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PERFORMANCE EVALUATION OF A NOVEL INTEGRATED ADSORPTION-ABSORPTION (AD-AB) THERMAL DRIVEN REFRIGERATION SYSTEM

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ABSTRACT

Regarding some serious problems like the energy crisis and environmental issues associated with the conventional compression refrigeration system, thermal refrigeration systems were therefore developed to overcome the mentioned problems. In this study, a completely novel integrated adsorption and absorption (AD-AB) refrigeration system driven by a low-grade heat source is proposed. Of importance, this novel cycle focuses on the inherent characteristics of the adsorption and absorption phenomena in the system. The innovation here is that the generator of the absorption cycle becomes the evaporator of the adsorption cycle. Therefore, the generation and evaporating pressure is no longer determined by the cooling and chilled water temperatures and the pressure is associated with the heat source temperature. This results in a new phenomenon of absorption, adsorption and the coupling of generation of solution and adsorption of refrigerant. The results reveal that the system enjoys a considerable high COP when a low-grade heat source is available.

Keywords: **i**ntegrated AD-AB system, absorption, adsorption, COP, low-grade thermal energy, energy Efficiency.

NONMENCLATURE

Abbreviations	
AD-AB	Adsorption-Absorption
COP	Coefficient of Performance
Symbols	
M	Total amount of mass in each component (kg)
T	Temperature of components (K)
C	concentration of solution
h	specific enthalpy (jkg^{-1})
ρ	Density (kgm^{-3})
c_p	specific heat capacity ($\mathrm{jkg}^{-1}\mathrm{K}^{-1}$)
V	volume of components (m^3)
q^*	adsorption equilibrium uptake (kgkg^{-1})
q	instantaneous adsorption uptake (kgkg^{-1})
R	universal gas constant (8.314472 $\mathrm{jmd}^{-1}\mathrm{K}^{-1}$)
θ	temperature of working fluids (K)
X	Concentration of solution at the exit of the absorbent and the generator
$\dot{m}$	mass flow rate between components ($\mathrm{kg}s^{-1}$)
UA	conductance (KWK^{-1})
A	area (m^2)
R_p	adsorbent particle radius (m)
E_a	activation energy (jmol^{-1})
D_{S0}	Pre-exponential term ($\mathrm{kg}s^{-1}$)

1. INTRODUCTION

In recent years, the increasing fossil fuels price, the energy crisis and environmental problems such as global warming and ozone layer depletion have been extremely significant issues in international community as most countries are endeavoring to find alternative ways to reduce the carbon dioxide emission from combustion of fossil fuels. Such critical problems therefore made researchers to concentrate on innovative technologies, which can either utilize low-grade energy sources like the waste energy from industrial processes, or solar and geothermal energy. Sorption refrigeration system is one of the most reliable and favored technologies widely used recently in most countries all over the world.

The first commercial sorption refrigeration system is the absorption cooling system. Over the last 50 years, a

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plenty of novel absorption systems have been designed and developed and researchers have performed various studies on different areas such as system components, heat and mass recovery, different working pairs to increase the system performance and avoid crystallization. Published review papers on the absorption refrigeration technology have summarized these research efforts and achievements and [1]. These efforts led to the wide application of absorption systems in solar energy and geothermal energy [2]. The single-effect absorption system is the simplest kind of absorption system and theoretically and experimentally demonstrated as an effective means of energy conversion in the temperature range of 90-150℃ [3]. Nevertheless, the performance of the single-effect absorption system is very poor when the heat source temperature is lower than 85℃.

With regard to associated problems related to the absorption, another sorption refrigeration system called adsorption was received a great attention from the early 1990 [4], and therefore many investigators shifted their research efforts to this new system [5]. Adsorption systems have been widely applied in geothermal energy and solar energy over the last two decades [6]. The adsorption system works very well at 80 ℃ without losing much system efficiency. However, the adsorption system did not show a appropriate system performance at the low heat source temperature and the Coefficient of Performance (COP) was less than 0.3 with a sizeable cooling capacity.

In this work, a completely novel integrated adsorption-absorption (AD-AB) refrigeration system which combines the absorption cycle and adsorption cycle in one united cooling cycle is proposed. As it will be described comprehensively in the following section, the integrated system could be driven by a low temperature heat source with an acceptable value of COP. Of importance, this novel cycle will focus on the inherent characteristics of the adsorption and absorption phenomena in the system. The innovation here is that the generator of the absorption cycle becomes the evaporator of the adsorption cycle. Therefore, the generation and evaporating pressure is no longer determined by the cooling and chilled water temperatures and the pressure is associated with the heat source temperature. This results in a new phenomenon of absorption, adsorption and the coupling of generation of solution and adsorption of refrigerant.

