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1 *Investigation of thermal characteristics of strontium*
2 *chloride composite sorbent for sorption refrigeration*

3 Ke Tang ^{a,b}, Yiji Lu ^{a,b,*}, Long Jiang ^{b,*}, Liwei Wang ^c,
4 Yaodong Wang ^b, Anthony Paul Roskilly ^{a,b}, Xiaoli Yu ^{a,b}

5 ^a Department of Energy Engineering, Zhejiang University, Hangzhou 310027, China

6 ^b Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle, NE1 7RU, UK

7 ^c Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai, 200240, China

8 **Abstract:**

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

22 **Keywords:** Thermal conductivity, Permeability, Composite sorbent, Sorption
23 characteristic, Strontium chloride

* Corresponding author

E-mail address: luyiji0620@gmail.com; (Y. Lu)

Long.jiang@ncl.ac.uk; (L. Jiang)

1 HIGHLIGHTS

- 2 • The composite sorbent material SrCl₂-ENG under various mixture ratios was
- 3 developed
- 4 • Heat and mass transfer performance of the composite materials were investigated
- 5 • The sorption performance for refrigeration application was studied

6 Nomenclature

A_c	Cross section area of the ammonia vessel (m ²)
AC	Activated Carbon
B	Shape factor
C_p	Specific heat (J/(g·K))
d	The thickness of the test sample (mm)
ENG	Expanded Natural Graphite
g	The acceleration of gravity (9.8 m/s ²)
K	Permeability (m ²)
m_a	Gas mass flow rate (kg/s)
m_{am}	Gross mass of the ammonia in the vessel (kg)
p	Pressure (Pa)
p_d	Pressure difference (Pa)

q	Gas volume flow rate (L/min)
R	Gas constant (J/(kg·K))
S	Cross section area of the sample (m ²)
T	Temperature (°C)
TSA	Treated with sulfuric acid
t_{50}	Semi-heating time (s)
V	The Internal volume of the ammonia vessel (m ³)
v_a	Axial velocity (m/s)
X	Global conversion ratio
Y	Intrinsic characteristic

1 **Greek letters**

α	Thermal diffusivity (mm ² /s)
λ	Thermal conductivity (W/m·K)
μ	Gas viscosity (Pa·s)
ρ	Density (kg/m ³)
v	Specific volume (m ³ /kg)

2 **Subscripts**

a	Sorbent
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c	Condensing
de	Desorption
f	Fluid
g	Gas
In	Inlet
Out	Outlet
s	sample
sorb	Sorbent
SrCl ₂	Strontium chloride

1

1 ***1. Introduction***

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

6 The sorption refrigeration cycles generally are all discontinuous batch processes
7 involving sorption and desorption phases [3]. Building adsorption simulation models
8 is a standard and efficient method to explore, evaluate and optimise adsorption cycle
9 technologies instead of conducting large quantities of experiments. The accurate and
10 detailed parameters such as thermal conductivity and permeability of adsorption
11 sorbents are critical and important for the simulation study. One of the inevitable
12 challenges in completing an efficient adsorption cycle is to achieve the high heat
13 transfer and mass transfer performance of the sorbent. To overcome this challenge,
14 the researchers have studied the composite sorbent to improve the heat and mass
15 transfer performance of the sorbent. As one major important matrix of composite
16 sorbent, Expanded Natural Graphite (ENG) has been widely investigated [4], which
17 was invented by the Carburet Company [5]. It was made from the expandable graphite
18 which is prepared by the methods of electrochemistry and chemistry oxidation [6].
19 Early studies about the consolidated composite sorbent impregnated with ENG as the
20 matrix was investigated by Mauran et al. [7], who indicated the better heat transfer
21 performance for CaCl_2 . Later, Han and Lee [8] investigated the gas permeability of

