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Investigation of thermal characteristics of strontium chloride composite sorbent for sorption refrigeration

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Abstract:

Thermal characteristics such as thermal conductivity, permeability, and sorption kinetics, which determines the overall sorbent performance, play as the critical roles in the sorption refrigeration system. In this paper, composite strontium chloride (SrCl2) developed with a host matrix of Expanded Natural Graphite (ENG) has been comprehensively investigated under different densities and mass ratios of salt. Results indicate that the composite sorbent has overall good heat and mass transfer performance. The highest thermal conductivity is 3.07 W/(m.K), which is 15 times higher than normal granular SrCl2. The permeability of composite sorbent ranges from 9.5×10^{-10} to 9.36×10^{-14} m². Sorption performance of composite SrCl2 has also been tested, and the results showed that for the sorption amount ranged between 400 to 700 (g/kg SrCl2) ammonia at 40 minutes in the adsorption process. These quantitative results obtained from this study can be used as crucial parameters to conduct the simulation modelling for the SrCl2-ENG sorption system.

Keywords: Thermal conductivity, Permeability, Composite sorbent, Sorption characteristic, Strontium chloride
HIGHLIGHTS

• The composite sorbent material SrCl$_2$-ENG under various mixture ratios was developed

• Heat and mass transfer performance of the composite materials were investigated

• The sorption performance for refrigeration application was studied

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$A_c$</td>
<td>Cross section area of the ammonia vessel (m$^2$)</td>
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<tr>
<td>AC</td>
<td>Activated Carbon</td>
</tr>
<tr>
<td>$B$</td>
<td>Shape factor</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat (J/(g·K))</td>
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<tr>
<td>$d$</td>
<td>The thickness of the test sample (mm)</td>
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<tr>
<td>ENG</td>
<td>Expanded Natural Graphite</td>
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<tr>
<td>$g$</td>
<td>The acceleration of gravity (9.8 m/s$^2$)</td>
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<td>$K$</td>
<td>Permeability (m$^2$)</td>
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<td>$m_a$</td>
<td>Gas mass flow rate (kg/s)</td>
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<tr>
<td>$m_{am}$</td>
<td>Gross mass of the ammonia in the vessel (kg)</td>
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<td>$p$</td>
<td>Pressure (Pa)</td>
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<td>$p_d$</td>
<td>Pressure difference (Pa)</td>
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<td>Definition</td>
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<tr>
<td>$q$</td>
<td>Gas volume flow rate (L/min)</td>
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<td>$R$</td>
<td>Gas constant (J/(kg·K))</td>
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<td>$S$</td>
<td>Cross section area of the sample (m$^2$)</td>
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<td>$T$</td>
<td>Temperature (°C)</td>
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<tr>
<td>$TSA$</td>
<td>Treated with sulfuric acid</td>
</tr>
<tr>
<td>$t_{50}$</td>
<td>Semi-heating time (s)</td>
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<tr>
<td>$V$</td>
<td>The Internal volume of the ammonia vessel (m$^3$)</td>
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<td>$v_a$</td>
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<td>$X$</td>
<td>Global conversion ratio</td>
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<td>$Y$</td>
<td>Intrinsic characteristic</td>
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### Greek letters

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<tr>
<td>$\alpha$</td>
<td>Thermal diffusivity (mm$^2$/s)</td>
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<tr>
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<td>Thermal conductivity (W/m·K)</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Gas viscosity (Pa·s)</td>
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<tr>
<td>$\rho$</td>
<td>Density (kg/m$^3$)</td>
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<tr>
<td>$\nu$</td>
<td>Specific volume (m$^3$/kg)</td>
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### Subscripts

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<td>Condensing</td>
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<td>---------</td>
<td>--------------------------</td>
</tr>
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<td>Desorption</td>
</tr>
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<td>Outlet</td>
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<td>sample</td>
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<tr>
<td>sorb</td>
<td>Sorbent</td>
</tr>
<tr>
<td>SrCl$_2$</td>
<td>Strontium chloride</td>
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1. Introduction

As one of the environmental benign energy-saving technologies, sorption refrigeration has drawn increasing attention when considering its advantages such as easy to control and utilise green refrigerants without Ozone Depletion Potential (ODP) and Global Warming Potentials (GWP) [1, 2].

