Experimental investigation of a $\text{MnCl}_2/\text{CaCl}_2\text{-NH}_3$ two-stage solid sorption freezing system for a refrigerated truck

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Abstract: A $\text{MnCl}_2/\text{CaCl}_2\text{-NH}_3$ two-stage solid sorption freezing system consisting of a MnCl_2 sorption bed, a CaCl_2 sorption bed, an evaporator and a condenser is established for a refrigerated truck, for which the required refrigerating capacity is 1.13 kW at a refrigerating temperature of -5°C . Composite adsorbents of MnCl_2 and CaCl_2 developed by expanded natural graphite treated with sulfuric acid are utilized. The sorption/desorption process and the resorption process are coupled in the two-stage cycle. The experimental results show that the maximum refrigerating capacity of 1.25 kW and COP of 0.143 are obtained at a resorption time of 120 min when the hot air and refrigerating temperatures are 230°C and -5°C , respectively. In addition, the refrigerating capacity of 1.19 kW is achieved even when the hot air temperature is as low as 210°C , and such a result can satisfy the requirement for transporting fresh goods. The refrigerating capacity is 1.32 kW when the hot air and refrigerating temperatures are 270°C and -10°C , respectively, and the data are higher than the required refrigerating capacity. However, for refrigerating temperatures of -15°C and -18°C , the refrigerating capacity experimentally obtained could meet the requirement only when a truck is utilized for long-distance transportation.

Keywords: solid sorption freezing system; two-stage; composite adsorbent; refrigerated truck; exhaust heat

Nomenclature

A	heat transfer area, m^2
AV	ammonia valve
C	specific heat, $\text{kJ}/(\text{kg}\cdot\text{K})$
CV	air valve
EV	exhaust valve
ENG-TSA	expanded natural graphite treated with sulfuric acid
H	sorption reaction heat, J/kg
K	heat transfer coefficient, $\text{W}/(\text{m}^2\cdot\text{K})$
HTS	high-temperature salt
MTS	middle-temperature salt
M	total mass, kg
m	mass flow rate, kg/s
Q	heat transfer rate, W
T	temperature, K
t	time, s
Δx	cycle sorption quantity, kg/kg
φ	safety factor
W	electric power, W
η	heat -work conversion coefficient

Subscripts

ambient,env	ambient environment
cabin, in	interior of the cabin
des	desorption
cyc	cycle
met	metallic materials of the sorption bed
exh, in	inlet of the exhaust gas

exh, out	outlet of the exhaust gas
tot, ads	total mass of the adsorbent
ads	adsorbent
ref	refrigerant
tot	total
ins, ref	instantaneous refrigeration
ave, ref	average refrigeration
sorp, HTS	sorption process of the HTS bed
chilled air, in	inlet of the chilled air
chilled air, out	outlet of the chilled air
<i>COP</i>	coefficient of performance
<i>SCP</i>	specific cooling power per kilogram adsorbent

1. Introduction

Currently, more and more refrigerated trucks are widely employed to transport frozen, fresh and perishable goods. Mechanical vapour compression refrigeration systems are installed in most refrigerated trucks, and the compressors are driven by the engines, which certainly will increase greenhouse gas and particulate matter emissions. The typical refrigerated transport equipment produces approximately 50 tons of CO₂ annually with a fuel consumption of 0.47 L/h per 1 kW of refrigerating capacity, operating at an ambient temperature of 30°C and a -20°C box inside temperature. The CO₂ emission will increase more than 30% after six years and more than 50% after nine years [1].

Considering that the engine exhaust gas has a relatively high temperature and a large amount of heat, the

solid sorption refrigeration cycle can be used to recover the exhaust heat and provide refrigerating capacity [2, 3, 4].

Solid sorption refrigeration systems mainly involve an adsorption cycle or a solid chemisorption cycle. The working pairs for the adsorption cycle are silica gel-water, zeolite-water, activated carbon-water, etc., and the working pairs for the chemisorption cycle are solid halides-ammonia and solid halides-water. Solid sorption air-conditioning systems for vehicle HVAC (heating ventilation air conditioning) applications have been investigated extensively. Zhang [5] designed an adsorption cooling system driven by the waste heat of a diesel engine; the adsorber was composed of some cylindrical steel double-tube to enhance the heat transfer between the exhaust gas and the adsorber. Jiangzhou et al. [6] and Lu et al. [7] established a locomotive driver-cabin adsorption air-conditioner using zeolite-water as the working pair that was directly driven by the exhaust gas of the internal-combustion engine. Zhong et al. [8] designed a zeolite-water adsorption air-conditioning system for heavy-duty truck applications, and this system was designed to satisfy the cooling requirement for idle reduction of long-haul trucks. Mohammad et al. [9] investigated the physicochemical properties of oil palm shell-based activated carbon and its feasibility for application in adsorption air-conditioning systems. Syed et al. [10] presented a two-stage indirect exhaust heat recovery system for an automotive engine employing an effective lumped parameter model to simulate the dynamic behaviours of an adsorption chiller, which was established for air conditioning purposes in the vehicle cabin. However, the above adsorption refrigeration systems are all employed for vehicle air conditioning, and the refrigerating temperature is generally above 5°C. Consequently, these systems cannot be employed for refrigerated trucks whose refrigerating temperature is below 0°C.