1 different chlorides with ENG using Darcy's law in the ammonia atmosphere. Results
2 indicated the gas permeability was in the range of 5.0×10^{-16} - 10^{-12} m² depending on the
3 reaction pair, bulk density and weight fraction of the graphite powder [8]. Biloe et al.
4 [9] researched the permeability of compact ENG by using Helium as a gas source, and
5 the results showed that the value of permeability varied from 10^{-15} - 10^{-12} m². Wang et
6 al. [10] measured the effective thermal conductivity of ENG-CaCl₂-nNH₃ (n = 2, 4, 8)
7 compound sorbent by using the hot wire method at a fixed pressure and temperature
8 under ammonia atmosphere, and the values were in the range of 7.05-9.2 W/(m.K).
9 The steady-state heat source method had been utilised by Tamainot-Telto and Critoph
10 [11, 12], leading to the thermal conductivity up to 0.44 W/(m.K). Jiang et al. [13, 14]
11 investigated thermal conductivity and permeability of eight different chlorides with
12 ENG and compared the properties of different consolidated composite sorbents in the
13 sorption process. Nonetheless, due to the characteristics of anisotropic heat and mass
14 transfer performance, some testing method may cause some inaccuracies.
15 Recently, expanded natural graphite treated with sulfuric acid (ENG-TSA)
16 manufactured by Mersen in France is introduced to further improve the heat and mass
17 transfer performance of the sorbent. As one prospective heat transfer matrix, the
18 highest thermal conductivity for this matrix could reach 337 W/(m.K) at a bulk
19 density of 831 kg/m³, which can be applied for both physical and chemical sorbent
20 [15]. For physical sorbent, the thermo-physical properties of composite AC with the
21 matrix of ENG-TSA was evaluated, and the results showed that the highest effective

1 thermal conductivity was 34.2 W/(m.K), that is 150 times higher than ordinary
2 granular AC [15]. Silica gel with ENG-TSA as the matrix was investigated.
3 Experimental results showed that the highest thermal conductivity of consolidated
4 composite sorbents is 19.1 W m⁻¹ K⁻¹ [16]. For chemical sorbent, CaCl₂ impregnated
5 with ENG-TSA (Treated with sulfuric acid) can reach the highest thermal
6 conductivity of 88.1 W m⁻¹ K⁻¹ [17]. Nonetheless, one shortcoming is that ENG-TSA
7 requires relatively high manufacturing price, which is 60 times higher than that of
8 ENG per unit mass. Also noting that for the conventional finned tube heat exchanger
9 for the sorbent, the primary heat resistance relies on the heat resistance between the
10 sorbent and metal tube rather the sorbent itself [18]. Therefore, considering both the
11 performance and thermo-economy, ENG has been more frequently used in the
12 practical sorption system for refrigeration and thermal energy storage rather than
13 ENG-TSA [19, 20].

14 The strontium chloride has been recommended as one of the promising chemisorption
15 salt for low-grade heat recovery application and thermal energy storage [21, 22]. For
16 example, the authors have previously reported and investigated the potential
17 application of using novel strontium chloride composite sorbent to form a power
18 generation system [23]. Results indicated the developed system can be potentially
19 used to recover low-grade heat sources such as solar energy, geothermal energy and
20 industrial waste heat under the temperature over 120 °C [23]. However, compared
21 with the reported researches on composite CaCl₂ [24], limited quantitative data can be

1 found for the sorbents using strontium chloride (SrCl_2), which leads to the difficulty
2 of generating a highly accurate simulation model to predict the performance of
3 sorption system using SrCl_2 sorbents. Therefore, in this paper, the thermo-physical
4 properties including thermal conductivity and permeability of SrCl_2 impregnated with
5 ENG as a matrix under various mixture ratios have been comprehensively
6 investigated. Moreover, a sorption performance test rig has been used to examine the
7 selected mass ratio SrCl_2 composite for sorption refrigeration application.

