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Performance analysis on a novel sorption air conditioner for electric vehicles

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Abstract: A novel sorption air conditioner for electric vehicles is presented, which is expected to reduce electricity consumption of on-board battery with a longer cruising mileage. This technology may be an alternative solution to conventional vapor compression air conditioner for current electric vehicles. Expanded natural graphite is selected in the development of composite sorbent. Performance of novel sorption air conditioner is analyzed based on sorption characteristic of composite sorbent, and a model electric car is chosen for detailed evaluation. It is indicated that sorption technology is able to be applied into electric vehicles. Energy density in winter and in summer ranges from 757 kJ·kg⁻¹ to 1980 kJ·kg⁻¹ and 387 kJ·kg⁻¹ to 990 kJ·kg⁻¹ whereas energy efficiency ranges from 0.34 to 0.82 and from 0.19 to 0.42. Also worth noting that the extra mass of sorption air conditioner system will have limited influence on cruising mileage of electric vehicles, which results in a reduction less than 4.3%. In winter, the highest saved cruising mileage by using novel sorption air conditioner is close to 100 km. Even the lowest saved mileage in summer is still able to reach 21 km, which is about 7.5% of the maximum mileage.

Keywords: Sorption; Air conditioner; Electric vehicles; Composite sorbent

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23 Nomenclature

AC	Air conditioner
CD	Cold density ($\text{kJ} \cdot \text{kg}^{-1}$)
COP	Coefficient of performance
D	Power density ($\text{kW} \cdot \text{kg}^{-1}$)
ENG	Expanded natural graphite
EVs	Electric vehicles
F	Driving resistance
GWP	Global warming potential
GVs	Gasoline vehicles
HD	Heat density ($\text{kJ} \cdot \text{kg}^{-1}$)
M	Mass (kg)
ODP	Ozone depletion potential
P	Pressure (Pa)
PTC	Positive temperature coefficient
Q	Heat (J)
R	Gas constant ($\text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$)
S	Cruising mileage (km)
T	Temperature ($^{\circ}\text{C}$)

24 Greek letters

ΔH	Reaction enthalpy of sorbent ($\text{J} \cdot \text{mol}^{-1}$)
ΔS	Reaction entropy of sorbent ($\text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$)
η	Efficiency

25 Subscripts

a	Ambient
am	Ammonia
b	Battery
c	Cold
con	Condensation
eq	Equilibrium

eva	Evaporation
H	High
h	Heat
in	Input
L	Low
max	Maximum
mc	Mechanical and control
out	Output
q	Discharge of battery
R	Reaction
sorb	Sorbent
T	Transmission

26

27 **1. Introduction**

28 Energy specifically that from fossil fuels, is becoming increasingly scarce and expensive. It is
 29 extensively acknowledged that urban gasoline vehicles (GVs) have become a major source of energy
 30 consumption and pollution. To deal with this issue, electric vehicles (EVs) are considered as an
 31 alternative solution with few emission by using one or more electric motors for propulsion[1]. A long
 32 cruising mileage is expected as a ultimate goal for EVs in driving process with less consumption of
 33 on-board battery[2].

34 For GV, a compressor driven by the engine is performed to realize air cooling in summer. In
 35 winter waste combustion heat diverted from engine cooling circuit could supply the heat to cabin inside.
 36 Different from internal combustion engines, considerable energy is consumed to heat the interior of
 37 EVs, which inevitably requires extra electricity up to 65% from vehicles' battery in term of various
 38 operating conditions[3]. Although part of the heat could be harvested from electric motor and battery,
 39 there remains to be a large demand of heating power supplied from on-board battery, which will
 40 decrease the overall driving range by up to 60% under typical standard heating conditions[4, 5]. In
 41 order to reduce the impact of air conditioner (AC) on battery in winter, current methods mainly lie in
 42 positive temperature coefficient (PTC) heating[6], semiconductor heating[7] and vapor compression
 43 heat pump[8]. Although PTC heating has been commonly applied in commercial EVs, a large amount