The exhaust gas temperature of refrigerated trucks changes with the load of the engine and is

between 200°C and 500°C [11]. Simultaneously, the ambient temperature during the summer is relatively high, generally above 30°C. To simplify the sorption refrigeration system, the sorption bed is heated directly by the exhaust gas and cooled directly by the ambient air. Such a heat transfer process has a low heat transfer coefficient if it is compared with a sorption refrigeration system heated or cooled by water or thermal oil [12, 13, 14, 15]. To satisfy such critical operating conditions, one highly desirable approach is the two-stage chemical solid sorption freezing cycle [16, 17]. Wang et al. [18] constructed a $\text{CaCl}_2/\text{BaCl}_2\text{-NH}_3$ two-stage solid sorption freezing machine. Experiments showed that the desorption temperature of the machine decreased from 98°C to 75°C at a condensing temperature of 30°C, and meanwhile the sorption temperature increased from 16°C to 43°C at an evaporating temperature of -20°C. Such a machine provided a novel way of adapting to the low desorption temperature and the high sorption temperature. After that, Jiang et al. [19] compared different working pairs of $\text{CaCl}_2/\text{NaBr-NH}_3$, $\text{CaCl}_2/\text{BaCl}_2\text{-NH}_3$, $\text{SrCl}_2/\text{BaCl}_2\text{-NH}_3$ and $\text{SrCl}_2/\text{NH}_4\text{Cl-NH}_3$ for heat source temperatures below 100°C and the cooling temperatures of approximately 30°C. Then, Gao et al. [20] proposed a novel working pair of $\text{MnCl}_2/\text{CaCl}_2\text{-NH}_3$ for utilizing the exhaust gas of the refrigerated truck, particularly for the low engine load condition in summer, and the results showed that the cycle could satisfy the critical operating conditions.

In this paper, a series of experiments of the $\text{MnCl}_2/\text{CaCl}_2\text{-NH}_3$ two-stage solid sorption freezing system is conducted to verify the optimal performance. The system is investigated under different resorption time, hot air temperatures and refrigerating temperatures, and the corresponding experimental results are analysed.

2. System description

A refrigerated light truck with a rated power of 80 kW is analysed; the rated load capacity of this refrigerated truck is 1500 kg. Refrigerated trucks transport chilled or frozen goods, and the required refrigerating temperature generally ranges from -18°C to 0°C. The required refrigerating capacity of refrigerated trucks is given by

$$Q_{\text{cabin}} = \phi K_{\text{cabin}} A_{\text{cabin}} (T_{\text{ambient,env}} - T_{\text{cabin,in}}) \quad (1)$$

where ϕ is the safety factor. K_{cabin} represents the total heat transfer coefficient, 0.35 W/(m²·K). A_{cabin} is the surface area of the cabin. $T_{\text{ambient,env}}$ and $T_{\text{cabin,in}}$ are the ambient temperature and the refrigerating temperature, respectively. $T_{\text{ambient,env}}$ of 30°C, which is the maximum average ambient temperature in China, is chosen.

According to the Agricultural Trade Policy (ATP) regulations, the minimum safety factor is 1.75. Generally, a coefficient of 2.5 is chosen by considering two conditions. The first condition is that the rear door is opened for loading the truck 20 times within 8 hours, and each opening lasts for 5 min. The second condition is that the thermal insulation property of the cabin deteriorates with time.

Based on eq.1, the required refrigerating capacity under different refrigerating temperatures is calculated, as shown in Tab.1. Tab. 1 shows that the required refrigerating capacity is higher when the refrigerating temperature is lower. For a refrigerating temperature of 0°C, the required refrigerating capacity is only 971.2W. However, for a refrigerating temperature of -18°C, the required refrigerating capacity is up to 1554 W.