8 ***2. Methodologies***

9 ***2.1 Preparation of composite sorbents***

10 The Expanded Natural Graphite (ENG) used in this study is manufactured by
11 Shanghai Yi Fan Graphite Company with 50-80 mesh size, and the purity of the ENG
12 is larger than 99 %. The ENG has been expanded in an oven at the temperature of 600
13 °C for 8 minutes [25]. Detailed development processes of the SrCl_2 composite sorbent
14 can be found in the authors' previous publication [26]. The previously reported study
15 on the anisotropic thermal conductivity and permeability of the consolidated ENG
16 matrix indicated both optimal heat and mass transfer directions are perpendicular to
17 the compression direction [27]. Therefore, plate samples are utilised to experimentally
18 investigate the thermal conductivity and permeability with different density and mass
19 ratio of salt. The mass ratio of salt and density are two significant factors, which
20 affect the permeability and thermal conductivity performance of SrCl_2 composite

1 sorbent. In this study, mass ratios of salt range from 50 % to 83 % and densities are
2 selected in the range of 400-600 kg/m³.

3 ***2.2 The thermal conductivity of composite sorbents***

4 Thermal conductivity was investigated by the Laser flash method, and the type of the
5 instrument is a Laser Flash Apparatus (LFA) 467 manufactured by Netzsch. The
6 accuracy of the thermal diffusivity and the specific heat is $\pm 3\%$ and $\pm 5\%$,
7 respectively, declared by the supplier. Diagram for the principle of the equipment is
8 shown in Fig.1. The unit mainly includes an infrared detector, a sample changer, a
9 heater, an optical filter, a reflector and a flash lamp. The sorbent sample was made
10 into a cylinder with the diameter of 12.7 mm and the height of 3 mm. Under a set
11 temperature T (controlled by the temperature controller of the machine), a beam of
12 light pulses is emitted instantaneously by the laser light source or a xenon flash lamp,
13 which can uniformly illuminate the surface of the test sample. The radial heat
14 conduction on the sample can be ignored due to the uniform illumination on the small
15 size of the sample and the rapid temperature changes in the longitudinal direction of
16 the sample. Therefore, the longitudinal heat conduction of the sample can be
17 recognised as the only heat conduction process in the LFA tests. The trend of the
18 temperature can be measured by using an infrared detector. By analysing the curves of
19 temperature-versus-time, the thermal diffusivity can be determined.