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2. DESCRIPTION OF THE NEW INTEGRATED AD-AB SORPTION REFRIGERATION SYSTEM

2.1 Cycle construction

Fig. 1 illustrates a schematic of an integrated AD-AB sorption cooling system. As seen from the figure, the system components are an integration of the main components of both absorption and adsorption systems in one integrated system. The integrated system comprises six main components including a condenser, an evaporator, an absorber, a generator, and two adsorption beds called the adsorber and the desorber.

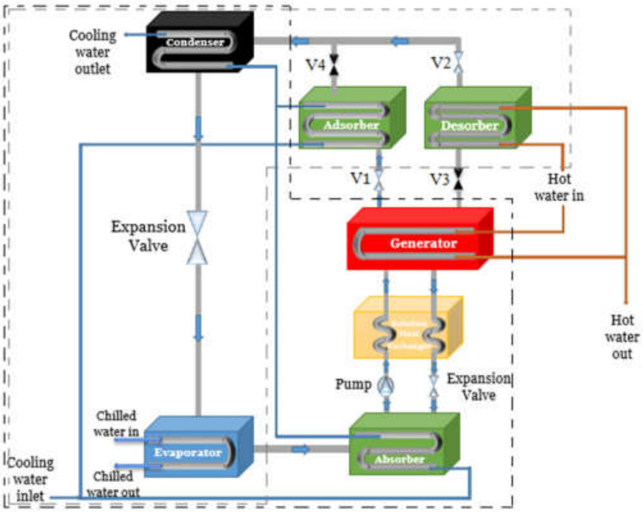

Fig. 1. A schematic of an integrated AD-AB refrigeration system.

The thermodynamic process of the integrated system can be initially described in the evaporator where the water vaporizes to provide the cooling of the system. The produced vapor is then absorbed by the solution which is actively cooled in the absorber. The produced weak solution is then pumped to the generator to generation whereas the strong solution in the generator is throttled back to the absorber to absorb the water vapor coming from the evaporator. In the generator, the water vapor is desorbed from the solution and is next adsorbed by the adsrobents in the adsorber. Once the adrorber is saturated at the corresponding temperature and pressure, the adsrober is then switched to work as a desorber, where the water vapor is thermally desorbed from the adsorbents with the input heat, and then flows into the condenser. Next, the water vapor is cooled and condensed in the condenser. Thereafter, the liquid water phase expands to a lower pressure through an expansion valve and flows back to the evaporator to make up the evaporator water. Simultaneously, the desorber is switched to work as an adsorber, which continues to adsorber the water vapor generated in the generator.

2.2 *Mathematical modeling*

A lumped-parameter approach is employed to derive the mathematical modelling of the integrated system. Conservation of mass and energy is applied to all components comprising the integrated system:

$$\frac{\partial M}{\partial t} = \sum\nolimits_{in} \dot{m} - \sum\nolimits_{out} \dot{m} \qquad \text{Eq. (1)}$$

$$\frac{\partial (MC)}{\partial t} = \sum\nolimits_{in} (\dot{m}X)_{weak} - \sum\nolimits_{out} (\dot{m}\,X)_{strong} \qquad \text{Eq. (2)}$$

$$Mc_p \frac{\partial T}{\partial t} = \sum\nolimits_{in} (\dot{m}h) - \sum\nolimits_{out} (\dot{m}h) \pm UA\Delta T_{lm} \qquad \text{Eq. (3)}$$

$$\left(\rho c_p V\right) \frac{\partial \theta}{\partial t} = \dot{m}_{water} (h_{in} - h_{out}) \pm UA\Delta T_{lm} \qquad \text{Eq. (4)}$$

Where M stands for mass of refrigerant or solution inside each component, C is for concentration of absorbent inside the generator and the absorber, T represents the temperature of each component and θ is defined for the working fluid circulating through components.

The rate of adsorption and desorption in sorption beds is calculated by the linear driving force (LDF) kinetic equation:

$$\frac{dq}{dt} = 15 \frac{D_{S0} exp(-E_a/RT)}{R_P^2} (q^* - q) \qquad \text{Eq. (5)}$$

The energy performance of the system is calculated by the following equation:

$$COP = \frac{\int_0^{t_{cycle}} \dot{m}_{chilled} (h_{in} - T_{out})_{chilled}\, dt}{\int_0^{t_{cycle}} \dot{m}_{hot} (h_{in} - T_{out})_{hot}\, dt} \qquad \text{Eq. (6)}$$

3. DISCUSSION

In the integrated AD-AB system the generation pressure is associated with the heat source temperature and can be adjusted according to the solution concentration and generation temperature. In the integrated system, the adsorption process happens at this new generation pressure which is more than the evaporating pressure and lower than the condensing pressure in the adsorption system and absorption system, respectively. This new pressure is shown with the red dash line in the Fig. 2.