The sorption refrigeration cycles generally are all discontinuous batch processes involving sorption and desorption phases [3]. Building adsorption simulation models is a standard and efficient method to explore, evaluate and optimise adsorption cycle technologies instead of conducting large quantities of experiments. The accurate and detailed parameters such as thermal conductivity and permeability of adsorption sorbents are critical and important for the simulation study. One of the inevitable challenges in completing an efficient adsorption cycle is to achieve the high heat transfer and mass transfer performance of the sorbent. To overcome this challenge, the researchers have studied the composite sorbent to improve the heat and mass transfer performance of the sorbent. As one major important matrix of composite sorbent, Expanded Natural Graphite (ENG) has been widely investigated [4], which was invented by the Carburet Company [5]. It was made from the expandable graphite which is prepared by the methods of electrochemistry and chemistry oxidation [6]. Early studies about the consolidated composite sorbent impregnated with ENG as the matrix was investigated by Mauran et al. [7], who indicated the better heat transfer performance for CaCl$_2$. Later, Han and Lee [8] investigated the gas permeability of
different chlorides with ENG using Darcy’s law in the ammonia atmosphere. Results indicated the gas permeability was in the range of $5.0 \times 10^{-16} - 10^{-12}$ m$^2$ depending on the reaction pair, bulk density and weight fraction of the graphite powder [8]. Biloe et al. [9] researched the permeability of compact ENG by using Helium as a gas source, and the results showed that the value of permeability varied from $10^{-15} - 10^{-12}$ m$^2$. Wang et al. [10] measured the effective thermal conductivity of ENG-CaCl$_2$-nNH$_3$ ($n = 2, 4, 8$) compound sorbent by using the hot wire method at a fixed pressure and temperature under ammonia atmosphere, and the values were in the range of 7.05-9.2 W/(m.K). The steady-state heat source method had been utilised by Tamainot-Telto and Critoph [11, 12], leading to the thermal conductivity up to 0.44 W/(m.K). Jiang et al. [13, 14] investigated thermal conductivity and permeability of eight different chlorides with ENG and compared the properties of different consolidated composite sorbents in the sorption process. Nonetheless, due to the characteristics of anisotropic heat and mass transfer performance, some testing method may cause some inaccuracies. Recently, expanded natural graphite treated with sulfuric acid (ENG-TSA) manufactured by Mersen in France is introduced to further improve the heat and mass transfer performance of the sorbent. As one prospective heat transfer matrix, the highest thermal conductivity for this matrix could reach 337 W/(m.K) at a bulk density of 831 kg/m$^3$, which can be applied for both physical and chemical sorbent [15]. For physical sorbent, the thermo-physical properties of composite AC with the matrix of ENG-TSA was evaluated, and the results showed that the highest effective
thermal conductivity was 34.2 W/(m.K), that is 150 times higher than ordinary granular AC [15]. Silica gel with ENG-TSA as the matrix was investigated. Experimental results showed that the highest thermal conductivity of consolidated composite sorbents is 19.1 W m⁻¹ K⁻¹ [16]. For chemical sorbent, CaCl₂ impregnated with ENG-TSA (Treated with sulfuric acid) can reach the highest thermal conductivity of 88.1 W m⁻¹ K⁻¹ [17]. Nonetheless, one shortcoming is that ENG-TSA requires relatively high manufacturing price, which is 60 times higher than that of ENG per unit mass. Also noting that for the conventional finned tube heat exchanger for the sorbent, the primary heat resistance relies on the heat resistance between the sorbent and metal tube rather the sorbent itself [18]. Therefore, considering both the performance and thermo-economy, ENG has been more frequently used in the practical sorption system for refrigeration and thermal energy storage rather than ENG-TSA [19, 20].

The strontium chloride has been recommended as one of the promising chemisorption salt for low-grade heat recovery application and thermal energy storage [21, 22]. For example, the authors have previously reported and investigated the potential application of using novel strontium chloride composite sorbent to form a power generation system [23]. Results indicated the developed system can be potentially used to recover low-grade heat sources such as solar energy, geothermal energy and industrial waste heat under the temperature over 120 °C [23]. However, compared with the reported researches on composite CaCl₂ [24], limited quantitative data can be
found for the sorbents using strontium chloride (SrCl$_2$), which leads to the difficulty of generating a highly accurate simulation model to predict the performance of sorption system using SrCl$_2$ sorbents. Therefore, in this paper, the thermo-physical properties including thermal conductivity and permeability of SrCl$_2$ impregnated with ENG as a matrix under various mixture ratios have been comprehensively investigated. Moreover, a sorption performance test rig has been used to examine the selected mass ratio SrCl$_2$ composite for sorption refrigeration application.