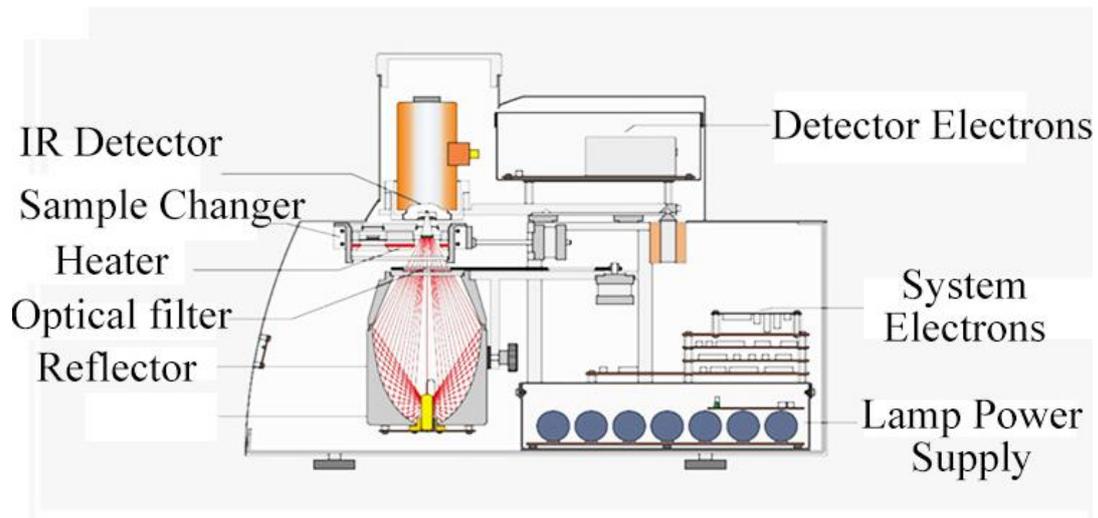


Fig.1. The schematic of thermal conductivity testing unit

1 The thermal diffusivity can be defined by the following equation, where α is thermal
 2 diffusivity, d is the thickness of the testing samples, and t_{50} is the semi-heating time
 3 (defined as the half-time required as the temperature of the sample in the upper
 4 surface is raised after receiving the light pulse irradiation) [28].

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

5 The thermal conductivity can be calculated by the Eq. (2), where $\lambda(T)$ is the thermal
 6 conductivity at a certain temperature, $\alpha(T)$ is the thermal diffusivity at a certain temperature,
 7 C_p is specific heat at a certain temperature, $\rho(T)$ is the density of the sample at a certain
 8 temperature. The density is determined by the sample volume and the sample weight. The
 9 sample was made by a self-manufactured sample maker, by which the volume random error is
 10 less than $\pm 1\%$. The accuracy of the analytical balance, product code Sartorius AZ612, is
 11 $\pm 0.02\text{g}$. Through the Error Propagation Formula, the relative accuracy of the thermal
 12 conductivity for this LFA machine is calculated in Equation (3). $\Delta\lambda$, $\Delta\alpha$, and ΔC_p is the

1 uncertainty of the thermal conductivity, the thermal diffusivity, and the specific heat,
2 respectively.

$$\lambda(T) = \alpha(T) \times C_p(T) \times \rho(T) \quad (2)$$

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\alpha}{\alpha} + \frac{\Delta C_p}{C_p} = 8\% \quad (3)$$

3 **2.3 The permeability of composite sorbents**

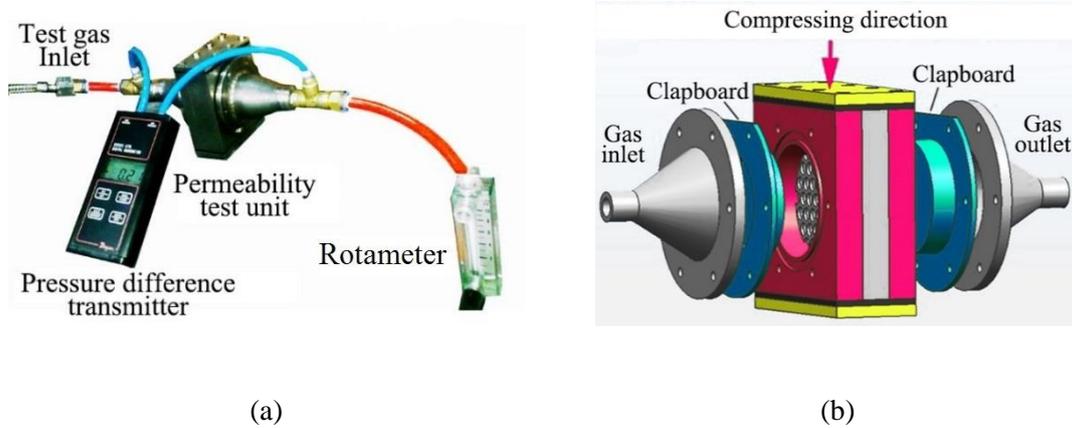


Fig.2. The permeability test system (a) photo of the rig, (b) drawing of the test unit[27]