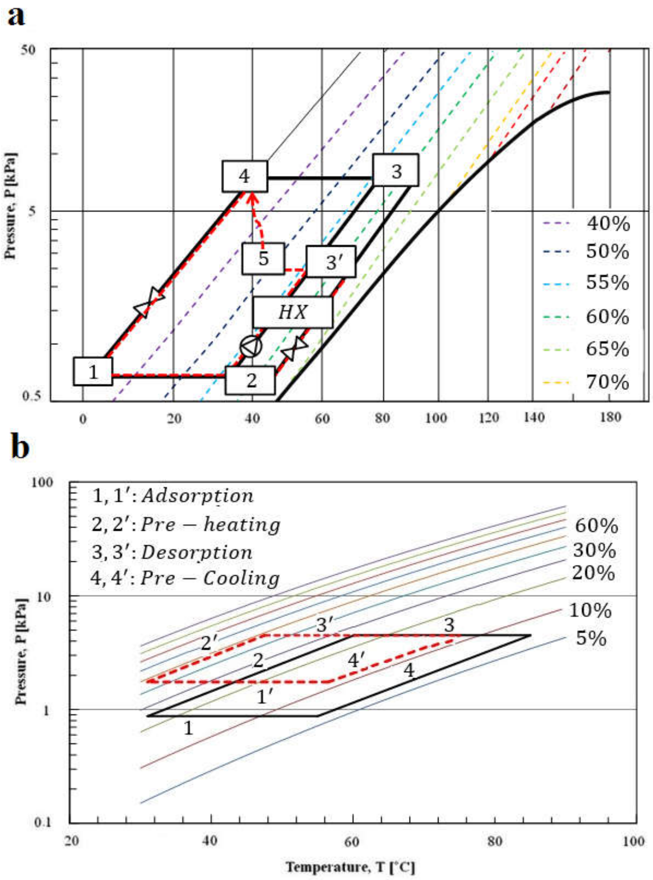

Fig. 2. (a) Schematic of absorption thermodynamic cycle in Duhring plot, and (b) schematic of adsorption thermodynamic cycle in Duhring plot; black line presents standard sorption cycle and the red dashed line proposes the new AD-AB cycle.

From Fig. 2 it is obvious that the generation pressure, Pgen, at low heat source temperature is much lower than the normal condensing pressure, Pcond. When the generation happens at this new pressure, the solution concentration difference between the generator and absorber of the integrated system (ABCD) is greater or stays at least the same as that in the high temperature driven absorption system (abcd), Fig. 3a. This generation pressure is also the evaporating pressure for the adsorption cycle which is much higher than that in the standard adsorption system as shown in Fig. 3b. The diagram reveals that the difference of adsorption uptake in the adsorber and desorber at this new evaporating pressure in the integrated system (ABCD) is much larger than that in the standard adsorption cycle (abcd) even though the driven temperature is much lower.

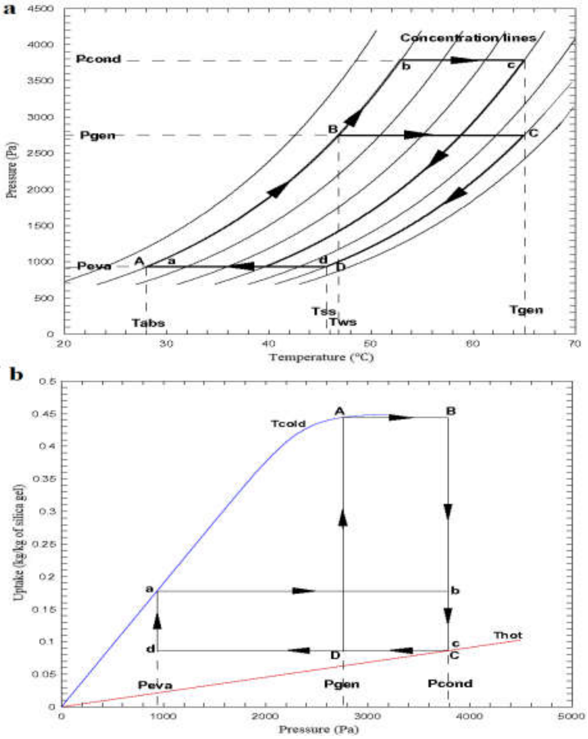

Fig. 3. (a) Solution concentration difference between absorber and generator, and (b) adsorption uptake difference between adsorber and desorber.