of electricity is consumed due to its relatively low energy efficiency, which sometimes results in lack of motivation. Considering semiconductor heating for EVs, there are several shortcomings e.g. low coefficient of thermoelectric materials and poor ideal cooling performance. Also worth noting that thermoelectric reactor production is limited by the production of thermoelectric elements. Comparably, vapor compression heat pump is more inclined to be selected for EVs due to its high heating efficiency. It seems to be flexibly adapted to different types of EVs with few modification, which was once regarded as a future developing trend of AC for EVs[9]. But in the case of low ambient temperature i.e. below -10°C , heating performance of vapor compression heat pump will be remarkably attenuated, which cannot meet heating requirements of EVs since evaporation temperature of refrigerant is too low[10, 11]. When evaporator frosts in winter, heating performance will be further reduced with extra energy for defrosting, which also leads to safety problems in driving process[12]. In fact, vapor compression heat pump technology for EVs still needs to consume the electricity of on-board battery. Besides, most of the current researches of EVs focus on technology innovation to improve the capacity and efficiency of battery since battery is considered as the only energy resource. Nonetheless, it is admitted that heat and electricity load are often mutually independent, and electricity has a higher energy grade than heat. If electricity and heat can be charged and discharged respectively, vast potential working performance i.e. cruising mileage of EVs will be further explored. It is quite desirable to seek for an alternative method which could supply heat and cold without extra electricity consumption.

Sorption technology has been generally recognized as a prospective energy conversion method, which demonstrates various functions of refrigeration[13], heat pump[14], energy storage[15], carbon dioxide capture[16] and electricity generation[17]. Actually sorption refrigeration in GVs has been investigated theoretically and experimentally[18]. The core concept is to supply cooling power for vehicles through sorption systems driven by the exhaust heat of engine since waste combustion heat of GVs still has a high temperature[19]. Comparably, this could be completely different scenario for EVs, i.e. both heat and cold should be supplied with non-simultaneous heat input. Also no waste heat could be recovered to drive sorption system. To effectively overcome these difficulties, chemisorption AC could be a suitable candidate for EVs, which could flexibly adjusted to external conditions by using different metal halides due to its monovariant reaction process [20]. The intermittent operating mode and performance of heat and cold cogeneration[21] also meet the requirements, which simultaneously has a capability of energy storage[22]. Interaction between ammonia and metal halides is able to

provide a remarkable energy potential in exothermic process. It is worth noting that heat e.g. electric heat could be charged through sorption reaction when battery charges the electricity. The discharging processes of electricity and heat are also independent. Advantages of chemisorption AC such as high energy density, long-term storage with little heat loss, time and space discrepancy adjustment happens to overcome the problems of AC for EVs[23]. High energy density is consistent with lightweight concept of EVs while time and space discrepancy adjustment with little heat loss provides more flexibilities for AC. Compared with conventional vapor compression AC for EVs, a main modification is that compressor is replaced with sorption reactor, and other equipment are remained. Various researchers have investigated working pairs for various types of sorption reactors[24]. One remarkable fact is that granular metal halides usually have low sorption and desorption capacity due to the fact that heat and mass transfer performance will be attenuated by swelling and agglomeration in working processes[25]. Small sorption and desorption capacity increase the required mass of sorbent, which will inevitably result in excessive loads for EVs. Composite sorbent is usually considered as a common solution to overcome drawbacks of granular metal halides by using various porous matrices[26], which provides the possibility of EVs' air conditioner for real applications[27].

Our previous research has initially verified the feasibility of such type AC for EVs by using sorption and desorption characteristics of multi-salt chemisorption working pairs. The research is to present and compare the possible heat and cold output for EVs without considering metal part of reactor [28]. Since rare related researches are reported in terms of sorption AC for EVs, this paper aims to investigate working performance of novel sorption AC for EVs in terms of theoretical thermodynamics and practical factors i.e. metal ratio, mileage, etc. Sorption and desorption characteristics of composite sorbent are also used for detailed analysis.

2. Working principle of AC cycles for EVs

For better elaboration of sorption AC, conventional vapor compression AC for EVs is first introduced briefly as shown in Fig.1, which is mainly composed of a compressor, an evaporator, a condenser, a liquid receiver, and an expansion valve. Working process of conventional vapor compression AC is illustrated as follow: After expansion process of expansion valve, the refrigerant is evaporated in the evaporator, which will supply cooling power. Then the refrigerant vapor needs to be compressed to a higher pressure by a compressor and condensed in the condenser. In this process, part

of electricity will be consumed through on-board battery which will inevitably reduce the cruising mileage of EVs. As mentioned above, vapor compression AC of commercial EVs is generally used for supply cooling power in summer. If it is required for heating, flow direction of the refrigerant is reversed and the condensation heat will be used.

Fig.1. Conventional vapor compression AC for EVs.