4 The permeability test rig used in this work is shown in Fig.2. (a), mainly containing a
5 permeability test chamber, a differential pressure transmitter (Dwyer477A-7), and a
6 rotameter (Dwyer MMA-23). The sorbents were compressed into the chamber of the
7 permeability test unit of intended densities and salt mass ratios as illustrated in Fig.2.
8 (b), with a compressing direction perpendicular to the gas flow. This direction is the
9 optimal choice for permeability test [25]. A metal mesh plate was applied on the two
10 sides of the sorbent surfaces to maintain the structure and prevent its breakage.
11 Nitrogen was used as the test gas because of its chemical stability and no reaction
12 with sorbents or test rig. Treated as an ideal gas, nitrogen was assumed not to

1 accumulate in the sorbent sample during the test. The test gas inlet was opened to start
 2 the permeability of the sorbent sample by letting the nitrogen gas entering in the test
 3 rig. The gas phase nitrogen flow through the permeability test unit and the pressure
 4 drop Δp across the sample and the flow rate q_v of nitrogen were therefore measured
 5 during the gas flow period.

6 Since the tested samples are porous media with anisotropic characteristics, the Ergun
 7 model is applicable in the measurement because no compressibility effects exist [29].

8 The intrinsic characteristic of the sample can be expressed by the following equations
 9 (4) and (5), where K is the permeability of the samples (m^2), B is the shape factor of
 10 the samples, p_{in} and p_{out} are the inlet pressure and outlet pressure of the nitrogen, S is
 11 the sample cross section (m^2), R is the gas constant ($J/(kg \cdot K)$), T is the sample
 12 temperature (K), Δz is the thickness of the compact sample, μ and ρ are the gas
 13 viscosity (Pa·s) and density (kg/m^3), respectively; m_a is the gas mass flow rate (kg/s),
 14 v_a is the axial velocity of the sample (m/s). The accuracy of this test could be derived
 15 by Equation (6), (7) and (8). The accuracy of the pressure difference transmitter is
 16 $\pm 0.1\%$, and that of the rotameter is $\pm 4\%$, declared by the supplier. ΔK , ΔY , ΔX , Δp ,
 17 and Δv are the errors of the relative parameters.

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

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

$$\frac{\Delta K}{K} = \frac{\Delta Y}{|Y - BX|} + \left| \frac{B}{Y - BX} \right| \cdot \Delta X \quad (6)$$

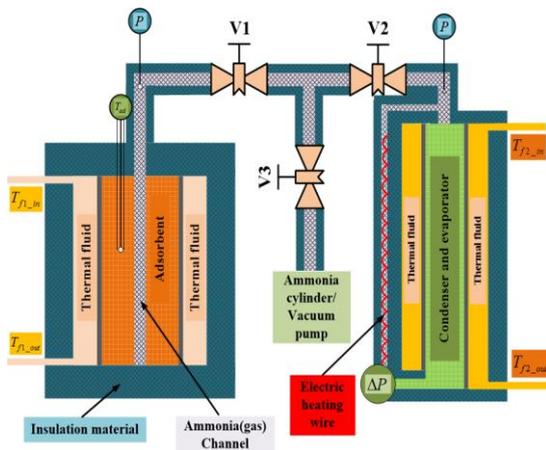
$$\frac{\Delta Y}{Y} = \frac{2(p_{in} + p_{out}) \cdot \Delta p}{p_{in}^2 - p_{out}^2} + \frac{\Delta v}{v} \quad (7)$$

$$\frac{\Delta X}{X} = \frac{\Delta v}{v} \quad (8)$$

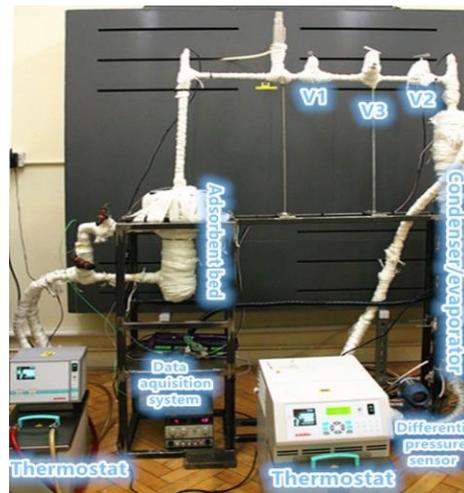
1 The maximum relative error of the permeability is $\pm 14.2\%$, obtained when the
 2 permeability reaches the lowest in this test. The average relative error is $\pm 13.6\%$.