2. Methodologies

2.1 Preparation of composite sorbents

The Expanded Natural Graphite (ENG) used in this study is manufactured by Shanghai Yi Fan Graphite Company with 50-80 mesh size, and the purity of the ENG is larger than 99%. The ENG has been expanded in an oven at the temperature of 600$^\circ$C for 8 minutes [25]. Detailed development processes of the SrCl$_2$ composite sorbent can be found in the authors’ previous publication [26]. The previously reported study on the anisotropic thermal conductivity and permeability of the consolidated ENG matrix indicated both optimal heat and mass transfer directions are perpendicular to the compression direction [27]. Therefore, plate samples are utilised to experimentally investigate the thermal conductivity and permeability with different density and mass ratio of salt. The mass ratio of salt and density are two significant factors, which affect the permeability and thermal conductivity performance of SrCl$_2$ composite.
sorbent. In this study, mass ratios of salt range from 50 % to 83 % and densities are selected in the range of 400-600 kg/m$^3$.

2.2 The thermal conductivity of composite sorbents

Thermal conductivity was investigated by the Laser flash method, and the type of the instrument is a Laser Flash Apparatus (LFA) 467 manufactured by Netzsch. The accuracy of the thermal diffusivity and the specific heat is $\pm$ 3% and $\pm$ 5%, respectively, declared by the supplier. Diagram for the principle of the equipment is shown in Fig.1. The unit mainly includes an infrared detector, a sample changer, a heater, an optical filter, a reflector and a flash lamp. The sorbent sample was made into a cylinder with the diameter of 12.7 mm and the height of 3 mm. Under a set temperature $T$ (controlled by the temperature controller of the machine), a beam of light pulses is emitted instantaneously by the laser light source or a xenon flash lamp, which can uniformly illuminate the surface of the test sample. The radial heat conduction on the sample can be ignored due to the uniform illumination on the small size of the sample and the rapid temperature changes in the longitudinal direction of the sample. Therefore, the longitudinal heat conduction of the sample can be recognised as the only heat conduction process in the LFA tests. The trend of the temperature can be measured by using an infrared detector. By analysing the curves of temperature-versus-time, the thermal diffusivity can be determined.
The thermal diffusivity can be defined by the following equation, where $\alpha$ is thermal diffusivity, $d$ is the thickness of the testing samples, and $t_{50}$ is the semi-heating time (defined as the half-time required as the temperature of the sample in the upper surface is raised after receiving the light pulse irradiation) [28].

$$\alpha = 0.1388 \times d^2 / t_{50} \quad (1)$$

The thermal conductivity can be calculated by the Eq. (2), where $\lambda(T)$ is the thermal conductivity at a certain temperature, $\alpha(T)$ is the thermal diffusivity at a certain temperature, $C_p$ is specific heat at a certain temperature, $\rho(T)$ is the density of the sample at a certain temperature. The density is determined by the sample volume and the sample weight. The sample was made by a self-manufactured sample maker, by which the volume random error is less than ±1%. The accuracy of the analytical balance, product code Sartorius AZ612, is ±0.02g. Through the Error Propagation Formula, the relative accuracy of the thermal conductivity for this LFA machine is calculated in Equation (3). $\Delta\lambda$, $\Delta\alpha$, and $\Delta C_p$ is the
uncertainty of the thermal conductivity, the thermal diffusivity, and the specific heat, respectively.

\[
\lambda(T) = \alpha(T) \times C_p(T) \times \rho(T) \tag{2}
\]

\[
\frac{\Delta \lambda}{\lambda} = \frac{\Delta \alpha}{\alpha} + \frac{\Delta C_p}{C_p} = 8\% \tag{3}
\]

2.3 The permeability of composite sorbents

Fig.2. The permeability test system (a) photo of the rig, (b) drawing of the test unit[27]

The permeability test rig used in this work is shown in Fig.2. (a), mainly containing a permeability test chamber, a differential pressure transmitter (Dwyer477A-7), and a rotameter (Dwyer MMA-23). The sorbents were compressed into the chamber of the permeability test unit of intended densities and salt mass ratios as illustrated in Fig.2. (b), with a compressing direction perpendicular to the gas flow. This direction is the optimal choice for permeability test [25]. A metal mesh plate was applied on the two sides of the sorbent surfaces to maintain the structure and prevent its breakage. Nitrogen was used as the test gas because of its chemical stability and no reaction with sorbents or test rig. Treated as an ideal gas, nitrogen was assumed not to
accumulate in the sorbent sample during the test. The test gas inlet was opened to start
the permeability of the sorbent sample by letting the nitrogen gas entering in the test
rig. The gas phase nitrogen flew through the permeability test unit and the pressure
drop $\Delta p$ across the sample and the flow rate $q_v$ of nitrogen were therefore measured
during the gas flow period.

