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Integrated energy storage and energy upgrade, combined cooling and heating supply, and waste heat recovery with solid–gas thermochemical sorption heat transformer

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ABSTRACT

Thermal energy storage is a key technology for global energy sustainability. It plays a vital role in renewable energy application and waste heat recovery by adjusting the time-discrepancy, space-discrepancy and instability between energy supply and energy demand. A promising multifunctional solid–gas thermochemical sorption heat transformer is proposed in this paper for integrated energy storage and energy upgrade, combined cooling and heating supply, and recovering waste heat. Thermal energy is stored in form of chemical potential resulting from thermochemical sorption process of solid–gas working pair. The operating principle and working performance of the proposed thermochemical sorption heat transformer is analyzed and compared at different operating conditions. Thermodynamic analysis showed that the advanced thermochemical sorption heat transformer has multipurpose energy application for integrated energy storage as well as energy upgrade, combined cooling and heating supply, and waste heat recovery. Moreover, it has a distinct advantage of 10 times energy density higher than conventional sensible heat and latent heat storage methods. This makes it a very promising compact high energy density heat storage method for integrated energy storage and energy upgrade. The presented energy storage technology can promote the application of thermal energy storage and waste heat recovery in large-scale industrial processes as well as the use of renewable energy sources.

1. Introduction

There has been growing efforts to improve energy utilization efficiency around the world, especially in recent years, to overcome energy shortage. These efforts have sparked the development of different thermal energy storage technologies to make them effectively utilize the low-temperature heat from industrial factories, buildings, homes, and electric appliances, or even use renewable energy sources [1–5]. The common methods used for thermal energy storage include sensible heat energy storage, latent heat energy storage using phase change material (PCM), and thermochemical energy storage. It has been widely acknowledged that thermal energy storage technology is an effective method for adjusting the time-discrepancy, space-discrepancy and instability between energy supply and energy demand, such as solar energy utilization, peak and off time consumption of electricity, energy conservation, cold storage, thermal energy management, among others [6].

A lot of efforts have been devoted within the past several decades to recovery waste heat from industrial processes. Thermal energy storage is one of optimizational methods for energy utilization systems in enhancing the working reliability and energy efficiency of a wide range of residential and industrial energy devices. With economic development, however, energy consumption in industrial processes has consequently increased. It is estimated that an enormous amount of low-grade thermal energy is lost as waste heat every year, which results to thermal pollution to environment. These low-grade waste heats can become useful energy resources if well harvested, through contribution to industrial development by reducing primary energy consumption and protecting the environment. Conventional methods of waste-heat recovery employed heat exchangers for preheating the combustion air or process water. In recent years, heat pump technologies have been proposed to recover low-temperature waste heats as efficiently as possible by upgrading them to higher temperatures using advanced heat transformer methods [7,8].

There is increased need for the development of advanced, compact and high energy density thermal energy storage for large-scale industrial processes and the utilization of renewable energy.

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Nomenclatures

COP_c	coefficient of performance for cold production
COP_h	coefficient of performance for heat production
C_{p-NH_3}	specific heat of ammonia [kJ/(kg °C)]
C_{p-R}	specific heat of metallic reactor [kJ/(kg °C)]
C_{p-s}	specific heat of reactant [kJ/(kg °C)]
M_R	mass of metallic part of reactor [kg]
M_s	mass of reactant [kg]
$M_{s-reaction}$	mass of reactant that has reacted with refrigerant [kg]
M_{NH_3}	mass of ammonia [kg]
M_{NH_3-R}	mass of metallic part in ammonia evaporator [kg]
P_c	condensation pressure [Pa]
P_e	evaporation pressure [Pa]
P_{eq}	reaction equilibrium pressure [Pa]
P_h	high evaporation pressure of refrigerant [Pa]
P_l	low evaporation pressure of refrigerant [Pa]
P^0	reference pressure [1×10^5 Pa]
Q_{cond}	condensation heat of refrigerant [kJ]
Q_{evap}	evaporation heat of refrigerant [kJ]
Q_{H-evap}	heat consumption by evaporator during charging phase [kJ]
Q_{in}	total amount of heat consumption during charging phase [kJ]
Q_{L-evap}	useful cold production by evaporator during discharging phase [kJ]
Q_{out}	useful heat production during the discharging phase [kJ]
Q_R	reaction heat of reactant [kJ]
$Q_{s-metal}$	sensible heat consumption of metallic part of reactor [kJ]
Q_{s-salt}	sensible heat consumption of reactant [kJ]
q_c	cold storage density [$kJ/kg_{reactant}$]
q_h	heat storage density [$kJ/kg_{reactant}$]
R_0	universal gas constant [kJ/(mol °C)]
S_xCl_y	metal chloride
T_c	condensation temperature [°C]
T_e	evaporation temperature [°C]
T_{eq}	reaction equilibrium temperature [°C]
T_{he}	high evaporation temperature of refrigerant [°C]
T_{in}	heat input temperature [°C]
T_{le}	low evaporation temperature of refrigerant [°C]
T_0	ambient temperature [°C]
T_{out}	heat output temperature [°C]
X	global conversion of chemical reaction