3 ***2.4 Sorption performance test of composite sorbents***

4 An adsorption performance test rig using volumetric testing method was used to
 5 measure the sorption performance of the chemisorption composite. The rig mainly
 6 includes an adsorbent bed, a condenser/evaporator, two oil bath units, a differential
 7 pressure sensor, two pressure sensors, five temperature sensors and an electric heating
 8 wire as shown in Fig.3.



(a)



(b)

Fig.3. Sorption performance test rig (a) Schematic diagram, (b) photo of the apparatus

1 The prepared composite sorbents were compressed into the adsorbent bed with a
 2 density of 450 kg/m^3 and a salt mass ratio of 50%. During the desorption process, the
 3 adsorbent bed was heated to desorb ammonia by the thermal oil from the oil bath,
 4 while a cryostat controls the temperature of the condenser. The ammonia gas then
 5 condensed in the condenser. In the period of the adsorption process, the adsorbent bed
 6 was cooled using tap water to reject the adsorption heat and the condenser vessel in
 7 desorption process acted as an evaporator at the testing temperature by the controlling
 8 from a connected cryostat. The ammonia gas absorbed evaporation heat from the
 9 condenser and was adsorbed by the sorbents in the sorbent bed, thus providing
 10 refrigeration from condenser vessel. The gross mass of gas phase ammonia in the
 11 system could be calculated by the readings of a differential pressure sensor, which is
 12 located at the bottom of the condenser. The calculation method of the gross mass of
 13 the ammonia in the condenser/evaporator can be described by the following equation
 14 [30, 31], where A_c and V is the internal area and internal volume of the
 15 condenser/evaporator, respectively. $v_f(T_e)$ and $v_g(T_e)$ is the specific volume of the
 16 saturated liquid and vapour phase ammonia under the controlled temperature T_e of
 17 the condenser/evaporator. The accuracy of the pressure differential sensor is $\pm 2\%$.
 18 Through Equation (10), the error of the ammonia mass would be the same as $\pm 2\%$.

$$m_{am} = \left[1 - \frac{v_f(T_e)}{v_g(T_e)}\right] \cdot \frac{A_c}{g} \cdot \Delta p + \frac{V}{v_g(T_e)} \quad m_{am} = \left[1 - \frac{v_f(T_c)}{v_g(T_c)}\right] \cdot \frac{A_c}{g} \cdot p_d + \frac{V}{v_g(T_c)} \quad (9)$$

$$\Delta m_{am} = \Delta p_d \quad (10)$$

1 The chemical reaction equations between SrCl₂ and NH₃ in the range of experimental
2 temperature can be found in Eq. (11).



3 Compared with the adsorption ability of SrCl₂, the Natural Expanded Graphite can
4 only adsorb quite limited ammonia, which is suitable to be ignored in this test.
5 Therefore the global adsorption conversion ratio of the chemisorption composite can
6 be calculated by the following equation, where $m_{am(SrCl_2 \cdot 8NH_3)}$ and $m_{am(SrCl_2 \cdot NH_3)}$ is the
7 gross ammonia inside the condenser/evaporator at the beginning and end of the
8 desorption process, respectively. Equation (13) is used to ensure the accuracy of the
9 adsorption conversion ratio.

