



A new target-oriented methodology of decreasing the regeneration temperature of solid–gas thermochemical sorption refrigeration system driven by low-grade thermal energy

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ABSTRACT

In this paper, an innovative target-oriented desorption methodology for decreasing the regeneration temperature of solid–gas thermochemical sorption refrigeration system is presented. This method uses a two-stage desorption thermodynamic cycle with two different reactive salts to decrease the overall driving heat source temperature. The working principle of the proposed desorption methodology is based on the different thermochemical equilibrium characteristics of reactive salts. Experimental verification showed that the proposed two-stage desorption methodology is feasible and effective in lowering the regeneration temperature of solid–gas thermochemical sorption refrigeration system. Moreover, the extent to which the regeneration temperature is lowered can be regulated by choosing the appropriate secondary reactive salt according to the available driving heat source temperature. The presented target-oriented desorption methodology can contribute to the widening of the scope of application of thermochemical sorption refrigeration technology utilizing low-grade thermal energy or renewable energy.

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1. Introduction

Solid–gas sorption refrigeration technologies have received a lot of attentions in the recent past due to the recognition of their potential for efficient energy utilization and ecological protection [1]. Unlike the conventional vapor compression refrigeration systems, solid–gas sorption refrigeration systems use environmentally friendly refrigerants as the working substance, and do not contribute to the depletion of ozone layer or global warming [2]. Moreover, sorption refrigeration systems have a large energy-saving potential because they can be driven by low-grade thermal heat source such as waste heat or solar energy.

Besides the basic intermittent sorption cycle, many advanced sorption refrigeration thermodynamic cycles have been reported, such as the cascading cycle [3], the thermal wave cycle [4], the forced convection cycle [5], the heat recovery cycle [6], the mass recovery cycle [7], the mass and heat recovery cycle [8], the double-effect cycle with internal heat recovery process [9,10], the combined double-way cycle based on adsorption and desorption processes [11], the triple-effect cycle with two internal heat recovery processes [12], and the multi-effect cycle based on internal heat recovery and combined double-way sorption processes [13]. These advanced thermodynamic cycles were mainly developed with the aim of enhancing the working performance of sorption

refrigeration systems. For example, the multi-effect sorption refrigeration system can have four cold productions at the expense of only one high-temperature heat input during one cycle, hence can significantly improve performance. Numerical analysis performed by Oliveira et al. [14] showed that the advanced multi-effect cycle has the highest working performance among the conventional sorption thermodynamic cycles and the COP obtained was higher than one.

In efforts to widen the scope of application of sorption refrigeration technology, other advanced multi-stage thermodynamic cycles have been proposed to lower the driving heat source temperature of solid–gas sorption refrigerators. This makes it possible for a sorption refrigerator to effectively utilize the relatively low-grade thermal energy from a wider range of waste heat sources. Saha et al. [15] developed a three-stage sorption refrigeration cycle with six sorption beds, in which the different beds were filled with silica gel as the sorption material. Simulation results showed that the three-stage sorption system can be driven effectively by low-grade thermal heat with a temperature ranging between 40–95 °C. Hamamoto et al. [16] analyzed the influence of different mass allocation between the top and the bottom beds on the performance of a two-stage silica gel–water adsorption chiller. This chiller could be powered by waste heat at a temperature of 55 °C with the heat sink at environment temperature. Later, a two-stage activated carbon–ammonia sorption ice maker with mass recovery was investigated by Oliveira et al. [17] with the aim of improving the system performance. Experimental results showed

