Next and etc., However, silica gel–water adsorption is not suitable under freezing condition. So chemical adsorbent-ammonia adsorption refrigeration was proposed and test units were developed [11,12]. Unfortunately, chemical adsorbents have the disadvantages of swelling, disintegration and agglomeration [13]. In this case, composite adsorbents, like calcium chloride/activated carbon, calcium chloride/expanded graphite, barium chloride/vermiculite and etc., were developed and studied.

Composite adsorbents, which consist of chemical adsorbents and porous medium, can enlarge the thermal conductivity and adsorption quantity simultaneously. Adding activated carbon into calcium chloride can solve the problem of agglomeration and improve adsorption quantity by 0.15 kg $kg^{-1}$ [14]. Researchers also

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**Nomenclature**

| | |
|---|---|
| COP | coefficient of performance |
| *m* | mass (kg) |
| *P* | pressure (MPa) |
| *Q* | heat (kW) |
| *r* | COP ratio |
| SCP | specific cooling power (W kg$^{-1}$) |
| *T* | temperature (°C) |
| *t* | time (s) |
| Δ | error |

*Subscripts*

| | |
|---|---|
| A1 | adsorber1 |
| A2 | adsorber2 |
| *a* | composite adsorbent |
| *B* | boiler |
| *c* | calcium chloride |
| cy | cycle |
| E1 | evaporator1 |
| E2 | evaporator2 |
| *e* | cooling |
| *h* | heating |
| hl | heat loss |
| *i* | inlet |
| id | ideal |
| *m* | metal |
| *n* | ammonia |
| *o* | outlet |

found that ammonia uptake is increased when calcium chloride is inserted in γ-$Al_2O_3$ or vermiculite host matrix [15]. Effective thermal conductivity of the calcium chloride-expanded graphite consolidated composite adsorbent is in the range of 7.05–9.2 W m$^{-1}$ K$^{-1}$, which is greatly increased if compared with the granular adsorbents with the thermal conductivity of 0.3–0.4 W m$^{-1}$ K$^{-1}$ [16]. In the research of Fujioka [17], effective thermal conductivity of calcium chloride/expanded graphite composite bed is larger than 60% that of untreated calcium chloride bed. As the excellent performance of composite adsorbents, several adsorption refrigeration prototypes using composite adsorbent are developed and tested. A novel multifunction heat pipe adsorption icemaker for fishing boats utilizing calcium chloride/activated carbon was experimentally studied by Lu [7], of which COP and SCP were 0.2 and 369.1 W kg$^{-1}$, respectively. A lab-scale prototype of an ammonia adsorption chiller using barium chloride/vermiculite was tested by Veselovskaya [18], which gave COP ranging from 0.52 to 0.55 and SCP ranging from 300 to 680 W kg$^{-1}$ under air conditioning condition. After that Li [19] developed a novel calcium chloride/expanded graphite-ammonia adsorption refrigerator with only 3 valves, obtaining COP and SCP of 0.27 and 422.2 W kg$^{-1}$, respectively. The results obtained from Li [19] were almost the best experimental results under the adsorption freezing condition. However, such type of the refrigerator has not yet been commercialized because of the large size and the low reliability. Base on the work of Li [19], size and reliability were improved in this paper. A new prototype with smaller size, higher reliability and optimized operation procedure was developed and tested under different conditions, which met the requirements of fishing boats icemaker or solar/gas-powered refrigerator.

## 2. Experimental prototype

### 2.1. Working processes

The schematic of adsorption refrigerator prototype is shown in Fig. 1 and the detailed working processes are listed as follows.

(1) Stage 1: Adsorber A1 in desorption and A2 in adsorption. For this process, the valve V1-a, V1-b, V2-a, V2-b, V3-b, and V3-c are open, heating fluid flows into A1 and cooling fluid flows into A2. Therefore, adsorbent in A1 is heated and adsorbent in A2 is cooled. The refrigerant desorbs from A1, then condenses in condenser C1, and finally stores in evaporator E1. Meanwhile, under the function of the adsorption reaction in A2, the refrigerant evaporates in E2 and yields cooling capacity, which is transferred outside by chilled fluid. The refrigerant gas flows through C2, being superheated by the cooling water and finally is adsorbed by the adsorbent in A2.
(2) Stage 2: Mass recovery from E1 to E2. For this stage, V4 is open, mass recovery proceeds between E1 and E2. Large pressure difference drives part of refrigerant flowing from E1 to E2. Since the pressure of E1 is much higher than that of E2, and the pressure in two evaporators is very easy to be balanced in a short time. In this process the pressure in E1 decreases and the pressure in E2 increases, such a process could improve the desorption in A1 and adsorption in A2 effectively. Consequently the system performance is improved [20].
(3) Stage 3: A1 in adsorption and A2 in desorption. For this stage V1-a, V1-c, V2-a, V2-c, V3-a, and V3-c are open. The process of this stage is similar to Stage 1 except that the A1 and A2 exchange the roles, i.e. A1 adsorbs and A2 desorbs, consequently the cooling capacity is yielded in E1.
(4) Stage 4: Mass recovery from E2 to E1. The V4 is open for this stage. The process is similar to Stage 2, whereas E1 is at the low pressure side and E2 is at the high pressure side. So, mass recovery process is from E2 to E1.

The operation procedure of the system is shown in Table 1. This operation is optimized by adding a quiescing process of pump when adsorption and desorption phases switch. The sudden contact between heating and cooling fluid will cause a negative impact on the system since the huge temperature difference. However, the

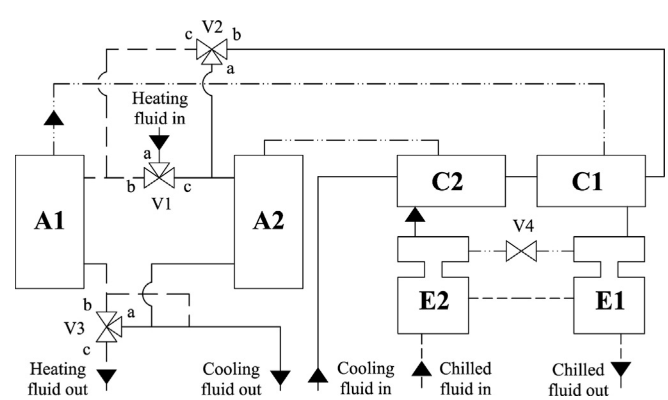


**Fig. 1.** Schematic of adsorption refrigeration prototype—*A*: adsorber; *C*: condenser; *E*: evaporator; *V*: valve.