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

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

10 **3. Results and discussion**

11 **3.1 The thermal conductivity of SrCl₂-ENG under various mass ratio** 12 **and density**

13 To study the effect of various mass ratios of the salt and densities of the composite
14 adsorbent SrCl₂-ENG, the project tested the thermal conductivity of composite

1 SrCl₂-ENG, and the results with error bars are drawn in Fig.4. The thermal
 2 conductivity of the tested samples ranges from 1.25 to 3.07 W/(m·K). The highest
 3 sample thermal conductivity is about 3.07 W/(m·K) with a density of 600 kg/m³ and a
 4 salt mass ratio of 50%. The thermal conductivity plays the most essential role in the
 5 application of composite adsorbent SrCl₂-ENG. Therefore, high densities and low
 6 mass ratios of salt are generally desirable as they enable high conductivities. The
 7 detailed values of thermal conductivities with densities from 400 to 600 kg/m³ and
 8 SrCl₂ mass ratios from 50% to 83% could be retrieved from the figure for further
 9 sorption simulations.

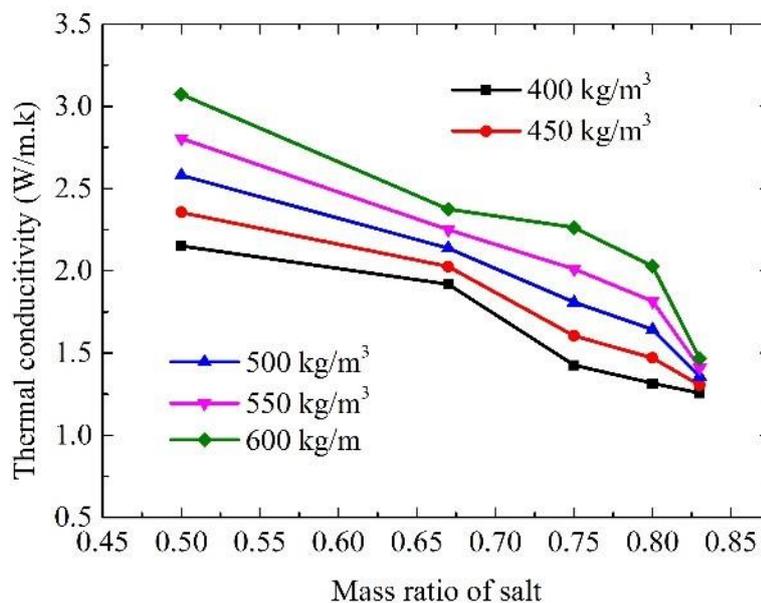


Fig.4. The thermal conductivity of SrCl₂-ENG under different mass ratios of salt and density

3.2 The permeability of SrCl₂-ENG under various mass ratio and density

1 Permeability data of composite SrCl₂-ENG with different densities and mass ratios of
 2 salt can be found in Table 2, which shows the permeability of different samples
 3 ranging from 9.37×10^{-14} to 9.51×10^{-10} m². The results are plotted in Fig.5 to obtain the
 4 overview of the relationship between permeability and mass ratio of salt. In contrast
 5 to the thermal conductivity results, the increase of SrCl₂-ENG density and the
 6 decrease of the mass ratio of the salt will decrease the permeability, which means the
 7 mass transfer performance of the sorption system will be reduced. Results indicate
 8 when the mass ratio of salt ranges from 50 % to 67 %, the effect of the increasing salt
 9 mass ratio is quite limited on improving the permeability while the permeability of
 10 SrCl₂-ENG can be significantly increased when the mass ratio of SrCl₂ is higher than
 11 75 %.