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Nomenclature

A_{EV}	cross section area of evaporator [m^2]	T_f	Heat transfer fluid temperature [$^{\circ}C$]
$L(t)$	liquid level inside the evaporator during the synthesis phase [m]	T_o	heat sink temperature [$^{\circ}C$]
$L(t_0)$	liquid level inside the evaporator at the beginning of the synthesis phase [m]	T_r	mean temperature of reactor [$^{\circ}C$]
$m_{ad}(t)$	amount of ammonia adsorbed by PRS [$kg_{NH_3} \cdot kg^{-1}_{PRS}$]	t	cycled time during the synthesis reaction phase [s]
m_{PRS}	mass of primary reactive salt [kg]	X	global conversion of chemical reaction
n_1	order of chemical reaction during the decomposition phase	<i>Greek letters</i>	
n_2	order of chemical reaction during the synthesis phase	ΔH_{evap}	evaporation enthalpy of refrigerant [$kJ \cdot mol^{-1}$]
P_c	condensation pressure of refrigerant [Pa]	ΔH_R	enthalpy of transformation [$kJ \cdot mol^{-1}$]
P_e	evaporation pressure of refrigerant [Pa]	ΔP	driving pressure difference [Pa]
P_{eq}	equilibrium pressure [Pa]	ΔT	driving temperature difference [$^{\circ}C$]
P^o	reference pressure [1×10^5 Pa]	ΔT_{drop}	decreasing range of regeneration temperature [$^{\circ}C$]
Q_{ads}	adsorption heat during the synthesis reaction heat [kJ]	ΔT_{SRS}	temperature difference during the synthesis reaction phase [$^{\circ}C$]
Q_{cond}	condensation heat of refrigerant [kJ]	ΔS	entropy of transformation [$kJ \cdot mol^{-1} \cdot ^{\circ}C^{-1}$]
Q_{des}	desorption heat during the decomposition reaction heat [kJ]	κ_1	kinetic coefficient during the decomposition phase
Q_{evap}	evaporation heat of refrigerant [kJ]	κ_2	kinetic coefficient during the synthesis phase
R	universal gas constant [$kJ \cdot mol^{-1} \cdot ^{\circ}C^{-1}$]	$\rho(T_e)$	density of liquid ammonia at evaporation temperature [$kg \cdot m^{-3}$]
T_a	adsorption temperature [$^{\circ}C$]	<i>Subscripts</i>	
T_c	condensation temperature [$^{\circ}C$]	<i>ads</i>	adsorption
T_d	desorption temperature [$^{\circ}C$]	<i>des</i>	desorption
T_e	evaporation temperature [$^{\circ}C$]	<i>eq</i>	equilibrium
T_{ea}	synthesis equilibrium temperature [$^{\circ}C$]	<i>PRS</i>	primary reactive salt
T_{ed}	decomposition equilibrium temperature [$^{\circ}C$]	<i>R</i>	reactor
T_{eq}^1	equilibrium temperature [$^{\circ}C$]	<i>SRS</i>	secondary reactive salt
T_{eq-PRS}^1	decomposition equilibrium temperature of PRS in conventional desorption cycle [$^{\circ}C$]	<i>L/G</i>	liquid–gas equilibrium line
T_{eq-PRS}^2	decomposition equilibrium temperature of PRS in two-stage desorption cycle [$^{\circ}C$]	<i>S/G</i>	solid–gas equilibrium line

that the cycled mass of refrigerant could be enhanced by more than 42% by employing a mass recovery process in the two-stage sorption cycle. This shows that mass recovery is an effective technique to enhance the performance of sorption machines for ice making. However, for the aforementioned two/multi-stage physisorption refrigeration cycles, the decreasing extent of regeneration temperature cannot be regulated according to the available heat source temperature due to its inherent bivariant characteristic. Moreover, the cycled mass of refrigerant usually become lower in the two-stage cycles when compared with the conventional single-stage cycles, and thus the cooling capacity of physisorption refrigeration would be reduced.

Solid–gas sorption refrigeration can be divided into thermochemical sorption and physical sorption based on the type of sorption working pairs [18]. The different sorption beds in the above-mentioned advanced multi-stage cycles contain the same physisorption material. However, it would be difficult to lower the driving heat source temperature when these advanced multi-stage cycles are employed in the case of thermochemical sorption refrigeration cycles. This is because physisorption has bivariant characteristics, whereas chemisorption has monovariant characteristic. Therefore, only chemical sorption working pairs with at least two reaction equilibrium lines can be used to lower the driving heat source temperature in a multi-stage sorption cycle [19]. It is therefore not feasible to reduce the regeneration temperature of a thermochemical sorption refrigeration system by using conventional multi-stage desorption technologies based on the same sorption materials. This is because there will be no variance in the equilibrium reaction lines. Moreover, the extent to which the driving temperature can be lowered depends on how far the

different reaction equilibrium lines for the chemical sorption working pair used. The further is the equilibrium lines of the working pair, the larger is the decrease magnitude in the regeneration temperature.

For solid sorption cooling systems, chemical working pairs usually have the advantage of higher sorption capacity and volume cooling density over physical adsorbents. This means that a sorption refrigeration system based on thermochemical process has a potential of reduced size and hence maybe lower the manufacturing costs of refrigeration devices, compared to a system based on physisorption process. Researchers in the field of solid–gas sorption refrigeration have recently paid more attention to the thermochemical sorption refrigeration due to the above well-known advantages [20]. However, for most metallic salt–ammonia chemical working pairs, the driving heat source temperatures are usually high. Furthermore, the driving temperature may be even higher if a lower evaporation temperature is required such as in sorption ice making or deep-freezing process [21]. High driving temperature hinders the widespread application of thermochemical sorption systems, especially for the utilization of solar energy or relatively low-grade thermal energy.

In this paper, an innovative target-oriented desorption methodology for decreasing the regeneration temperature of solid–gas thermochemical sorption refrigeration system is proposed to overcome the drawbacks of the conventional desorption cycle. A two-stage thermochemical desorption thermodynamic cycle based on two different reactive salts is employed to lower the driving heat source temperature. The decreasing extent of regeneration temperature can be changed according to the available heat source temperature by choosing the secondary reactive salt. Moreover,

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