Tab.1 Required refrigerating capacity under different refrigerating temperatures

Refrigerating temperature/°C	Required refrigerating capacity/W
0	971.2
-5	1133.1
-10	1295
-15	1456.8
-18	1554

Typically, the exhaust heat of the engine, which is equal to approximately 30% of the engine power, is discharged directly into the environment, and the engine exhaust gas temperature is between 200°C and 500°C. When the engine is at low-medium load, the engine exhaust gas temperature is below 300°C [11]. To make the sorption freezing system adapt to the relatively low exhaust gas temperature, the $\text{MnCl}_2/\text{CaCl}_2\text{-NH}_3$ two-stage solid sorption freezing cycle is designed and implemented to recover the waste heat to produce the refrigerating capacity.

The two-stage solid sorption freezing cycle is the combination of the conventional sorption cycle and the resorption cycle. The working process of the two-stage solid sorption freezing system consists of the sorption/desorption process and the resorption process, and the system outputs the refrigerating capacity only at the sorption process of the MnCl_2 bed.

The schematic diagram of the $\text{MnCl}_2/\text{CaCl}_2\text{-NH}_3$ two-stage solid sorption freezing system is shown in Fig. 1a and Fig. 1b. The components in the system are a high-temperature salt sorption bed (HTS bed), a middle-temperature salt sorption bed (MTS bed), an evaporator, a condenser, five ammonia valves (AV), two exhaust valves (EV), two air valves (CV) and other auxiliary equipment. There are two

liquid storage tanks in the sorption freezing system to store the ammonia refrigerant. Composite adsorbents of MnCl_2 and CaCl_2 developed by the matrix of ENG-TSA are filled in the HTS bed and MTS bed, respectively. Additionally, four electric fans are employed in this system.

Fig.1 Two-stage solid sorption freezing system: (a) Sorption process of the HTS bed and desorption process of the MTS bed; (b) Resorption process between the HTS bed and the MTS bed; (c) $\ln P$ - T

diagram

The detailed working principles of the system are as follows:

(1) Sorption process of the HTS bed and desorption process of the MTS bed. For this process, in

Fig. 1a, air valve CV1, exhaust valve EV2, and ammonia valves AV1 and AV2 are open. The HTS bed is

cooled by the ambient air, and the MTS bed is heated by the engine exhaust gas. The ammonia inside the

evaporator evaporates and is adsorbed by the HTS bed, and at the same time, the ammonia in the MTS bed is desorbed and condensed in the condenser. The liquid ammonia flows into liquid storage tank 1. The evaporation process of the ammonia inside the evaporator produces the refrigeration effect, and the chilled air transfers the refrigerating capacity into the cabin. Compared with the $\text{CaCl}_2\text{-NH}_3$ solid sorption cycle, for the evaporating temperature of T_e , the sorption temperature of the two-stage solid sorption cycle increases from T_{a1}' to T_{a1} (shown in Fig. 1c), which demonstrates good adaptability to the high ambient temperature.

(2) Resorption process between the HTS bed and MTS bed. For this process, in Fig. 1b air valve CV2, exhaust valve EV1, and ammonia valves AV3 and AV4 are open. The HTS bed is heated by the engine exhaust, and the MTS bed is cooled by the ambient air. The ammonia is desorbed from the HTS bed and flows to the MTS bed. The MTS bed adsorbs the ammonia and releases the reaction heat to the ambient air. Simultaneously, the liquid ammonia from liquid storage tank 1 enters liquid storage tank 2. Compared with the $\text{MnCl}_2\text{-NH}_3$ solid sorption cycle, for a condensing temperature of T_c , the desorption temperature of the two-stage solid sorption cycle decreases from T_{g1}' to T_{g1} (shown in Fig. 1c), which demonstrates good adaptability to the low heat source temperature.

The resorption process is the regeneration process of HTS bed, and the ammonia flows from the HTS bed to the MTS bed. In this process, no refrigerating capacity is output. However, such a process is the prerequisite condition for the sorption process of the HTS bed. Compared with the conventional desorption process of the HTS bed directly connected with the condenser, the resorption process could make the regeneration process of HTS bed fast and thorough at the low desorption temperature of T_{g1} ; this is because of the lower working pressure of P_{re} . Consequently, the lower desorption temperature of T_{g1} and the higher sorption temperature of T_{a1} make this sorption freezing system suitable for the

critical working conditions, such as the high ambient temperature in the summer and the low-medium load of the truck engine.

The installation of the sorption freezing system on the truck is shown in Fig.2. Two sorption beds are mounted on the two sides of the truck beam. The condenser is installed at the upper side of the cabin, and it is cooled by the ambient air. The evaporator is installed inside the cabin, which is similar to the traditional vapour compression refrigeration system.