Greek letters

ΔH_R	enthalpy of transformation [kJ/mol]
ΔH_{evap}	vaporization enthalpy of refrigerant [kJ/mol]
ΔS	entropy of transformation [kJ/(mol °C)]
$\Delta T_{upgrade}$	magnitude of temperature upgrade [°C]
ΔT_c	temperature difference during condensation process [°C]
ΔT_e	temperature difference during evaporation process [°C]
ξ_R	the percentage of chemical reaction heat of reactant
n, m	number of the moles of refrigerant

Subscripts

L/G	liquid–gas equilibrium line
S/G	solid–gas equilibrium line
load	loaded state
unload	unloaded state

In recent years, much attention has been paid on thermochemical energy storage due to its high energy storage density as compared to conventional thermal energy storage technologies [9–14]. Thermochemical sorption energy storage (TSES) is one of thermochemical energy storage methods and it is based on solid–gas thermochemical sorption process. They store thermal energy in form of chemical potential resulting from thermochemical sorption process of a solid–gas working pair. Based on exergy analysis, TSES system may be as efficient as other types of thermal energy storage system [15]. Moreover, TSES is more compact and has the ability to store thermal energy for several months at ambient temperature with only a little energy losses. For these reasons, this kind of storage method is becoming interesting for long-term seasonal thermal energy storage in comparison with sensible heat and latent heat storage methods [16–20]. Although TSES can avoid the risk of energy release ahead of desirable storage time, conventional TSES process faces a challenge of low-temperature heat production during the discharging phase (especially in winter when this kind of technology is used for seasonal energy storage). Mauran and co-workers [21,22] investigated a solid–gas thermochemical sorption energy storage process using strontium bromide–water sorption working pair for long-term solar thermal storage system. Their system prototype had a driving heat input temperature of 70–80 °C during the charging phase in summer while produced a heat out temperature of 35 °C during the discharging phase in transition-seasons. Such a low heat out temperature would become even lower in case of heat production during winter due to the decrease in ambient temperature. In order to overcome the drawback of conventional TSES systems, Li et al. [23] proposed a novel dual-mode thermochemical sorption energy storage system for long-term seasonal storage of solar thermal energy using calcium chloride–ammonia sorption working pair. The stored thermal energy was released during winter under two discharging modes depending on the ambient temperatures. At relatively higher ambient temperature in winter, it produced useful heat directly, whereas at lower ambient temperatures, the stored thermal energy was upgraded using a solid–gas thermochemical sorption heat transformer cycle. This method of employing seasonal energy storage can assure an appropriate heat output temperature for space heating application in winter even at an ambient temperatures as low as −30 °C.

Solid–gas thermochemical sorption heat transformer can be used to upgrade the temperature of low/middle-grade waste heat. It can also provide high storage capacity and wide range of working temperatures when compared with other kinds of heat transformers. Yu et al. [24] reviewed research on the different solid–gas thermochemical sorption heat transformer technologies based on adsorption or resorption processes. In order to achieve energy storage and energy upgrade of low-temperature waste heat as well as assure a stable heat output temperature during the discharging phase, Li et al. [25] developed an innovative target-oriented solid–gas thermochemical sorption heat transformer. The stored thermal energy was effectively upgraded by introducing a pressure-reducing desorption method during energy storage process and a temperature-lift adsorption technique during energy release process. This thermochemical sorption heat transformer had distinct advantages due to its target-oriented characteristics in comparison with the conventional thermochemical sorption heat transformer. One of the outstanding advantages is that the thermochemical sorption heat transformer could give the flexibility of deciding the temperature magnitude of energy upgrade of low-grade thermal energy.