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Thermodynamic study of a combined double-way solid–gas thermochemical sorption refrigeration cycle

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ABSTRACT

A combined double-way thermochemical sorption refrigeration thermodynamic cycle was proposed and tested. Both adsorption refrigeration and resorption refrigeration processes were combined in order to improve the system performance. Two different consolidated composite materials were used as the reactive sorbents and ammonia was used as the refrigerant. Experimental results showed that a system operating with such proposed cycle can have two useful cold productions during one cycle at the expense of only one heat input at high temperature. The average specific cooling power (SCP) during the adsorption refrigeration phase was 301 W kg^{-1}. Analysis of the experimental data showed that the driving equilibrium drop during the resorption process was much lower than that during the adsorption process, when the cold production temperature was similar. The proposed combined double-way sorption cycle has a larger cooling capacity per unit of heat input and the maximum theoretical coefficient of performance (COP) is 1.24 when $MnCl_2$ and $BaCl_2$ are used as the reactive sorbents.

Etude thermodynamique d'un cycle frigorifique à sorption thermochimique solide/gaz

Mots clés : Système à absorption ; Système à résorption ; Ammoniac ; Chlorure ; Baryum ; Manganèse ; Cycle thermodynamique ; Étude ; Performance

1. Introduction

Environmental pollution and energy shortage are becoming more and more serious as the industrial economies develop rapidly worldwide. This energy shortage has become one of major constraining factors to the economic and social development in some countries. Every year, enormous amount of waste heat (e.g. industrial waste heat, exhaust gases from

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Nomenclature

A_{EV}	cross section area of evaporator (m^2)
COP	coefficient of performance
$H_c(T_c)$	enthalpy of refrigerant at condensation temperature ($kJ\,mol^{-1}$)
$H_e(T_e)$	enthalpy of refrigerant at evaporation temperature ($kJ\,mol^{-1}$)
$L(t)$	liquid level inside the evaporator during the synthesis phase (m)
$L(t_0)$	liquid level inside the evaporator at the beginning of the synthesis phase (m)
M	molar mass of refrigerant ($g\,mol^{-1}$)
$m_{ad}(t)$	amount of ammonia adsorbed by reactive salt ($kg_{NH_3}\,kg_{salt}^{-1}$)
$m_{ad}(max)$	the maximum theoretical amount of ammonia adsorbed by reactive salt ($kg_{NH_3}\,kg_{salt}^{-1}$)
m_S	mass of reactive salt (kg)
P_c	constraint pressure (Pa)
$P_{eq}(T_{eq})$	equilibrium pressure (Pa)
P_o	reference pressure (1×10^5 Pa)
R	universal gas constant ($J\,mol^{-1}\,K^{-1}$)
SCP	specific cooling power ($W\,kg^{-1}$)
$T_{eq}(P_{eq})$	equilibrium temperature (K)
t	cycle time during the synthesis reaction phase (s)
X	global conversion of chemical reaction

Greek letters

ΔH_R	enthalpy of transformation ($kJ\,mol^{-1}$)
ΔH_{evap}	vaporization enthalpy of refrigerant ($kJ\,mol^{-1}$)
ΔH_{RH}	reaction enthalpy of HTS ($kJ\,mol^{-1}$)
ΔH_{RL}	reaction enthalpy of LTS ($kJ\,mol^{-1}$)
ΔS	entropy of transformation ($kJ\,mol^{-1}\,K^{-1}$)
ΔP	local equilibrium pressure drop (Pa)
n	order of chemical reaction
$\rho(Te)$	density of liquid ammonia at evaporation temperature ($kg\,m^{-3}$)
κ	kinetic coefficient of chemical reaction

Subscripts

ad	adsorption
de	desorption
eq	equilibrium
HTS	high-temperature salt
i	ideal
LTS	low-temperature salt
re	resorption

engines, etc) are directly released to the atmosphere or surface water without rational reutilization. These low-grade waste heats would become useful energy resources if they can be reutilized efficiently. In order to reduce the primary energy consumption and promote the economic and social sustainable development, it is desirable to recycle these low-grade waste heats and improve the energy efficiency by developing advanced energy utilization systems. Solid sorption refrigeration systems, powered by a wide range of low-grade thermal energy, received considerable attention in recent years due to its large energy saving potential (Wang et al., 2007). Furthermore, these systems have a lower environmental impact in comparison with vapor mechanical compression refrigeration systems because they employ nature friendly fluids (e.g. water, methanol, ammonia, etc) as refrigerants (Meunier, 1998).

Solid sorption refrigeration technology usually has the drawback of low coefficient of performance (COP) and specific cooling power (SCP). However, these figures may be improved by using better sorption materials, by enhancing heat and mass transfer in the reactive beds and by employing advanced sorption thermodynamic cycles (Wang and Oliveira, 2006). Some porous materials like expanded graphite (Mauran et al., 1993; Lu et al., 1996; Han et al., 1998; Wang et al., 2006; Oliveira and Wang, 2007), carbon fibers (Dellero et al., 1999; Aidoun and Ternan, 2002) and activated carbon (Cacciola et al., 1995; Wang et al., 2004) can be employed as additives to improve the mass transfer in reactive salts and prevent the agglomeration phenomenon.

Moreover, many better heat management strategies were used to improve the system performance in some advanced sorption cycles, such as the cascading cycle (Meunier, 1986), thermal wave cycle (Shelton et al., 1990), forced convection cycle (Critoph, 1996), heat and mass recovery cycle (Wang, 2001) and multi-stage cycle (Saha et al., 2003). In order to further improve the COP, several researchers proposed internal heat recovery strategy between different reactors in chemical heat pump. To accomplish such a task, the different reactors were filled with different reactive salts, and the reaction heat released by one salt during the synthesis reaction phase was utilized to regenerate the other salt during the decomposition reaction phase. This type of advanced cycle includes double-effect sorption cycle (Neveu and Castaing, 1993; Sorin et al., 2002), double-effect resorption cycle (Spinner, 1993; Goetz et al., 1997) and multi-effect sorption cycle (Li et al., 2007).

Conventional adsorption refrigeration systems based on the evaporation process have been widely discussed and they are already commercialized. The useful cold is produced by the vaporization heat of refrigerant during the adsorption phase. However, useful cold can also be obtained from the desorption heat of reactive salt at a low temperature for thermochemical sorption refrigeration system based on the resorption process. In this type of a system, the evaporator is replaced by a solid–gas reactor, and the reaction heat consumed during the decomposition reaction phase of the reactor is employed to produce the cooling effect.

In this paper, a combined double-way thermochemical sorption refrigeration thermodynamic cycle is proposed. Adsorption refrigeration process and resorption refrigeration process were combined to produce the useful cold during one cycle. The cycle characteristics of the double-way sorption cycle were experimentally investigated using a simple test unit. Moreover, the thermodynamic analysis of the combined double-way sorption refrigeration cycle was performed during the adsorption refrigeration process and the resorption refrigeration process, and the system performance operating with the proposed cycle was also predicted.