3.1 Results

Conservation of Mass and energy equations of the all system components have been solved numerically using a computer code developed in Matlab programming language. Since the system of ordinary differential equations proposed for the integrated AD-AB system was explicitly integrated in time, a fourth-order Runge-Kutta method is implemented to simulate the governing equations involved in the proposed mathematical model. Figs. 4 displays the temperature histories of the heat exchanger components (sorption beds (adsorber and desorber), condenser, evaporator, absorber and generator) and the outlet temperature profiles of heat transfer working fluids at the exits of different components of the system. Moreover, a parametric analysis is performed to study the influences of different operating conditions and particularly hot water inlet temperatures on the energy performance of the integrated AD-AB cooling system.

Fig. 5 indicates the variation of the integrated system performance at a wide range of driving heat source temperatures. The COP at each heat source temperature has been obtained at the optimum

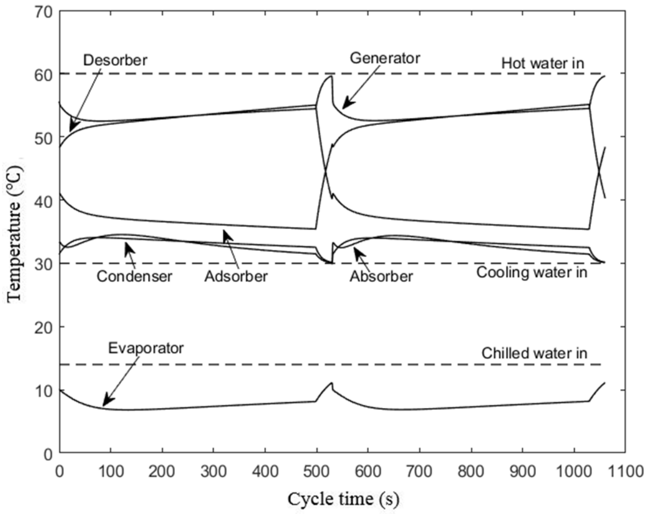

Fig. 4. Temperature profiles for different components of the integrated AD-AB system.

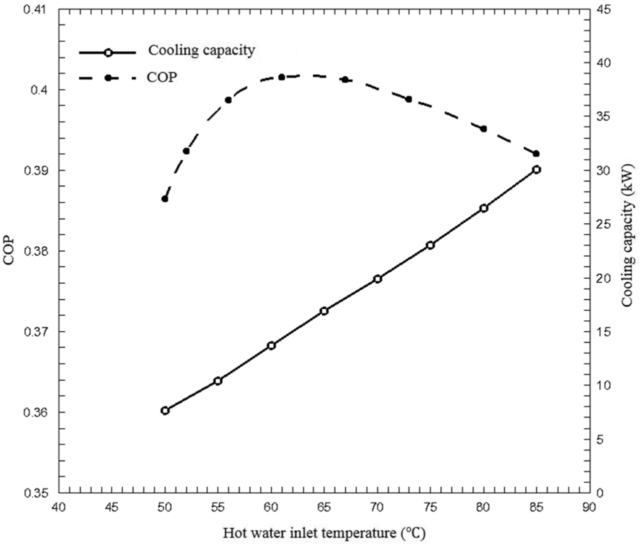

Fig. 5. Variation of COP and cooling capacity with heat source temperature.

which is determined by the generation solution and hot water temperature. It is revealed from this diagram that the COP tends to increase as the heat source temperature increases and it reaches its maximum value when the heat source temperature varies between 60-70°C which is considerably higher than the adsorption system performance under the same heat source. However, it can be seen a relatively small decline in COP value for higher hot water inlet temperatures applied to the system. It is also observed that the increase in the heat source temperature leads to an increase in the amount of cooling produced in the system. Moreover, the amount of cooling produced in the integrated system is considerably higher than that produced in the individual adsorption system under the same heat source temperature.

4. CONCLUSION

A completely novel integrated AD-AB sorption cooling system is numerically investigated. In the integrated system, the adsorption process happens in the generation pressure which is determined through the generation temperature and solution concentration in the generator. The result reveals that the system indicates a great promise for use with low driving heat source temperature varying between 60-70℃ with a considerably high efficiency. Thus, the proposed system could be a very effective and promising design when low-grade thermal sources are available.

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