Fig.2 indicates the basic principle of sorption AC, which could supply heat and cold, separately or heat and cold cogeneration. Sorption AC is composed of a sorption reactor, a condenser and an evaporator as shown in Fig.2a. Sorption reactor and condenser/evaporator i.e. liquid tank are connected with a mass channel and a refrigerant valve. In the charging process, sorption reactor is heated by external heat. Refrigerant is desorbed from sorption reactor to liquid tank, and then condensed by releasing its condensation heat to ambient heat sink. When charging process is finished, refrigerant valve between sorption reactor and liquid tank will be closed so that sorbent and refrigerant will be mutually separated. Thermal energy could be stored in form of chemical potential. Once heat and cold demands are required, refrigerant valve between sorption reactor and evaporator will open again. During the discharging process, liquid tank will be cooled to refrigeration temperature, and refrigerant evaporates and sorbed by sorption reactor. Evaporation latent heat of the refrigerant will supply useful cold for passengers inside the vehicles in summer while sorption heat could supply heat for passengers in winter.

In regard of chemisorption process, working pressure is determined by working temperature, which can be according to equation 1. On basis of this monovariant characteristic, sorption AC could be easily controlled and adapted to external heating and cooling conditions. Due to high reaction heat,

ammonia working pairs will be selected for further elaboration. Fig.2b indicates P - T schematic diagram of sorption AC. During the charging process, sorbent is heated from point D to point A. Refrigerant i.e. ammonia will be desorbed and flows into condenser. Desorption process happens from point A to point B. For real application, constraining temperature should be higher than T_{in} , which will result in a temperature driving potential. The higher driving temperature difference is, the faster desorption rate becomes. In the discharging process, evaporator is cooled from point B to point C whereas sorption reactor is cooled from point A to point D. Ammonia will be evaporated and then be sorbed by sorption reactor. Sorption process will proceed from point C to point D. In this process, the stable cold and heat output could be obtained by adjusting the temperature of sorption reactor and evaporator.

$$\ln(P_{eq}) = -\frac{\Delta H_R}{RT_{eq}} + \frac{\Delta S}{R} \quad (1)$$

Fig.2. The basic principle of sorption AC (a) schematic; (b) P - T diagram.

Compared with conventional vapor compression AC for EVs, a compressor is replaced with a sorption reactor in novel sorption AC system, and other equipment are still remained as shown in Fig.3.

The concerning working processes are listed as follow:

(1) Desorption process for charging heat. In this process valve 1 is closed and valve 2 is open. When

EV is charging the electricity for on-board battery, sorption reactor is charging the heat which could come from electric heat or low grade heat. Thus temperature difference potential will promote the desorption of sorbent i.e. ammoniates. The desorbed ammonia is then condensed in the condenser by rejecting condensation heat to environmental heat sink. The ammonia liquid is gradually accumulated in the receiver.

(2) Sorption process for heat and cold output. Valve 2 is closed and valve 1 is open in this process.

Ammonia in the receiver is expanded through expansion valve and then flow into the evaporator. In summer, sorption reactor will be cooled by ambient air outside EV and evaporator is circulated by air inside. Ammonia is evaporated in the evaporator and then be sorbed by sorption reactor. Cooling effect could be obtained by evaporation process, which will be supplied to the passenger inside EV. In winter, evaporator is circulated by the outside air while sorption reactor is circulated by the inside air. Sorption heat will be used for supplying heat inside the cabin.

Fig.3. Novel sorption AC system for EVs.

It is widely recognized that sorption reactors has various types, which could be determined by sorbents and external heating conditions[29]. With regard to its specific application for EVs, sorption reactor is expected to be well designed. It will have a great influence on the performance of sorption AC, which is worth elaborating in details.

Fig.4a shows the reasonable schematic diagram of sorption reactor for the application of EVs, which is composed of several unit tubes as shown in Fig.4b. Staggered arrangement and aligned arrangement are two main arrangement methods for unit tubes, which have their respective advantages. For the better overall heat transfer coefficient of sorption reactor, staggered arrangement is applied to connect unit tubes[30]. For further optimizing heat transfer, it is desirable to enhance thermal conductivity of sorbents inside each unit tube due to the fact that large thermal contact resistance for sorbent side has become a remarkable barrier[31]. Thus composite sorbent developed with the matrix of expanded natural graphite (ENG) is selected and compressed into unit sorption tube with mass channel remained, which is verified to improve thermal conductivity of sorbent effectively.

Fig.4. Sorption reactor of sorption AC system for EVs (a) schematic of sorption reactor;
(b) schematic of unit sorption tube.

3. Evaluation of sorption AC for EVs

Heat input of sorption AC for EVs in the charging process can be expressed as equation 2:

$$Q_{h,in} = Q_R + Q_{sorbent} + Q_{reactor} \quad (2)$$

where Q_R is reaction heat, $Q_{sorbent}$ is sensible heat consumed by ammoniate, $Q_{reactor}$ is sensible heat consumed by metal part of sorption AC.