Fig. 2 Two-stage solid sorption freezing system on the truck

3. Performance calculation

As mentioned above, the sorption bed is heated by the engine exhaust gas in the desorption process and cooled by the ambient air in the sorption process. Because the sorption bed after sorption is at a relatively low temperature that is a little higher than the ambient temperature, at the beginning of the desorption process, much heat is consumed by the metallic thermal capacity of the sorption bed and the sensible heat of the composite adsorbent. Thus, the heat input for the whole desorption process is mainly

composed of three parts, i.e., the desorption heat of the composite adsorbent, the sensible heat of the composite adsorbent and the metallic materials of the sorption bed.

The instantaneous heat input $Q_{\text{ins, heat}}$:

$$Q_{\text{ins, heat}} = C_{\text{exh}} \cdot m_{\text{exh}} \cdot (T_{\text{exh, in}} - T_{\text{exh, out}}) \quad (2)$$

The average heat input $Q_{\text{ave, heat}}$ in a cycle:

$$Q_{\text{ave, heat}} = Q_{\text{ave, des}} + \frac{1}{t_{\text{cycle}}} (C_{\text{ads}} M_{\text{tot, ads}} \Delta T_{\text{sensible}} + M_{\text{met}} C_{\text{met}} \cdot \Delta T_{\text{met}}) = \frac{\int_0^{t_{\text{cycle}}} C_{\text{exh}} \cdot m_{\text{exh}} \cdot (T_{\text{exh, in}} - T_{\text{exh, out}}) dt}{t_{\text{cycle}}} \quad (3)$$

where $M_{\text{tot, ads}}$ is total mass of the composite adsorbent, and the desorption heat $Q_{\text{ave, des}}$ is:

$$Q_{\text{ave, des}} = \frac{1}{t_{\text{cycle}}} M_{\text{tot, ads}} \Delta x_{\text{ads}} \Delta H_{\text{ads}} \quad (4)$$

where Δx_{ads} and ΔH_{ads} are the cycle sorption quantity and reaction heat, respectively. Δx_{ads} is:

$$\Delta x_{\text{ads}} = \frac{\Delta M_{\text{ref}}}{M_{\text{tot, ads}}} \quad (5)$$

The instantaneous refrigerating capacity $Q_{\text{ins, ref}}$:

$$Q_{\text{ins, ref}} = C_{\text{chilled, air}} \cdot m_{\text{chilled, air}} \cdot (T_{\text{chilled air, in}} - T_{\text{chilled air, out}}) \quad (6)$$

where the $T_{\text{chilled air, in}}$ and $T_{\text{chilled air, out}}$ are the chilled air inlet and outlet temperatures of the evaporator. The latent heat term is not considered.

The average refrigerating capacity $Q_{\text{avesorp, ref}}$ in the sorption process of the HTS bed:

$$Q_{\text{avesorp, ref}} = \frac{\int_0^{t_{\text{sorp, HTS}}} C_{\text{chilled, air}} \cdot m_{\text{chilled, air}} \cdot (T_{\text{chilled air, in}} - T_{\text{chilled air, out}}) dt}{t_{\text{sorp, HTS}}} \quad (7)$$

The average refrigerating capacity $Q_{\text{ave, ref}}$ in a cycle:

$$Q_{\text{ave, ref}} = \frac{\int_0^{t_{\text{cycle}}} C_{\text{chilled, air}} \cdot m_{\text{chilled, air}} \cdot (T_{\text{chilled air, in}} - T_{\text{chilled air, out}}) dt}{t_{\text{cycle}}} \quad (8)$$

The $Q_{\text{avesorp, ref}}$ is almost double the $Q_{\text{ave, ref}}$.

For calculating the coefficient of performance (COP), the power consumed by the fans for the MTS

and HTS beds is neglected. It is because they work only when the volumetric flow rate of the ambient air cannot meet the cooling requirement for the sorption beds, i.e., that the truck is stopped. Generally the fans for MTS and HTS beds don't work when the truck is running, which is due to that the ambient air can be forced to flow into the sorption beds through the air inlet. The power for fans for condenser and evaporator is considered for calculating COP , and the equation is:

$$COP = \frac{Q_{ave, ref}}{Q_{ave, heat} + W_{fan} / \eta} \quad (9)$$

where η is the heat-work conversion coefficient of the engine [22], which is approximately 0.4 for the engine utilized.

