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# Experimental investigation on a novel solid-gas thermochemical sorption heat transformer for energy upgrade with a large temperature lift

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ABSTRACT

Heat transformer is an effective technology for the recovery and reutilization of low-grade waste heat by upgrading its temperature to meet the energy demand. Low temperature-lift capacity is the common drawback for conventional heat transformers based on sorption process or heat pumps. A novel solid-gas thermochemical sorption heat transformer was developed for the energy upgrade of low-grade waste heat with a large temperature lift based on the pressure-reducing desorption and temperature-lifting adsorption techniques. The working performance and feasibility of the large-temperature-lift thermochemical sorption heat transformer was investigated and analyzed using a group of sorption working pairs of $MnCl_2$-$SrCl_2$-$NH_3$. Expanded graphite was employed as the porous additive to enhance the heat and mass transfer of reactive salts. The experimental results showed that the proposed solid-gas thermochemical sorption heat transformer is feasible to achieve energy upgrade with a large temperature lift. It has the potential to upgrade the low-grade heat from 96 °C to 161 °C using $MnCl_2$-$SrCl_2$-$NH_3$ sorption working pairs, and the exergy efficiency and energy efficiency are as high as 0.75 and 0.43, respectively. The temperature-lift range is relevant to the global conversion of reactive salt and sensible heat consumption of reactor. It is desirable to improve the temperature-lift range and energy efficiency by increasing the global conversion and decreasing the mass ratio of metallic part of reactor to reactive salt.


## 1. Introduction

The depletion of fossil fuels and the challenge of global warming are urging the world community to take initiatives to steer energy sources toward renewable energy and take measures to improve the energy utilization efficiency. There exists an enormous amount of low-grade energy resources such as the industrial waste heat, renewable energy, and exhaust gases from engines. However, a large amount of low-grade heat is usually directly released to the atmosphere or surface water without reutilization due to the limitation of their relatively low temperatures. The rational utilization of low-grade thermal energy is an essential solution to compensate for the inconsistency between the insufficient energy supply and growing energy consumption [1–3]. These low-grade waste heats would become useful energy resources if they can be reutilized as efficiently as possible by upgrading their working temperatures using advanced heat transformer technologies. The common methods to realize the temperature lift of low-grade heat mainly include electrical-powered vapor compression heat pump and thermal-driven chemical heat pump/heat transformer based on solid/liquid-gas sorption process or chemical reactions. The electrical-powered heat pump usually has higher system efficiency than the thermal-driven heat transformer, but the former still consumes high-grade electricity as main energy. Thermal-driven heat transformers have the remarkable advantage of energy-saving due to the fact that it can be driven by the low-grade/middle-grade renewable energy or wasted heat [4,5].

Comparing to absorption and physical adsorption heat transformers, solid-gas thermochemical sorption heat transformer has the advantages of high energy density, stable working temperature, wide operating temperature range, etc. Recently, solid-gas thermochemical sorption heat transformer based on metal chloride/ammonia working pair has been developed rapidly among these heat transformers. It seems very suitable for the energy upgrade of different low-grade/middle-grade heat sources in the industrial heat recovery systems due to its wide candidates of

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**Nomenclature**

| | | | |
|---|---|---|---|
| HTR | high-temperature reactor | $T$ | temperature, °C |
| LTR | low-temperature reactor | $\dot{m}$ | mass flow rate, kg/s |
| PRS | primary reactive salt | $C$ | specific thermal capacity, J/kg K |
| SRS | secondary reactive salt | $CM$ | overall thermal capacity, kJ/K |
| EG | expanded graphite | $t$ | scanning interval time, s |
| AV | ammonia valve | $n$ | scanning times |
| $\eta$ | energy efficiency | $m$ | mass, kg |
| $\eta_{ex}$ | exergy efficiency | | |
| R | mass ratio | *Subscript* | |
| X | global conversion | in | inlet |
| L | liquid | out | outlet |
| G | gas | a | ambient |
| $\phi$ | sensible heat recovery efficiency | ev | evaporation/evaporator |
| | | cn | condensation/condenser |
| *Dimensional variables* | | H | high |
| $e_x$ | exergy quantity, kJ | L | low |
| $Q$ | heat quantity, kJ | | |

sorption working pairs with different operating temperatures and the monovariant characteristic of chemical reaction, which make it adapt to different occasions and have stable operating temperature [6–9].