Heat output of sorption AC for EVs in winter can be expressed as equation 3:

$$Q_{h,out} = Q_R - Q_{sorbent} - Q_{reactor} \quad (3)$$

Cold output of sorption AC for EVs in summer could be expressed as equation 4:

$$Q_{c,out} = Q_{eva} - Q_{am} - Q_{evaporator} \quad (4)$$

where Q_{eva} is evaporation heat of ammonia, Q_{am} is sensible heat of ammonia, Q_{am} is sensible heat consumed by metal part of evaporator when it is cooled from ambient temperature to evaporation temperature.

Heat density for heat output in winter could be expressed as equation 5:

$$HD = \frac{Q_{h,out}}{M_{sorb}} \quad (5)$$

where M_{sorb} is the mass of composite sorbent.

Heat efficiency for heat output in winter could be expressed as equation 6:

$$COP_h = \frac{Q_{h,out}}{Q_{h,in}} \quad (6)$$

Cold density for cold output in summer could be expressed as equation 7:

$$CD = \frac{Q_{c,out}}{M_{sorb}} \quad (7)$$

Cold efficiency for cold output in summer could be expressed as equation 8:

$$COP_c = \frac{Q_{c,out}}{Q_{h,in}} \quad (8)$$

4. Results and discussions

4.1 Theoretical performance of sorption AC

Since more electricity is consumed in winter than in summer, theoretical heat density and heat efficiency of sorption AC are analyzed in terms of various sorption and resorption working pairs, which are comprehensively compared as shown in Fig.5. Fig.5a and Fig.5b indicate heat density and COP_h , and the sensible heat of salt is considered for analysis. The detailed evaluation method in this part could refer to the reference[32]. It is indicated that heat input temperature of sorption AC for EVs is less than 160°C. With regard to heat density, one striking fact is that resorption working pairs have the same theoretical performance with that of sorption working pair. The highest theoretical heat density and

heat output efficiency could reach 2178 kJ·kg⁻¹ and 0.82 by using working pairs of CaCl₂-NH₃. This is mainly because CaCl₂ proceeds two reaction processes in the selected temperature range. Under this scenario, reaction heat of two reaction processes will be used for evaluating energy density and efficiency. Also worth noting that resorption working pair is not suitable to be applied in EVs, which will result in larger required volume and mass by using two sorption reactors. Thus CaCl₂-NH₃ working pair will be selected for further evaluation due to its higher heat output performance.

Fig.5. Theoretical heat density and COP_h of sorption AC for EVs (a) heat density; (b) COP_h .

Reaction processes of CaCl₂ with ammonia could be according to equation 9 to 11. Table 1 indicates the main parameters of CaCl₂ in regard of 30°C heat sink temperature, which is composed of equilibrium desorption temperature, reaction enthalpy, reaction entropy and maximum cycle sorption capacity. To simplify the description of chemisorption processes, phrases of CaCl₂ 8/4 and CaCl₂ 4/2 are used in the rest of this paper. E.g. CaCl₂ 4/2 represents the process in which CaCl₂ ammoniate reacts with ammonia from 2 moles to 4 moles.

Table 1. The main parameters of CaCl_2 [33].

Sorbent	Desorption temperature ($^{\circ}\text{C}$)	Reaction enthalpy ($\text{J}\cdot\text{mol}^{-1}$)	Reaction entropy ($\text{J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$)	Maximum cycle sorption capacity ($\text{kg}\cdot\text{kg}^{-1}$)
CaCl_2 4/2	97	42269	229.7	0.31
CaCl_2 8/4	86	41403	230.1	0.61

In order to evaluate working modes of sorption AC of EVs, CaCl_2 - NH_3 working pair is exemplified under a selected condition i.e. 35°C condensation temperature and 5°C evaporation temperature in summer as well as 10°C condensation temperature and 0°C evaporation temperature in summer, which is shown in Fig.6. As analyzed above, CaCl_2 proceeds two reaction processes, which means reaction will eventually proceed from CaCl_2 8/4 to CaCl_2 4/2. For clear illustration of working process, summer and winter condition are elaborated separately.