Since the tested samples are porous media with anisotropic characteristics, the Ergun
model is applicable in the measurement because no compressibility effects exist [29].
The intrinsic characteristic of the sample can be expressed by the following equations
(4) and (5), where $K$ is the permeability of the samples ($m^2$), $B$ is the shape factor of
the samples, $p_{in}$ and $p_{out}$ are the inlet pressure and outlet pressure of the nitrogen, $S$ is
the sample cross section ($m^2$), $R$ is the gas constant ($J/(kg \cdot K)$), $T$ is the sample
temperature ($K$), $\Delta z$ is the thickness of the compact sample, $\mu$ and $\rho$ are the gas
viscosity ($Pa \cdot s$) and density ($kg/m^3$), respectively; $m_a$ is the gas mass flow rate ($kg/s$),
$v_a$ is the axial velocity of the sample ($m/s$). The accuracy of this test could be derived
by Equation (6), (7) and (8). The accuracy of the pressure difference transmitter is
$\pm 0.1\%$, and that of the rotameter is $\pm 4\%$, declared by the supplier. $\Delta K$, $\Delta Y$, $\Delta X$, $\Delta p$,
and $\Delta v$ are the errors of the relative parameters.

\[
Y = BX + \frac{1}{K} \quad (4)
\]

\[
Y = \frac{(p_{in}^2 - p_{out}^2)S}{2RT\mu m\Delta z} \quad \text{; } \quad X = \frac{m}{\mu S}, \quad m = \rho S v \quad (5)
\]

\[
\frac{\Delta K}{K} = \frac{\Delta Y}{|Y-BX|} + \left| \frac{B}{Y-BX} \right| \cdot \Delta X \quad (6)
\]
\[
\frac{\Delta Y}{Y} = \frac{2(p_{in} + p_{out}) \Delta p}{p_{in}^2 - p_{out}^2} + \frac{\Delta v}{v}
\]

(7)

\[
\frac{\Delta X}{X} = \frac{\Delta v}{v}
\]

(8)

1. The maximum relative error of the permeability is ±14.2%, obtained when the permeability reaches the lowest in this test. The average relative error is ±13.6%.

2.4 Sorption performance test of composite sorbents

An adsorption performance test rig using volumetric testing method was used to measure the sorption performance of the chemisorption composite. The rig mainly includes an adsorbent bed, a condenser/evaporator, two oil bath units, a differential pressure sensor, two pressure sensors, five temperature sensors and an electric heating wire as shown in Fig.3.
The prepared composite sorbents were compressed into the adsorbent bed with a density of 450 kg/m³ and a salt mass ratio of 50%. During the desorption process, the adsorbent bed was heated to desorb ammonia by the thermal oil from the oil bath, while a cryostat controls the temperature of the condenser. The ammonia gas then condensed in the condenser. In the period of the adsorption process, the adsorbent bed was cooled using tap water to reject the adsorption heat and the condenser vessel in desorption process acted as an evaporator at the testing temperature by the controlling from a connected cryostat. The ammonia gas absorbed evaporation heat from the condenser and was adsorbed by the sorbents in the sorbent bed, thus providing refrigeration from condenser vessel. The gross mass of gas phase ammonia in the system could be calculated by the readings of a differential pressure sensor, which is located at the bottom of the condenser. The calculation method of the gross mass of the ammonia in the condenser/evaporator can be described by the following equation [30, 31], where $A_c$ and $V$ is the internal area and internal volume of the condenser/evaporator, respectively. $v_l(T_e)$ and $v_g(T_e)$ is the specific volume of the saturated liquid and vapour phase ammonia under the controlled temperature $T_e$ of the condenser/evaporator. The accuracy of the pressure differential sensor is ±2%.