The specific cooling power per kilogram of adsorbent can be expressed as:

$$SCP = \frac{Q_{ave, ref}}{M_{tot, ads}} \quad (10)$$

4. Experimental results and discussion

The two-stage solid sorption freezing system is shown in Fig. 3a. The HTS bed consists of 120 unit tubes and the MTS bed consists of 80 unit tubes. Composite adsorbents are filled in the unit tubes. The mass ratio between the metal chloride and the ENG-TSA is 5:1, and the packing density of the composite adsorbent is approximately 500 kg/m³. Both the condenser and evaporator are composed of finned tubes.

For the heating process of the sorption beds, the hot air heated by the electric heater, whose maximum power is 21 kW, is utilized to simulate the engine exhaust gas. The hot air temperature of the electric heater can be adjusted from the ambient temperature to 280°C with an accuracy of ±3°C. Two centrifugal fans are utilized to cool the two sorption beds separately to simulate the cooling process of

the sorption beds when the truck is running. To balance the refrigerating capacity, two electric heaters controlled by temperature controllers are installed in the return-air pipe of the evaporator, as shown in Fig.3b. Temperature sensors (PT100) and pressure transmitters (YSZK-31) are mounted in the experimental system; their accuracies are $\pm 0.1^{\circ}\text{C}$ and 0.3%R, respectively, where 0.3%R means that the measurement error of the pressure transmitters is 0.3% of the reading. The flow rate of the air is measured by the Pitot tube anemograph (ZC1000-1F); its accuracy is 0.5%. In addition, a high-pressure sight glass is installed in each liquid storage tank. To measure the liquid level in the evaporator, a glass level meter is used. A data acquisition unit (Agilent 34970A) is utilized for the collection of the data.

(a)

(b)

Fig.3 Two-stage solid sorption freezing system: (a)Test rig; (b) The method to measure the refrigerating capacity

To determine whether the two-stage solid sorption freezing system can meet the required refrigerating capacity of the refrigerated truck at the low-medium load of the engine or not, a series of experiments are conducted.

In the initial experiments, the hot air temperature is controlled at approximately 230°C and the ambient temperature is approximately 30°C. The air inlet and outlet temperatures of the sorption beds for a typical operational condition are shown in Fig.4a and Fig.4b. For the HTS bed, from 0 min to 120 min the resorption process between the HTS bed and the MTS bed occurs, and from 120 min to 240 min the HTS bed adsorbs the ammonia refrigerant from the evaporator. However, for the MTS bed, after 210 min the liquid level at the liquid storage tank 1 of the condenser is almost constant according to the sight glass, which means that there is no ammonia refrigerant desorbed from the MTS bed to the condenser. After that, the MTS bed is cooled by the ambient air, which is beneficial for the following resorption process.

Under the conditions mentioned above, the working pressure of the sorption beds is shown in Fig.4c. For the HTS bed, because the resorption happens between the HTS bed and the MTS bed, the working pressure is at a relative low value ranging from 0.083 MPa to 0.729 MPa. Based on the equilibrium lines of chlorides reacting with ammonia [21], the relatively low working pressure corresponds to the relatively low equilibrium temperature; i.e., such a process decreases the heat source temperature significantly. Meanwhile, for the MTS bed, because desorption occurs between the sorption bed and the condenser, the working pressure is much higher and ranges from 0.140 MPa to 1.734 MPa.

Fig.4 Performance of sorption beds: (a) Air inlet and outlet temperatures of HTS bed; (b) Air inlet and outlet temperatures of MTS bed; (c) Working pressure

4.1 Performance influenced by different resorption time

The performance of the system is investigated under different resorption time of 60, 80, 100 and 120 min; the corresponding hot air temperature and refrigerating temperature are 230°C and -5°C, respectively. The effective refrigerating time is studied; this refers in particular to the time that the chilled air outlet temperature is at the setting temperature, such as -5°C or -10°C. The volumetric flow rate of hot air and cooled air are 630 m³/h and 900 m³/h.

The instantaneous refrigerating capacity with the refrigerating temperature of -5°C for different resorption time is shown in Fig.5. Taking the resorption time of 100 min as an example (Fig.5c), when the HTS bed begins to adsorb the ammonia refrigerant, the chilled air outlet temperature of the evaporator drops gradually from 18°C to -5°C, and then, electric heaters installed in the return-air pipe begin to heat the chilled air. After that, the chilled air inlet temperature increases gradually. Based on eq.6, the instantaneous refrigerating capacity is calculated, and the result is shown in Fig.5c. Fig.5 shows

that the effective refrigerating time increases from 52 min (Fig.5a) to 92min (Fig.5d) with an increase in the resorption time because much more ammonia is desorbed from the HTS bed with the increasing resorption time.