During the charging process in summer, CaCl_2 is heated by external heat with input temperature of 104°C , which is determined by equation 1 in terms of 35°C condensation temperature. Since Fig.6 indicates the ideal thermodynamic process, heat input temperature is desorption temperature of CaCl_2 4/2 without considering temperature difference of heat transfer. Ammonia will be desorbed and condensed at a condensation pressure of 1.35 MPa by releasing condensation heat to heat sink. During the discharging process in summer, evaporation heat of ammonia could supply cooling effect at an evaporation temperature of 5°C . The concerning thermodynamic cycle is A-B-C-D-A, in which A-B represents charging process and C-D denotes discharging process

Considering winter condition, heat input temperature of CaCl_2 could be lower to 83°C in the charging process, which corresponds to condensation temperature of 10°C . This process proceeds as A'-B'. In the discharging process, ammonia is also evaporated and sorbed by sorbent. Sorption heat of CaCl_2 will be used to supply heat at a sorption temperature up to 74°C , which corresponds to C'-D'.

Sorption temperature reveals a capability of output temperature. It is usually supply heat of 25°C to cabin inside in winter. Thermodynamic cycle is A'-B'-C'-D'-A'. It is worth noting that thermodynamic cycle of sorption AC in summer will have a larger pressure difference between evaporation pressure and condensation pressure than that in winter, which will result in a higher energy efficiency of sorption AC system in winter than that in summer.

Fig.6. P - T schematic diagram of sorption AC for EVs.

Global conversion rate is usually considered as a key parameter which represents the percentage of sorbent reacting with the refrigerant in the sorption and desorption process. It is recognized that global conversion rate is determined by various factors e.g. temperature and pressure potential. Before testing sorption characteristics, it is quite desirable to preliminary investigate the influence of global conversion rate on performance of sorption AC. Different global conversion rates of $\text{CaCl}_2\text{-NH}_3$ working pair are assumed, which range from 0.1 to 1. The results are calculated based on each global conversion rate as shown in Fig.7. Fig.7a and Fig.7b demonstrate winter and summer condition respectively due to different heat and cold loads. It is indicated that energy efficiency is more sensitive

to global conversion rate than energy density. When global conversion rate varies from 0.1 to 1.0 in winter condition, COP_h increases remarkably from 0.075 to 0.82, and heat density increases from 33 $\text{kJ}\cdot\text{kg}^{-1}$ to 1993 $\text{kJ}\cdot\text{kg}^{-1}$. Also in summer condition, COP_c increases from 0.15 to 0.42, and cold density increases from 201 $\text{kJ}\cdot\text{kg}^{-1}$ to 1003 $\text{kJ}\cdot\text{kg}^{-1}$.

Fig.7. Theoretical energy density and COP of sorption AC vs. different global conversion rates

(a) winter condition; (b) summer condition.

4.2 Performance analysis based on sorption characteristics and thermal capacity

For theoretical analysis, global conversion rate is able to reach 100% with an infinite reaction time and large temperature and pressure differential potential. Nonetheless, a full global conversion rate could rarely be achievable with limited time and temperature difference. Thus experimental global conversion rate will be significant for comprehensive evaluation of sorption AC. The concerning experimental sorption characteristics are investigated in terms of different evaporation temperatures and condensation temperatures in summer and in winter, which are shown in Fig.8 and Fig.9, respectively. The detailed testing process by using a specially designed experimental unit could be referred to our previous work[34]. Composite CaCl_2 is developed with ENG as porous matrix for heat

and mass transfer enhancement. Different from desorption temperature of 104°C and 83°C, heat input temperature of composite CaCl_2 is selected as 120°C for testing, which considers heat transfer resistance and enough temperature driving potentials. This selected temperature is exemplified for investigating the performance in terms of different evaporation and condensation temperatures. Also electrical heat and possible low grade heat could be utilized, which results in less energy input.

For winter condition, evaporation temperature is chosen in the range from -15°C to 10°C and sorption temperature is taken as 25°C. For summer condition, condensation temperature is controlled from 20°C to 45°C, and evaporation temperature is 5°C.

It is demonstrated that global conversion rate and sorption capacity increase with the increase of evaporation temperature. This is because global conversion rate is mainly determined by pressure potential between constraining evaporation pressure and theoretical equilibrium pressure. The higher evaporation temperature is, a larger pressure potential could become, which will result in higher global conversion. Similar reason could also explain the pressure potential between constraining condensation pressure and theoretical equilibrium pressure. Global conversion rate increases from 0.66 to 0.99 as evaporation temperature varies from -15°C to 10°C, which covers most of ambient temperature ranges in winter. Results indicate that composite CaCl_2 could reach a maximum ammonia sorption capacity of 0.9 $\text{kg}\cdot\text{kg}^{-1}$ at an evaporation temperature of 10°C, which accounts for about 99% of the maximum theoretical sorption capacity. Also worth noting global conversion rate and sorption capacity increase with the decrease of condensation temperature. One remarkable fact is sorption capacity is more sensitive to condensation temperature when compared with evaporation temperature. Sorption capacity ranges from 0.56 $\text{kg}\cdot\text{kg}^{-1}$ to 0.9 $\text{kg}\cdot\text{kg}^{-1}$, which accounts for 61.4% to 98.7% of the maximum theoretical sorption capacity. Our previous research revealed that granular CaCl_2 merely reached up to

70% of the maximum sorption capacity due to the severe swelling and agglomeration phenomenon[35].