Through Equation (10), the error of the ammonia mass would be the same as ±2%.

$$m_{am} = \left[ 1 - \frac{v_l(T_e)}{v_g(T_e)} \right] \frac{A_c}{g} \Delta p + \frac{V}{v_g(T_e)} \quad m_{am} = \left[ 1 - \frac{v_f(T_e)}{v_g(T_e)} \right] \frac{A_c}{g} \cdot p_d + \frac{V}{v_g(T_e)}$$

(9)
$\Delta m_{am} = \Delta p_d$  \hspace{1cm} (10)

1. The chemical reaction equations between SrCl$_2$ and NH$_3$ in the range of experimental temperature can be found in Eq. (11).

$$SrCl_2 \cdot NH_3 + 7NH_3 \leftrightarrow SrCl_2 \cdot 8NH_3 + 7\Delta H_{SrCl_2}$$  \hspace{1cm} (11)

2. Compared with the adsorption ability of SrCl$_2$, the Natural Expanded Graphite can only adsorb quite limited ammonia, which is suitable to be ignored in this test. Therefore the global adsorption conversion ratio of the chemisorption composite can be calculated by the following equation, where $m_{am(SrCl_2 \cdot 8NH_3)}$ and $m_{am(SrCl_2 \cdot NH_3)}$ is the gross ammonia inside the condenser/evaporator at the beginning and end of the desorption process, respectively. Equation (13) is used to ensure the accuracy of the adsorption conversion ratio.

$$X = \frac{m_{am(SrCl_2 \cdot NH_3)} - m_{am}}{m_{am(SrCl_2 \cdot NH_3)} - m_{am(SrCl_2 \cdot 8NH_3)}}$$  \hspace{1cm} (12)

$$\Delta X = \frac{2\Delta m_{am}}{m_{am(SrCl_2 \cdot NH_3)} - m_{am}}$$  \hspace{1cm} (13)

3. Results and discussion

3.1 The thermal conductivity of SrCl$_2$-ENG under various mass ratio and density

To study the effect of various mass ratios of the salt and densities of the composite adsorbent SrCl$_2$-ENG, the project tested the thermal conductivity of composite
SrCl$_2$-ENG, and the results with error bars are drawn in Fig.4. The thermal conductivity of the tested samples ranges from 1.25 to 3.07 W/(m·K). The highest sample thermal conductivity is about 3.07 W/(m·K) with a density of 600 kg/m$^3$ and a salt mass ratio of 50%. The thermal conductivity plays the most essential role in the application of composite adsorbent SrCl$_2$-ENG. Therefore, high densities and low mass ratios of salt are generally desirable as they enable high conductivities. The detailed values of thermal conductivities with densities from 400 to 600 kg/m$^3$ and SrCl$_2$ mass ratios from 50% to 83% could be retrieved from the figure for further sorption simulations.

![Graph showing thermal conductivity of SrCl$_2$-ENG under different mass ratios of salt and density](image)

**Fig.4.** The thermal conductivity of SrCl$_2$-ENG under different mass ratios of salt and density

### 3.2 The permeability of SrCl$_2$-ENG under various mass ratio and density
Permeability data of composite SrCl$_2$-ENG with different densities and mass ratios of salt can be found in Table 2, which shows the permeability of different samples ranging from $9.37 \times 10^{-14}$ to $9.51 \times 10^{-10}$ m$^2$. The results are plotted in Fig.5 to obtain the overview of the relationship between permeability and mass ratio of salt. In contrast to the thermal conductivity results, the increase of SrCl$_2$-ENG density and the decrease of the mass ratio of the salt will decrease the permeability, which means the mass transfer performance of the sorption system will be reduced. Results indicate when the mass ratio of salt ranges from 50 % to 67 %, the effect of the increasing salt mass ratio is quite limited on improving the permeability while the permeability of SrCl$_2$-ENG can be significantly increased when the mass ratio of SrCl$_2$ is higher than 75 %.