Based on eq.7, the average refrigerating capacity in the sorption process of the HTS bed at different resorption time is calculated and is shown in Fig.6a, together with the *COP* and *SCP*, which are shown in Fig.6b. The average refrigerating capacities (Fig.6a) are almost constant when the resorption time is longer than 80min; they are 3.05 kW, 2.97 kW and 3.02 kW for the resorption time of 80 min, 100 min and 120 min. In the experimental system, the power of the evaporator fan is 196 W, and it works only during the sorption process of the HTS bed. Consequently, the average power consumed by it in a cycle is approximately 100 W. The average power consumed by the condenser fan is also approximately 100 W. Fig.6b indicates that the maximum *COP* of 0.143 is obtained at the resorption time of 120 min, and the *SCPs* at resorption time of 80 min, 100 min and 120 min are almost constant, at approximately 105 W/kg.

Fig.5 Instantaneous refrigerating capacity at the chilled air outlet temperature of -5°C vs. resorption time of: (a) 60 min; (b) 80 min; (c) 100 min; (d) 120 min

Fig.6 Performance under different resorption time: (a) The average refrigerating capacity in the sorption process of the HTS bed and the effective refrigerating time; (b) COP and SCP

4.2 Performance influenced by different hot air temperatures

The engine exhaust gas temperature changes with the load and speed of the truck. When the engine is at low-medium load, the engine exhaust gas temperature is below 300°C . Consequently, different hot air temperatures of 210°C , 230°C , 250°C , 270°C are employed to drive the two-stage solid sorption freezing system, and the resorption time and refrigerating temperature are controlled at approximately 80 min and -5°C , respectively. The instantaneous refrigerating capacity for different hot air temperatures is shown in Fig.7. Based on eq.7, the average refrigerating capacity in the sorption process of the HTS bed at different hot air temperatures is calculated. With increasing hot air temperatures, the average refrigerating capacity in the sorption process of the HTS bed is almost constant at approximately 3.0 kW, but the effective refrigerating time increases rapidly from 60 min to 98 min, as shown in Fig.8a. The increasing effective refrigerating time is related to the increasing driving temperature potential, which is the difference between the heat source temperature and the equilibrium desorption temperature. When the difference is larger, the heat transfer performance is better, and much more ammonia is desorbed from the HTS bed for the same resorption time. The COP and SCP under different hot air temperatures are shown in the Fig.8b. Both the maximum COP and the

maximum *SCP* are obtained at the hot air temperature of 270°C; they are 0.14 and 108 W/kg, respectively.

Comparing the average refrigerating capacity in the sorption process of the HTS bed and the effective refrigerating time for the resorption time of 80 min and hot air temperature of 270°C in Fig.8a with those for the resorption time of 120 min and hot air temperature of 230°C in Fig.6a shows that they are almost the same. Such a result indicates that a high hot air temperature effectively decreases the resorption time.

Fig.7 Instantaneous refrigerating capacity under different hot air temperatures of: (a) 210°C; (b) 250°C; (c) 270°C

Fig.8 Performance under different hot air temperatures: (a) The average refrigerating capacity in the sorption process of HTS bed and the effective refrigerating time; (b) *COP* and *SCP*

According to the Tab.1, the required refrigerated capacity for this refrigerated truck at a refrigerating temperature of -5°C is approximately 1.13 kW. Based on eq.8, the average refrigerating capacity of the two-stage solid sorption freezing system in a cycle vs. resorption time is analysed and is shown in Fig.9. Fig.9 shows that most conditions can satisfy the requirement except for the average refrigerating capacity of 1.06 kW obtained at a resorption time of 60 min and a hot air temperature of 230°C . The average refrigerating capacity in a cycle increases quickly with the increasing hot air temperature at the same resorption time of 80 min. The maximum average refrigerating capacity of 1.52 kW is obtained at the resorption time of 80 min and the hot air temperature of 270°C . Consequently, this two-stage solid sorption freezing system can meet the requirement for transporting fresh goods when the engine exhaust gas temperature is relatively low.