Comparably, composite CaCl_2 could almost reach the maximum sorption capacity due to the addition of porous matrix i.e. ENG.

Fig.8. Sorption characteristics of composite $\text{CaCl}_2\text{-NH}_3$ vs. different evaporation temperatures in winter

(a) global conversion rate; (b) sorption capacity.

Fig.9. Sorption characteristics of composite $\text{CaCl}_2\text{-NH}_3$ vs. different condensation temperatures in

summer (a) global conversion rate; (b) sorption capacity.

Based on experimental characteristics of composite CaCl_2 , performance of sorption AC for EVs is

analyzed and compared in terms of different mass ratios between composite sorbent and metal part. For evaluating energy efficiency and density, sensible heat of the reactor will be considered due to the fact that metal part will play a negative role on cruising mileage of EVs. Fig.10 indicates COP_h and heat density with regard to winter condition. It is worth noting that energy efficiency and energy density increase with the increase of evaporation temperature in winter. Energy efficiency increases more sharply than that of energy density due to the fact that the extra heat loss of metal part. It is also indicated that the highest COP_h and heat density could reach 0.82 and $1980 \text{ kJ}\cdot\text{kg}^{-1}$, respectively when evaporation temperature is 10°C in winter. For mass ratio from 0 to 12, COP_h and heat density range from 0.34 to 0.82 and $757 \text{ kJ}\cdot\text{kg}^{-1}$ to $1980 \text{ kJ}\cdot\text{kg}^{-1}$ when evaporation temperature increases from -15°C to 10°C . It is demonstrated that heat density is relatively higher than cold density. This could be attributed to the fact that heat output is provided by sorption heat which is much higher than evaporation latent heat for cold output. Also in summer, energy efficiency and density increase with the decrease of condensation temperature, which is shown in Fig.11. For different condensation temperatures and mass ratios, COP_c and cold density range from 0.19 to 0.42 and $387 \text{ kJ}\cdot\text{kg}^{-1}$ to $990 \text{ kJ}\cdot\text{kg}^{-1}$, respectively. Considering theoretical analysis, mass ratio between sorbent and metal part is usually considered as 0 or 1, which will lead to a relatively high energy output. Comparably, mass ratio of real sorption system is usually higher than 3, and this ratio is possible to be reached with the improved manufacturing technology and optimized design of reactor.

In order to have a comprehensive understanding of sorption AC technology, mass ratio is defined as 3 to assess its influence on EVs. A model EV i.e. IONIO Electric is selected for further illustration, which is produced by Hyundai. The weight of this EV is about 1880 kg with a battery of $28 \text{ kW}\cdot\text{h}$, which could reach a maximum mileage of 280 km in summer. This model has a generalized meaning

by using sorption AC, which is representative among most types of EVs due to its medium size and typical arrangement of apparatus. Under this scenario, the space under the bonnet of EV is enough for placing sorption AC, and its concerning analysis is reasonable with regard to a basic concept and similar design. For some mini EVs with limited front space, sorption reactor could also be designed in other places of EVs e.g. car chassis.

Fig.10. COP_h and heat density vs. different mass ratios in winter (a) COP_h ; (b) heat density.

Fig.11. COP_c and cold density vs. different mass ratios in summer (a) COP_c ; (b) cold density.

At current stage, the main working mode of EVs is used for driving the distance between home and work place. Thus the driving time is relatively limited which is usually no more than 3 hours. For the selected model EV, the required cooling or heating load could be assumed as 2.5 kW without considering defrosting process in winter. Thus total required energy for sorption AC should be the product of power and time i.e. 7.5 kW·h when the driving time lasts 3 h. Under this scenario, the extra required mass and volume of sorption AC system for EVs are evaluated by dividing the required energy by energy density as shown in Fig.12. The extra required mass and volume are mainly determined by sorption reactor and pipes. It is worth noting that the required mass and volume of sorption AC system decrease with the increase of evaporation temperature in winter and the decrease of condensation temperature in summer. As shown in Fig.12a, the highest required mass and volume in winter are about 72 kg and 60 L respectively, which is able to be placed under the bonnet of all EVs. Comparably in Fig.12b, the highest required mass and volume in summer are about 85 kg and 129 L, which is still acceptable for most of EVs except for several very small type EVs. The larger mass and volume in summer should be considered for the design of sorption AC for EVs.