**Table 2**

The permeability of composite sorbent SrCl$_2$-ENG (m$^2$)

<table>
<thead>
<tr>
<th>Ratio/Density</th>
<th>400</th>
<th>450</th>
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<th>550</th>
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<tr>
<td>50%</td>
<td>$1.03 \times 10^{-12}$</td>
<td>$8.3 \times 10^{-13}$</td>
<td>$3.15 \times 10^{-13}$</td>
<td>$2.77 \times 10^{-13}$</td>
<td>$9.37 \times 10^{-14}$</td>
</tr>
<tr>
<td>67%</td>
<td>$1.72 \times 10^{-12}$</td>
<td>$1.43 \times 10^{-12}$</td>
<td>$4.83 \times 10^{-13}$</td>
<td>$4.51 \times 10^{-13}$</td>
<td>$2.11 \times 10^{-13}$</td>
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<td>Mass Ratio</td>
<td>SrCl$_2$-ENG Sorption Performance for Refrigeration Application</td>
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</tr>
<tr>
<td>75%</td>
<td>$1.31 \times 10^{-11}$ $9.55 \times 10^{-12}$ $4.41 \times 10^{-12}$ $3.26 \times 10^{-12}$ $8.26 \times 10^{-13}$</td>
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</tr>
<tr>
<td>80%</td>
<td>$2.46 \times 10^{-10}$ $3.5 \times 10^{-11}$ $2.26 \times 10^{-11}$ $1.09 \times 10^{-11}$ $3.69 \times 10^{-12}$</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>83%</td>
<td>$9.51 \times 10^{-10}$ $4.86 \times 10^{-10}$ $1.62 \times 10^{-10}$ $5.24 \times 10^{-11}$ $9.24 \times 10^{-12}$</td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

Fig.5. The permeability of SrCl$_2$-ENG under different mass ratios of salt and density.

3.3 Study of SrCl$_2$-ENG sorption performance for refrigeration application

Desorption performance was tested under saturated sorbent condition. Before the start stage, the adsorbent bed was cooled by the tap water and the evaporator was set to -20
°C for the composite to fully absorb ammonia before the desorption performance test.

The error of the global conversion ratio is not higher than 4%. Fig.6. (a) shows the desorption performance test results under 90 °C and 100 °C heat source temperature, when the condenser temperature was controlled at -20 °C. Fig.6. (b) shows the desorption performance when the condensation temperature was set at -10 °C. When 80% of convertible ammonia in the chemical reaction desorbed from the SrCl₂-ENG under 1.91 bar restricted pressure (-20 °C condenser temperature), the required generation time is 34 minutes under 90 °C heat source temperature and 21.6 minutes under 110 °C generating temperature. When the restricted pressure is changed to 2.89 bar (-10 °C condenser temperature), the regeneration time of the SrCl₂-ENG under the same heat source temperatures are extended as illustrated in Fig.6. (b). When the global conversion ratio is at 0.2, the regeneration time of the SrCl₂-ENG under 90 °C and 110 °C heat source temperature is 40.0 and 23.3 minutes, respectively.

(a) the condenser was at -20 °C   (b) the condenser was at -10 °C
The adsorption performance was experimentally tested under six different working conditions to simulate different refrigeration conditions. The adsorbent bed was controlled at 20 °C to release the chemical reaction heat into the environment during the adsorption process. Results indicate that the SrCl$_2$-ENG rapidly absorbed ammonia within around 20 minutes and then slowed the reaction rate down after 20 minutes as shown in Fig.7. (a), when controlling the evaporator at 5, 10 and 15 °C for air conditioning applications. When the global conversion ratio was 0.7, the reaction duration for 5, 10 and 15 °C evaporation temperature is respectively 29.2, 21.8 and 15.8 minutes. Adsorption performance of SrCl$_2$-ENG for freezing condition (under zero Celsius) has been tested, and the results are plotted in Fig.7. (b). When the freezing temperature was set at -10 °C, it requires around 71 minutes for SrCl$_2$-ENG to reach the global conversion ratio at 0.7. For the other two freezing conditions, the reaction time is 48.1 minutes for -5 °C and 35.5 minutes for 0 °C under the global conversion ratio at 0.7.
(a) the evaporator was at 5, 10, 15 °C  
(b) the evaporator was at -10, -5, 0 °C

Fig.7. The adsorption performance of SrCl₂ consolidated sorbent

The sorption capacity of the tested samples was calculated and studied with different reaction times for refrigeration application. The adsorption amounts of ammonia in SrCl₂-ENG at different refrigeration temperatures and 35, 40 and 45 minutes reaction durations were calculated. Results were plotted as shown in Fig.8, indicating the composite adsorbent SrCl₂-ENG can respectively adsorb 700 g ammonia per 1 kg SrCl₂ for 15 °C cooling production and around 630 g ammonia per 1 kg SrCl₂ at 10 °C refrigeration temperature when the adsorption time is longer than 35 minutes. The adsorption amount is almost stable at 35, 40 and 45 minutes when the refrigeration temperature is set at 10 and 15 °C, while under the other evaporating temperatures could not hold a constant value on adsorption amount after 35 to 45 minutes adsorption time. When the composite sorbent is used for freezing application at -10 °C, the adsorption amount is 360 g ammonia per kg SrCl₂, which is only about half of that at the cooling temperature of 15 °C.