Fig.9 Average refrigerating capacity in a cycle vs. resorption time

Although no refrigerating capacity is output during the resorption process, the internal temperature of the cabin during the complete cycle will change little. Taking the example for transporting dairy products, the operational condition of 230°C heat source temperature and 80 min resorption time is chosen. Under such a condition the average refrigerating capacity in a cycle is 1.23 kW, which is higher than the required refrigerating capacity of approximately 1.13 kW shown in Tab.1. For the refrigerated truck analysed in this paper, the load capacity is approximately 1500kg. For the dairy products, the specific thermal capacity is approximately 2.5 kJ/(kg·K). As shown in Fig. 6a, the average refrigerating capacity in the sorption process of the HTS bed is 3.05 kW, so the temperature of the dairy products decreases gradually from 2.5°C to 0.5°C and the dairy products store the extra refrigerating capacity in this process. During the resorption process no refrigerating capacity is output, and the temperature of the dairy products increases from 0.5°C to 2.5°C, which is acceptable for storage process.

4.3 Performance influenced by different refrigerating temperatures

Sometimes, a refrigerating temperature between -10°C and -18°C is required for transporting frozen goods, so the performance of the two-stage system is tested under refrigerating temperatures of -10°C, -15°C and -18°C. The optimum resorption time is determined in Section 4.1. For the hot air temperature of 230°C and the chilled air outlet temperature of -5°C, the system performance is measured for the resorption time of 60, 80, 100 and 120 min. The analysis shows that the maximum *COP* and effective refrigerating time are obtained at the resorption time of 120 min. Consequently, the resorption time of 120 min is chosen with the hot air temperature of 230°C.

In addition, the refrigerating temperature of 0°C is also studied for transporting fresh goods, as

shown in Fig.10a. Fig.10a shows that the chilled air outlet temperature of the evaporator fluctuates significantly at the initial phase. This is because two electric heaters installed at the return-air pipe of the evaporator cannot balance the refrigerating capacity, which is too large because of the high refrigeration temperature. Corresponding instantaneous refrigerating capacities for different refrigerating temperatures are also shown in Fig.10. The lower the refrigerating temperature is, the lower the refrigeration capacity is.

Based on eq.7, the average refrigerating capacity in the sorption process of the HTS bed is calculated and is shown in Fig.11a. The average refrigerating capacity decreases gradually from 3.75 kW to 2.3 kW when the chilled air outlet temperature of the evaporator decreases from 0°C to -18°C. Simultaneously, the effective refrigerating time in Fig.11a increases slowly because the critical mass transfer performance under the lower saturated pressure of the ammonia refrigerant, i.e., the lower refrigerating temperature. Fig.11b shows that both *COP* and *SCP* increase gradually with the increase of the refrigerating temperature; they are 0.13~0.15 and 89.6W/kg~132W/kg, respectively.

(a)

(b)

(c) (d)

Fig.10 Instantaneous refrigerating capacity for different refrigerating temperatures of: (a) 0°C; (b) -10°C; (c) -15°C; (d) -18°C

Fig.11 Performance for different refrigerating temperatures: (a) The average refrigerating capacity in the sorption process of the HTS bed and the effective refrigerating time; (b) *COP* and *SCP*

Based on eq.8, the average refrigerating capacity in a cycle is calculated and is shown in Fig.12. It shows that the average refrigerating capacity for the refrigerating temperatures of 0°C, -10°C, -15°C, -18°C are 1.42kW, 1.09kW, 1.06kW and 1.04kW, respectively. Compared with the Tab.1, the system can reach the required refrigerating capacity at 0°C, but it cannot reach the required refrigerating capacity when the refrigerating temperature is lower than -10°C.

Fig.12 Average refrigerating capacity in a cycle vs. the chilled air outlet temperature

A hot air temperature of 270°C is employed to drive the two-stage solid sorption freezing system for the refrigerating temperature of -10°C, and the resorption time is controlled at approximately 80

min. The corresponding instantaneous refrigerating capacity is shown in Fig.13, and the average refrigerating capacity in a cycle is 1.32 kW, which is higher than the required refrigerating capacity of 1.295 kW shown in Tab.1.

Fig.13 Instantaneous refrigerating capacity with refrigerating temperature of -10°C and hot air temperature of 270°C

However, for the refrigerating temperatures of -15°C and -18°C , the analysis shows that the average refrigerating capacity in a cycle can reach the required refrigerating capacity only when the hot air temperature is heated to 330°C . This is because the resorption time is effectively decreased by the high heat source temperature. Consequently, this two-stage solid sorption freezing system cannot reach the required refrigerating capacity with the lower refrigerating temperature when the engine is at low-medium load. When the engine is at medium-high load, the engine exhaust gas temperature is expected to be higher than 300°C , and at the same time, the heat of the exhaust gas is relatively large. If a refrigerated truck is utilized for the long-distance transportation of frozen goods, the engine is always at a relatively heavy load. Therefore, the engine exhaust gas temperature is high enough to make this two-stage solid sorption freezing system reach the required refrigerating capacity, even at a refrigerating temperature of -18°C .