Fig.12. Extra required mass and volume of sorption AC system for EVs (a) in winter; (b) in summer.

It is worth noting that extra mass of sorption AC has a negative influence on cruising mileage of EVs, which will be further discussed in the rest of this paper. Cruising mileage of EVs in driving process can be expressed as equation 12[36]:

$$S = \frac{M_b D_b \eta_q \eta_{mc} \eta_T}{F} \quad (12)$$

where M_b is mass of battery, D_b is power density of battery, η_q is discharge efficiency of battery, η_{mc} is mechanical and control efficiency, η_T is transmission efficiency, F is driving resistance, which is mainly composed of friction and air resistance.

As mentioned above, the maximum cruising mileage of selected model EV could reach 280 km in summer when considering 20% energy consumption of the battery i.e. cruising mileage of selected model EV could reach up to 350 km without using AC. With regard to winter condition, at least 30% of electricity will be consumed for heating in terms of various operating conditions[12]. 30% of electricity consumption is selected for further evaluation, thus the maximum mileage of model EV in winter could reach 245 km. Due to the extra mass of system and varied sorption capacities, the maximum mileage cannot achieved. Therefore, Fig.13 demonstrates the cruising mileage of model EV and its concerning reduction under different operating conditions when considering the extra mass of sorption AC system. It is indicated that mileage of EV in winter ranges from 237.8 km to 239 km with reduction from 2.9% to 2.4% when compared with the maximum value of 245 km. Mileage of EV in summer ranges from 271.1 km to 268 km with reduction from 3.1% to 4.3%. One remarkable fact is that the extra mass of sorption system will have limited influence on cruising mileage of EV. The reason is elaborated as follow: The extra mass mainly affects friction which is a part of driving resistance according to equation 12. Also worth noting friction coefficient is quite low, which results in small increment for

driving resistance when other resistances keep constant. Since mileage and driving resistance are reversely related, the reduction of mileage is also limited.

Fig.14 reveals the saved mileage of sorption AC system for EVs in terms of various driving times, which range from 1 h to 3 h. -15°C evaporation temperature in winter and 45°C condensation temperature in summer are selected as severe working conditions, which represents the minimum saved mileage by using sorption AC. Influence of the mass of sorption AC is also taken into account. It is worth noting that saved mileage by using sorption AC in winter is much higher than that in summer due to the higher energy density in winter. The highest saved mileage in winter is close to 100 km. Even the lowest saved mileage in summer is still able to reach 21 km, which is about 7.5% of the maximum mileage of the selected model EV.

Fig.13. Cruising mileage of selected model EV and its reduction caused by extra mass

(a) in winter; (b) in summer.

Fig.14. Saved mileage of sorption AC system for selected model EV vs. driving time.

Table 2 demonstrates a comprehensive comparison between novel sorption AC system and conventional vapor compression AC system for EVs in terms of refrigerant, system compactness, energy source, mechanical stability, supply capacity, performance, cruising mileage and cost.

A controversial issue of sorption AC system is that ammonia is used as working fluid. Compared with Freon for vapor compression AC, ammonia is an environmental-benign refrigerant with zero ozone depletion potential (ODP) and global warming potential (GWP). It is admitted that ammonia is hazardous when it reaches a certain concentration. However, Freon could also be toxic under a high concentration. System maintenance and good design are considered as the solution, and then safety of sorption AC for EVs could be ensured. Also pungent smell of little ammonia could serve as a reminder for passengers inside EVs.

It is demonstrated that vapor compression AC for EVs is more compact than sorption AC since mass and volume of sorption reactor are larger than that of compressor. Nonetheless, there remains to be enough space under the bonnet of EVs, which could be used for placing sorption reactor. Thus the increased mass and volume of sorption AC is acceptable since there is no change to EVs' appearance.

Also worth noting that heat could be charged by electric heating or low grade heat. Two charging modes are proposed. One is that electricity is used to charge on-board battery and sorption AC, which doesn't change the current charging mode by using the same socket of EVs in charging station or other places with charging piles. It is quite convenient for users, but energy utilization efficiency is relatively low. The other is that low grade heat could be used for charging heat of sorption AC, which are independent of charging electricity for EVs. The advantage is that a higher system efficiency could be obtained. Charging station should also be reconstructed for the application of low grade heat.