The global conversion ratio of ammonia and the adsorption amount dropped with the evaporation temperature decrease, which indicated that a higher evaporation temperature would lead to more evaporated ammonia, and thus more ammonia was adsorbed by the sorbent, producing a higher cooling effect.
Fig. 8. The adsorption capacity of SrCl$_2$-ENG under different reaction time for refrigeration application

3.4 Short discussion for the performance of SrCl$_2$-ENG compared with other adsorbents

Results indicated by adding ENG to SrCl$_2$ can effectively improve the thermal conductivity of pure SrCl$_2$. The thermal conductivity of the commonly used salts is ranging from 0.3 to 0.5 W/(m·K) [3, 32], while the thermal conductivity of SrCl$_2$-ENG ranges from 1.25 to 3.07 W/(m·K). The highest thermal conductivity of the consolidated composite activated carbon adsorbent reported by Wang et al. is 2.47 W/(m·K) [33], which is lower than the maximum value obtained from the developed SrCl$_2$-ENG in this study. The gas permeability of other commonly used composite adsorbents including graphite–CaCl$_2$·nNH$_3$ (n=8, 4, 2), BaCl$_2$·nNH$_3$ (n=8, 0) and
MnCl$_2$·nNH$_3$ (n=6, 2) range from 5.0×10$^{-16}$ – 10$^{-12}$ m$^2$ [8], which is lower than the results obtaining from this work ranging from 9.37×10$^{-14}$ to 9.51×10$^{-10}$ m$^2$. The sorption performance results reported by Jiang et al. [17] using CaCl$_2$/ENG-TSA as the composite adsorbent range from 364 g/kg to 449.2 g/kg under the evaporation temperature set from −10 to 15 °C. The reported results in this paper using SrCl$_2$-ENG under the evaporation temperature at 0 °C can potentially achieve higher adsorption capacity compared to that of CaCl$_2$/ENG-TSA after 35 min reaction time.

4. Conclusions

In this work, the thermal conductivity and the permeability of SrCl$_2$-ENG composite adsorbents under different densities and salt mass ratios were investigated by a Laser Flash Apparatus and a permeability test rig. The sorption performance has been tested by a test rig using a volumetric testing method to obtain the dynamic sorption performance. The sorption quantity of the composite with different reaction durations has been tested to evaluate the refrigeration performance. The main conclusions drawn from this study can be summarised as

- The composite sorbents SrCl$_2$-ENG under various densities (400 – 600 kg/m$^3$) and mass ratios of salt (50% - 83%), the thermal conductivity ranges from 1.25 to 3.07 W/(m·K). The highest thermal conductivity is achieved at 3.07 W/(m·K), retrieving from the sample with a density of 600 kg/m$^3$ and the SrCl$_2$ mass ratio of 50%.
• The permeability of the tested samples ranges from $9.51 \times 10^{-10}$ to $9.37 \times 10^{-14}$ m$^2$. The largest value of permeability is obtained from the sample under the density of 400 kg/m$^3$ and salt mass ratio of 83%.

• When the sorbent desorbed 80% of convertible ammonia, the generation time was 34 minutes at 90 °C and 21.6 minutes at 100 °C under the restricted pressure at 1.91 bar. When the restricted pressure was set at 2.89 bar, in order to reach 80% global conversion ratio, it required 40.0 and 23.3 minutes under the desorption temperature at 90 °C and 100 °C, respectively.

• The results of adsorption performance analysis from six cases shown that the reaction duration for -10, -5, 0, 5, 10 and 15 °C evaporation temperature to reach 0.7 global conversion ratio is respectively around 71, 48.1, 35.5, 29.2, 21.8 and 15.8 minutes under 20 °C adsorbent temperature.

• The sorption capacity of the tested samples was analysed with different reaction times and refrigeration temperatures. The highest sorption capacity obtained in this study is 736.8 g/kg SrCl$_2$.

In summary, the quantitative data provide valuable thermophysical parameters of the SrCl$_2$ ENG composite adsorbents, which are critical and important to build simulation models for sorption systems.

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