To clearly demonstrate the refrigerating capacity (RC) obtained under different operational conditions, the values of RC are given in Tab.2, together with the experimental conditions.

Tab.2 Refrigerating capacity (RC) obtained under different operational conditions

		Hot air temperature/°C							
		210		230		250		270	
		Resorption time/min							
		80	60	80	100	120	80	80	
Refrigerating temperature/°C	Required RC/kW	RC/kW	RC/kW	RC/kW	RC/kW	RC/kW	RC/kW	RC/kW	
0	0.97					1.42			
-5	1.13	1.19	1.06	1.23	1.24	1.25	1.4	1.52	
-10	1.29					1.09		1.32	
-15	1.45					1.06			
-18	1.55					1.05			

5. Conclusions

In this paper, a $\text{MnCl}_2/\text{CaCl}_2\text{-NH}_3$ two-stage solid sorption freezing system is established for a refrigerated truck with a rated power of 80 kW. Composite adsorbents of MnCl_2 and CaCl_2 developed by ENG-TSA are utilized. To determine whether this two-stage solid sorption freezing system meets the requirement of the refrigerated truck or not, a series of experiments are conducted. The conclusions are as follows:

(1) The effective refrigerating time increases with the increase of the resorption time, and it increases from 52 min to 92 min when the resorption time increases from 60 min to 120 min. The maximum average refrigerating capacity of 3.05 kW in the sorption process of the HTS bed is obtained at a refrigerating temperature of -5°C .

(2) The average refrigerating capacity in a cycle can still reach the required refrigerating capacity for transporting fresh goods even when the hot air temperature is as low as 210°C . A relatively high hot air temperature can effectively shorten the resorption time and improve the average refrigerating capacity in a cycle. The maximum average refrigerating capacity of 1.52 kW in a cycle is obtained at a hot air temperature of 270°C and a refrigerating temperature of -5°C .

(3) The system can easily satisfy the requirement for transporting fresh goods at 0 and -5°C , even for the heat source temperature of 210°C . However, for transporting frozen goods with a refrigerating temperature of -10°C , a hot air temperature higher than 270°C is required, and the

refrigerating capacity obtained experimentally is 1.32 kW.

(4) Analysis shows that the refrigerating capacity obtained can meet the refrigerating requirement with the refrigerating temperature of -15°C and -18°C only when the hot air temperature is higher than 330°C . This means that a refrigerated truck is utilized for the long-distance transportation and the engine is at medium-high load.

Although the temperature fluctuation inside the cabin is not large, a shorter resorption time is desirable for improving the storage effect. A more reasonable design needs to be investigated in the future.

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Figures:

Fig. 1 Two-stage solid sorption freezing system: (a) Sorption process of the HTS bed and desorption process of the MTS bed; (b) Resorption process between the HTS bed and the MTS bed; (c) $\ln P$ - T diagram

Fig. 2 Two-stage solid sorption freezing system on the truck

Fig. 3 Two-stage solid sorption freezing system: (a) Test rig; (b) The method to measure the refrigerating capacity

Fig. 4 Performance of sorption beds: (a) Air inlet and outlet temperatures of HTS bed; (b) Air inlet and outlet temperatures of MTS bed; (c) Working pressure

Fig. 5 Instantaneous refrigerating capacity at the chilled air outlet temperature of -5°C vs. resorption time of: (a) 60 min; (b) 80 min; (c) 100 min; (d) 120 min

Fig. 6 Performance under different resorption time: (a) The average refrigerating capacity in the sorption process of HTS bed and the effective refrigerating time; (b) COP and SCP

Fig. 7 Instantaneous refrigerating capacity under different hot air temperatures of: (a) 210°C ; (b) 250°C ; (c) 270°C

Fig. 8 Performance under different hot air temperatures: (a) The average refrigerating capacity in the sorption process of HTS bed and the effective refrigerating time; (b) COP and SCP

Fig. 9 Average refrigerating capacity in a cycle vs. resorption time

Fig. 10 Instantaneous refrigerating capacity for different refrigerating temperatures of: (a) 0°C ; (b) -10°C ; (c) -15°C ; (d) -18°C

Fig. 11 Performance for different refrigerating temperatures: (a) The average refrigerating capacity in the sorption process of the HTS bed and the effective refrigerating time; (b) COP and SCP

Fig. 12 Average refrigerating capacity in a cycle vs. the chilled air outlet temperature

Fig. 13 Instantaneous refrigerating capacity with refrigerating temperature of -10°C and hot air temperature of 270°C