ARTICLE IN PRESS

Applied Energy xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Analysis of resorption working pairs for air conditioners of electric vehicles

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HIGHLIGHTS

- Resorption cycle is proposed for the air conditioners (ACs) of electric vehicles (EVs).
- Intermittent working modes of the cycle won't consume the electricity of on-board batteries.
- Resorption working pair of $CaCl_2$-NH_4Cl-NH_3 has reasonable energy density and high COP.
- Energy consumption of resorption AC is reasonable if compared with conventional AC of EVs.

ARTICLE INFO

Article history:
Received 5 January 2017
Received in revised form 13 June 2017
Accepted 27 June 2017
Available online xxxx

Keywords:
Electric vehicle
Air conditioner
Resorption
Halide
Energy density
COP

ABSTRACT

Conventional compression type air conditioners (ACs) consume a large part of the electricity of batteries on-board of electric vehicles, and that will make the cruising mileage shorter. Sorption and resorption cycles, which are intermittent, may solve this question by the energy storage phases. Both sorption and resorption cycles are analyzed and compared, and both of them have simpler structure if compared with conventional AC for that only two heat exchangers are required. The equilibrium performance analysis shows that resorption working pairs has higher energy density and coefficient of performance (COP) than that of sorption working pairs when the high temperature salt of resorption cycle is same with the halide of sorption cycle. The experimental Clapeyron curves are studied, and $CaCl_2$-NH_4Cl-NH_3 has best performance. Compared with $MnCl_2$-$CaCl_2$-NH_3 and $MnCl_2$-NH_4Cl-NH_3, the energy density and COP of $CaCl_2$-NH_4Cl-NH_3 improves by 160% and 35% at least, respectively. The performance of $CaCl_2$-NH_4Cl-NH_3 is also compared with that of $CaCl_2$-NH_3. They have similar smallest energy density, and $CaCl_2$-NH_4Cl-NH_3 has higher COP if consider the working conditions in the whole year. The energy required for the electric car with a resorption AC is 0.23–0.265 kWh/km, which is acceptable if compared with the results of conventional AC.

1. Introduction

Along with the lack of petroleum in the world, serious pollution of atmosphere, and the advance of battery technology, electronic vehicles (EVs) have been recognized as the main way of alteration and development of automobile industry in 21st century [1,2]. But EVs have two shortcomings of short driving distance and high cost owing to the batteries. The reducing energy consumption of on-board batteries in driving process is paramount for the long cruising mileage [3].

Air conditioner (AC) is the important component in the EVs to keep the cabin comfort. Currently the AC in EVs is mainly conventional compression type AC driven by the electricity of batteries onboard. It was reported that the air conditioning system constituted the major energy consumption of a EV, which was up to 65% [4]. More specifically, for EV with passengers the energy consumption due to air conditioning system can reduce the overall driving range by 40–60% under typical standard driving testing conditions [5,6].

But the research nowadays mainly focusses on increasing the comfort level other than reducing the energy consumption of the ACs for EVs. For example, Miranda et al. designed a new climate control system by using a direct energy conversion principle in the commercialization of modern EVs [7]. Chiu et al. investigated the regulation problem of thermal comfortableness and proposed control strategies for cabin environment. Results proved that the performance of the near optimal order-reduced control law was the most suitable method as that of standard LQR (Linear-Quadratic Regulator) [4]. Wang et al. established an integrated

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http://dx.doi.org/10.1016/j.apenergy.2017.06.077
0306-2619/

Please cite this article in press as: Wang LW et al. Analysis of resorption working pairs for air conditioners of electric vehicles. Appl Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.06.077

Nomenclature

a, *b*, *n*, *m*	reaction equilibrium constants
C_p	specific heat capacity (kJ/(kg K))
$C_{pAm(NH_3),hal}$	specific heat capacity of ammoniate compound with 1 kg sorbed ammonia (kJ/(kgK))
COP	coefficient of performance
E	energy density
ENG-TSA	expanded nature graphite treated with sulfuric acid
HTH	high temperature halide
LTH	low temperature halide
m_{hal}	mass of halide
p	pressure (Pa)
Q	heat quantity or refrigeration quantity (kJ)
T	temperature (K, °C)
x	sorption quantity
ΔH	evaporating latent heat of ammonia or the reaction heat for desorption process (kJ)

Subscripts

con	condensation
de, des	desorption
desL	desorption state of LTH
env	environmental
ev	evaporation
hal	halide
HP	heat pump
ref	refrigeration
res	resorption
sor	sorption
sorL	sorption state of LTH
sum	summer
win	winter

AC/HP (Heat Pump) system and applied it in a compact EV for improving the heating performance [8]. Qin et al. studied the traditional air source heat pump for EVs, and developed a refrigerant injection air source heat pump system in the cold region, which improved the heating capacity by 28.6% compared with the traditional system [9]. The ACs studied in all the references above have one common feature on the electricity input, which is provided by the on-board battery [10] because the cooling power output and electricity input processes proceed simultaneously.

