

Pressurized adsorption cooling cycles driven by solar/waste heat



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HIGHLIGHTS

- Description of the $T-s$, and $T-h$ diagrams of an adsorption cooling cycle.
- We regressed heterogeneous carbons + 6 commercial refrigerants pairs with improved phase volume.
- We analyzed the SCE and COP.
- We analyzed pair selections for given operational requirements: regeneration, ambient and the required cooling.

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ABSTRACT

This article presents the performance analysis of single-stage two bed adsorption refrigeration cycles working at pressurized conditions. Four specimens of activated carbon adsorbent and refrigerant pairs, which are Maxsorb III with Propane, *n*-butane, HFC-134a, R-32, and R507a are studied. The relationships between equilibrium pressures, adsorbent temperatures and equilibrium adsorption concentrations (Dühring diagram) are presented. Parametric analyses have been carried by varying the regeneration, cooling water and evaporation temperatures. Theoretical analysis for these adsorption cycles working pairs shows that the choice of refrigerants amongst these pairs depends on the operational requirements and conditions. The authors thus present in a graphical representation of the choice based on these requirements. At higher required chilling temperatures and lower ambient temperatures, R-32 is preferred with higher specific cooling capacities. When lower temperature cooling is required while the ambient temperature is high, Propane is preferred.

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1. Introduction

The increasing concerns related to the environment and ecology of recent years has brought about escalating interests in using heat sorption systems for cooling applications. This is due to its capability of directly utilizing thermal energy sources, including low-grade waste heat from various sources, including solar hot water, industrial waste heat as well as geothermal sources [1,2]. The adsorption (AD) is advantageous when lower temperature heat sources, as low as 55 °C are available [3,4]. Much work has been carried out to find novel solutions to integrate the AD Chiller technology into the existing refrigeration market [5]. The current state of the art of cooling applications is mostly water based with

silica gel or zeolite as the adsorbent, most of which has successfully been implemented in Japan and parts of Europe [6]. The main drawback of water based silica gel and zeolite systems lies in its requirement of advanced technologies and intricate design considerations so that high vacuum could be maintained, as leakages will drastically reduce its performance. Furthermore, due to the triple point of water, cooling systems which utilizes water as a refrigerant are inoperable as the evaporator approaches 0 °C [7,8]. This makes it restrictive in terms of application. In this work, refrigerants with lower normal boiling points (NBP) which relates to its operational ranges (below 0 °C) are considered. Propane, for example which has a low NBP of −42.114 °C may be utilized in extremely low temperature cooling. Another motivation of studying these refrigerants is that higher differential uptakes of the reactor beds at the condenser and the evaporator pressures may possibly result in greater cooling capacities and hence higher performances since they operate beyond Henry's region [9].

The detailed analysis of the adsorption cycle has previously been discussed by Cacciola and Restuccia [10]. Such an analysis is

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essential in choosing an appropriate adsorbent + adsorbate pair for practical applications which takes into consideration various properties of the pair including its physical, thermodynamics and chemical properties as well as their availability and costs [11–13]. There is however a lack of such analysis specifically for adsorbates in the moderately pressurized regions including those of hydrocarbons specifically *n*-butane and Propane which are relatively cheap and plentiful alternatives as working fluids [14,15]. In this work, a thermodynamic analysis of the equilibrium adsorption cooling cycle of assorted adsorbates with Maxsorb III is analyzed. The choice of Maxsorb III as the common adsorbent base is its relatively higher BET surface area and thus uptake quantities as compared to the other solid activated carbon choices [16–20].

In a thermally driven solid sorption system, there are three essential components that must be present. They are (i) the sorption beds where adsorption or desorption occurs, (ii) the evaporator and (iii) the condenser. As shown in Fig. 1, the basic processes that the bed undergoes are as follows

1. First, the bed is isolated from both the evaporator and the condenser and is cooled by an external coolant. This is known as the pre-cooling switching stage.
2. Then, adsorption occurs when the valve connecting the bed to the evaporator is opened. The adsorbent adsorbs the refrigerant vapor from the evaporator resulting in the release of heat which continues to be cooled by the external coolant.
3. The valve to the evaporator is closed and isolated from both the condenser and the evaporator. The external coolant supply is stopped while external heat source is applied to the sorption bed. As a result, there is pressure build up in the bed. This is known as the pre-heating switching stage.
4. Finally, the valve to the condenser is opened and the external heat source continues to be applied to the sorption bed resulting in refrigerant from the bed to be released to the condenser.