The overall mechanical stability of sorption AC system will not be influenced significantly due to the fact that only compressor is replaced with sorption reactor. Both AC systems have enough capacity for supplying heat and cold. As mentioned above, at least 30% of electricity is consumed for heating in winter. If sorption AC is used for EVs, this part of electricity could be used for driving, thus more than 30% of cruising mileage could be increased. Thus thermodynamic performance of both AC systems has not so much comparability since the charging source and effect produced are different.

Last but not least, innovative technology not only brings opportunities e.g. saved mileage but also comes along with challenges e.g. increased cost. Initial investment of sorption AC must be higher than that of vapor compression AC. Compared with compressor, sorption reactor is the main cost increment of sorption AC system, which is composed of composite sorbent, metal part and valves. If analyzing the selected EV model based on Chinese market price, cost of compressor is about 1500 RMB. For a sorption reactor with similar power output, it will cost about 3000 RMB, in which sorbent will accounts for 500 RMB, metal part costs about 2000 RMB, and valves cost about 500 RMB. Thus initial cost of sorption AC will be 1500 RMB higher than that of vapor compression AC. The initial cost will be even higher for larger EVs due to increased cost of sorption reactor. More electricity of battery will

also be saved for large EVs. By using sorption AC system, the increment of initial cost is actually less than 5% cost of selected model EV, which is acceptable for commercial sectors.

Table 2. Comparison between vapor compression AC and sorption AC system for EVs.

Type	Vapor compression	Sorption
Refrigerant	Freon	Ammonia
System compactness	High	Moderate
Energy source	Electricity	Electricity/low grade heat
Mechanical stability	High	High
Supply capacity	Desirable	Desirable
Thermodynamic performance	High	Moderate
Cruising mileage	Standard	At least 30% higher
Cost	Standard	Less 5% increment of the cost of EV

5. Conclusions

A novel sorption AC is presented and designed to reduce electricity consumption of on-board battery for EVs. It is considered to be an alternative solution to conventional vapor compression AC, which aims to achieve a longer cruising mileage. Performance of sorption AC is analyzed in terms of energy density, energy efficiency, extra mass and saved mileage. Conclusions are yielded as follows:

- (1) Resorption working pairs have a same theoretical performance with that of sorption working pair. The highest theoretical energy density and efficiency for heat output could reach 2178 kJ·kg⁻¹ and 0.82 by using CaCl₂-NH₃. Sorption working pair is more suitable to be applied in

AC for EVs than that by using resorption working pair, which has less modification to EVs.

(2) Global conversion rate and sorption capacity increase with the increase of evaporation temperature and the decrease of condensation temperature. Global conversion rate of composite CaCl_2 increases from 0.66 to 0.99 as evaporation temperature varies from -15°C to 10°C in winter. Composite CaCl_2 can reach a maximum ammonia sorption capacity of $0.9 \text{ kg}\cdot\text{kg}^{-1}$ at an evaporation temperature of 10°C . For different condensation temperatures in summer, sorption capacity ranges from $0.56 \text{ kg}\cdot\text{kg}^{-1}$ to $0.9 \text{ kg}\cdot\text{kg}^{-1}$, which accounts for 61.4% to 98.7% of the maximum sorption capacity.

(3) Energy efficiency and density increase with the increase of evaporation temperature in winter and the decrease of condensation temperature in summer. In winter, COP_h and heat density range from 0.34 to 0.82 and $757 \text{ kJ}\cdot\text{kg}^{-1}$ to $1980 \text{ kJ}\cdot\text{kg}^{-1}$ in terms of different evaporation temperatures and mass ratios. In summer, COP_c and cold density range from 0.19 to 0.42 and $387 \text{ kJ}\cdot\text{kg}^{-1}$ to $990 \text{ kJ}\cdot\text{kg}^{-1}$.

(4) The extra mass of sorption AC system will have limited influence on cruising mileage of EV. Mileage of the selected model EV in winter ranges from 237.8 km to 239 km with reduction from 2.9% to 2.4% whereas mileage of the EV in summer ranges from 271.1 km to 268 km with reduction from 3.1% to 4.3%. Saved mileage by using sorption AC in winter is much higher than that in summer. In winter, the highest saved mileage of the selected model EV is close to 100 km. Even the lowest saved mileage in summer is still able to reach 21 km.

With the potentially wide use of EV technology in the near future, vapor compression AC could be gradually replaced with sorption AC by using composite sorbent, which will solve the problem for huge energy consumption of AC in the driving process. Also worth noting that heat dissipation of

on-board battery could be recovered as a part of heating. Thus the best solution is the combination of battery cooling system and sorption AC system. Both electricity and low grade heat could be used in the charging process to further improve energy efficiency.

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