For solid-gas thermochemical sorption heat transformer, thermal energy is stored and upgraded using decomposition (also desorption) and synthesis (also adsorption) reaction processes between a sorption material (also adsorbent) and a gas (also adsorbate or refrigerant) [10]. The basic thermochemical heat transformers can be divided into the single-salt system and double-salt system. The single-salt system is made of a reactor and a condenser/evaporator, which is called the basic thermochemical sorption heat transformer. The double-salt system is made of two reactors with different reactive salts, which is called the basic thermochemical resorption heat transformer. Generally, the single-salt system needs high system pressure in order to realize the large temperature lift. It is very important to control the system pressure within a reasonable range by setting a suitable evaporation temperature to avoid the safety problem caused by high system pressure. Thus, the single-salt system usually has relatively low temperature-lift range due to the limitation of system pressure. To overcome this shortcoming, Goetz et al. [11] proposed a two-salt system using two reactors with different reactive salts, and analyzed the possibility of thermo-transformation up to 350 °C. Haije et al. [12] investigated the feasibility of a thermochemical resorption heat transformer with temperature lift from 155 to 200 °C based on the salts LiCl, $MgCl_2$ and $NH_3$ at ambient temperature of 20 °C, and the COP (0.11) was only 40% of the expected theoretical value. Later, a series of advanced thermochemical cycles were introduced in order to further lift the low-grade/middle-grade heat and improve the system efficiency, namely, two-stage three-salt cycle [13], double-effect three-salt cycle [14], two-stage two-salt cycle [15], two-stage three-salt cycle with internal heat recovery [16], and four-salt cycle with internal heat recovery [17]. Yu et al. [18] compared different thermochemical heat transformer cycles based on chloride/ammonia working pairs, and found that only the two-stage three-salt cycle and the two-stage four-salt cycle with internal heat recovery could realize the temperature lift more than 50 °C with energy efficiency about 0.28 and exergy efficiency about 0.42 when heat source temperature was about 100 °C.

However, these heat transformer cycles would be very complicated and have some drawbacks for practical application. For heat transformer cycles based on thermochemical resorption processes, they usually suffer from the fluctuation and decrease of heat output temperature due to the oscillation of system operating pressure, which is caused by the mismatch of chemical reaction rates in different reactors [16,18]. For heat transformer cycles based on thermochemical adsorption processes, the heat output temperature is determined by the operating pressure of working gas in the evaporator, so it can keep stable heat output temperature by controlling the evaporation temperature at a constant level. Even though the higher operating pressure in the evaporator contributes to higher heat output temperature in the reactor, it also causes the safety problem. To overcome the above-mentioned drawbacks of heat transformer cycles, Li et al. [19] proposed an innovative target-oriented solid-gas thermochemical sorption heat transformer for the integrated energy storage and energy upgrade of low-grade thermal energy. It had the capacity of realizing the stable heat output temperature and relatively large temperature lift by combining the merits of conventional thermochemical adsorption and resorption heat transformer cycles. A pressure-reducing desorption method was adopted by employing a thermochemical resorption process to lower heat input temperature during energy storage phase, and a temperature-lift adsorption technique was used by employing a thermochemical adsorption process to enhance energy upgrade capacity and avoid the fluctuation of heat output temperature during energy release phase.

In this paper, a lab-scale solid-gas thermochemical sorption heat transformer prototype is designed and developed for the energy upgrade of low-grade heat with a large temperature lift based on the target-oriented thermochemical sorption cycle using pressure-reducing desorption and temperature-lifting adsorption techniques. The working performance and feasibility of the large-temperature-lift thermochemical sorption heat transformer are verified and analyzed using a group of sorption working pairs of $MnCl_2$-$SrCl_2$-$NH_3$. Expanded graphite is employed as the porous additive to enhance the heat and mass transfer of reactive salts. Moreover, the temperature lift, energy efficiency and exergy efficiency are investigated experimentally and the potential improved performance method is discussed.

## 2. Fundamental and selection of sorption working pair

Fig. 1 shows the working principle of the novel solid-gas thermochemical sorption heat transformer for energy upgrade with a large temperature lift. The pressure-reducing desorption and