This ideal AD refrigeration cycle, from the viewpoint of the thermal compressor is represented as a Dühring diagram in Fig. 2 for the Maxsorb III/Propane pair. These were drawn based on the properties of Propane [21] as well as its equilibrium properties. It consists of (1) isosteric cooling (A–B) (2) isobaric adsorption (B–C), (3) isosteric heating (C–D), and (4) isobaric desorption (D–A). Since the thermal compressor is isolated from both the evaporator and condenser during pre-cooling and pre-heating, both these processes may be assumed to take place along a constant uptake q , i.e. an isostere. It is during isosteric cooling (A–B) that the temperature of the adsorbent bed initially at T_A , which is the maximum temperature of the cycle, is decreased to T_B [22]. Similarly, during isosteric heating, the temperature of the adsorbent bed is increased

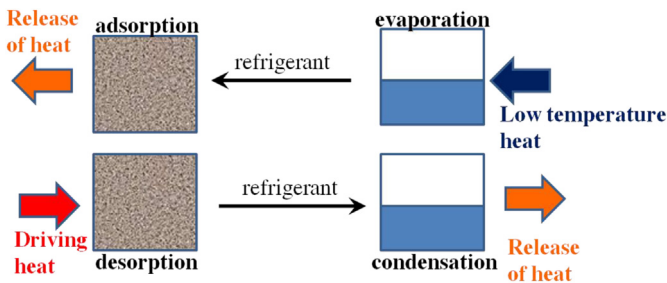


Fig. 1. Process diagram of a thermally driven adsorption chiller. During the regeneration step (bottom), heat source desorbs the adsorbent at a higher temperature, while the released refrigerant is then liquified in the condenser. In the adsorption process (top), the refrigerant is evaporated by the low temperature load. Heat is released during adsorption bed and in the condenser.

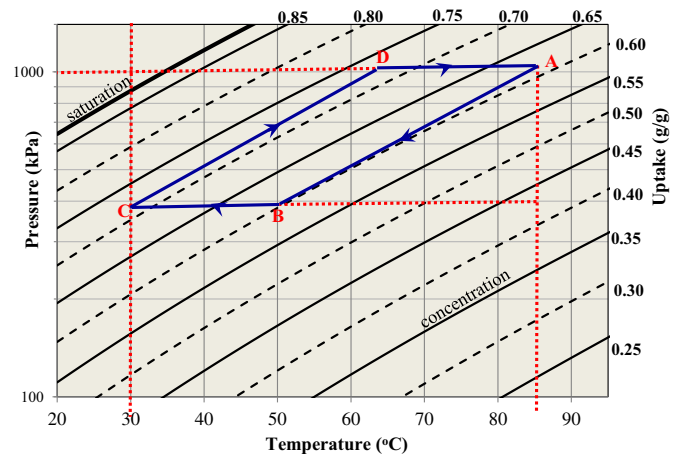


Fig. 2. The Dühring diagram from the regressed D–A equation (ABCD represents a refrigeration cycle for a given evaporator/condenser pressure) for an adsorption cycle running with Propane and Maxsorb III.

from T_C to T_D by external heating. The thermal compressors are assumed to be at constant pressure as per previous works [23–26] during both the adsorption (B–C) and desorption (D–A) processes following the pressures of the evaporator and condenser respectively. Since heat is released during the isobaric adsorption process, while heat is removed during the isobaric desorption process (Fig. 3), external cooling and heating takes place accordingly until the temperature reaches the inlet cold (T_C) or hot water temperature (T_D). Fig. 4(a) and (b) shows the schematic of a single staged 1-bed pressurized adsorption chiller during desorption and adsorption respectively.

2. Temperature–enthalpy/entropy diagram ($T-h$, $T-s$)

From the formulations developed in previous works [27,28], the adsorption cycle for any single-stage two bed chillers may be comprehensively represented in either an enthalpy–temperature or entropy–temperature diagram. Fig. 5(a) and (b) depicts the enthalpy–temperature and entropy–temperature plots for the Maxsorb III + Propane adsorption pair. All properties of Propane used in this report had been determined utilizing the equation of state (EOS) introduced by Lemmon [21]. In both these figures, the solid black line represents the saturated liquid, forming the well-

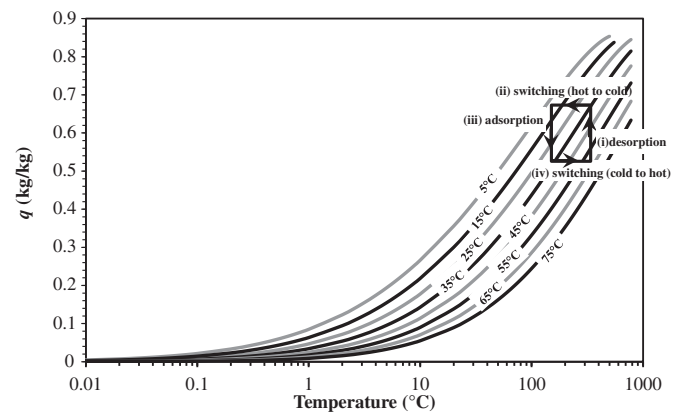


Fig. 3. Processes (i)–(iv) shows the thermodynamic process of the adsorption cycle for a Maxsorb III + Propane pair. The isotherm lines, fitted from the experiments for the various temperatures are shown.

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