If the electricity consumption and cooling power output phases of AC are able to be fulfilled by other alternative technologies separately, the energy consumption of AC can be provided by the mains electricity other than the batteries of EVs, and that means the cooling power energy can be stored in the system when a EV is charged by the mains electricity. Then the drawback of short driving distance caused by the AC will be overcome and the potential of the EVs will be further expected. The sorption refrigeration technology provides the possibility for that.

The sorption technology driven by the heat is recognized as one of the most prospective energy conversion technologies, which manifest various functions of refrigeration [11], energy storage [12,13], and electricity generation [14]. The intermittent working modes for heating and cooling of a sorption cycle [15,16] make it possible for serving as a type of energy storage AC [17,18]. It takes the advantages of high energy density, little heat loss, time and space discrepancy adjustment, which happens to overcome the problems for conventional EVs' AC [19]. High energy density accords with the concept of lightweight while time and space discrepancy adjustment with little heat loss provides more flexibilities. The research nowadays mainly focuses on the thermal energy storage with different sorption working pairs. Such as that Lourdudoss et al. [20] evaluated the three phase sorption cycle for thermal energy storage, which indicated that three phase sorption processes enjoyed a higher heat supply when compared with the sensible and latent heat energy storage. But the study didn't analyze the cooling power supply, which is required by the AC of EVs. Yu et al. [21] investigated on $LiCl_2$-water sorption thermal energy storage system for combined heat and cold output. Results showed that the novel composite adsorbent could reach a cold and heat storage density of 108 kWh/m^3 and 163.6 kWh/m^3, respectively. Such a working pair cannot be used for the EVs as well because the volume of the system is quite big for the low density of the sorbent. Later, an innovative dual-mode ammonia thermochemical energy storage cycle was proposed for seasonal storage and heat supply with little heat loss. It was indicated that coefficient of performance (COP) for heat storage could reach 0.6, and energy density was higher than 1000 kJ/kg under different working conditions [22]. Nonetheless, there will be one possible deficiency of such technology because ammonia is used as working fluid. The safety problem caused by liquid ammonia will be difficult to be dealt with for the bumps and vibrations of the EVs in the driving process.

Similar as sorption technology, resorption technology also could be applied for refrigeration and thermal energy storage. The basic resorption cycle is composed of two reactors with different halides, and evaporator/condenser is replaced by a reactor. Compared with sorption systems, resorption system has no ammonia liquid in the system [23]. Bao et al. [24] established one resorption system for cold storage and long distance air conditioning transportation. Results pointed out that COP under different conditions ranged between 0.20 and 0.31. Li et al. [25] analyzed $MnCl_2$-$CaCl_2$-NH_3 resorption cycle, and indicated its potential for high energy storage density. Moreover, our previous work have investigated the characteristics of resorption system for both direct heat supply [26] and combined heating and cooling modes [27]. Experimental results indicated that the largest energy storage density could reach 1706 kJ/kg. The maximum average cooling power achieved 1.07 kW during cold releasing phase. But there is no research work for adopting such type of cycles for AC of EVs.

In order to verify the feasibility of such types of ACs for EVs, based on our previous research on resorption system, different sorption and resorption working pairs are analyzed. The Clapeyron curves and sorption/desorption properties of sorbents are both tested under non-equilibrium conditions. Based on the results, the performance of resorption energy storage AC for EVs is analyzed.

2. Working principle of the cycles and development of sorbents

The conventional compression type AC includes the compressor, evaporator, condenser, liquid receiver, and expansion valve. The refrigerant vapor needs to be compressed by the compressor, and such a process consumes the electricity of batteries when the EVs are in motion, and will make the cruising mileage shorter.

Comparably, the sorption and resorption technology will separate the heat input (that is provided by the electricity) and cooling power output into intermittent phases, then the heat will be pro-

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