12 **Table 2**

13 The permeability of composite sorbent SrCl₂-ENG (m²)

Ratio/Density	400	450	500	550	600
50%	1.03×10^{-12}	8.3×10^{-13}	3.15×10^{-13}	2.77×10^{-13}	9.37×10^{-14}
67%	1.72×10^{-12}	1.43×10^{-12}	4.83×10^{-13}	4.51×10^{-13}	2.11×10^{-13}

75%	1.31×10^{-11}	9.55×10^{-12}	4.41×10^{-12}	3.26×10^{-12}	8.26×10^{-13}
80%	2.46×10^{-10}	3.5×10^{-11}	2.26×10^{-11}	1.09×10^{-11}	3.69×10^{-12}
83%	9.51×10^{-10}	4.86×10^{-10}	1.62×10^{-10}	5.24×10^{-11}	9.24×10^{-12}

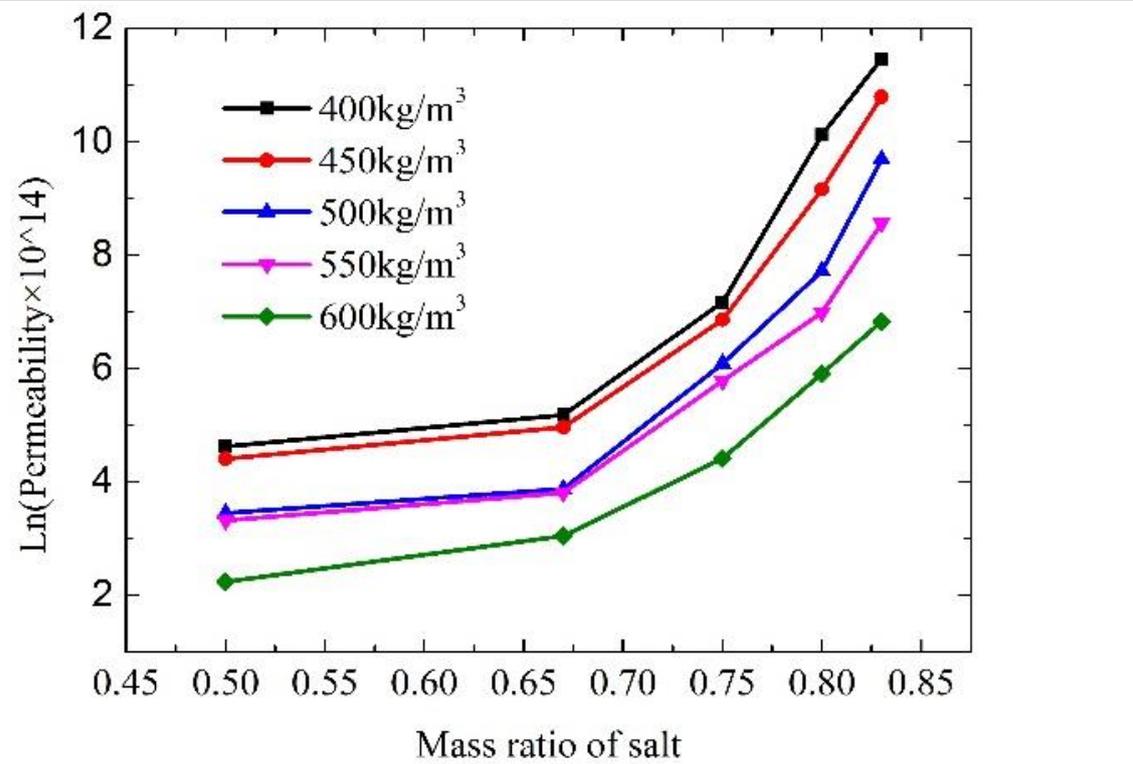


Fig.5. The permeability of SrCl₂-ENG under different mass ratios of salt and density

1 **3.3 Study of SrCl₂-ENG sorption performance for refrigeration**
2 **application**

3 Desorption performance was tested under saturated sorbent condition. Before the start
4 stage, the adsorbent bed was cooled by the tap water and the evaporator was set to -20

1 °C for the composite to fully absorb ammonia before the desorption performance test.

2 The error of the global conversion ratio is not higher than 4%. Fig.6. (a) shows the

3 desorption performance test results under 90 °C and 100 °C heat source temperature,

4 when the condenser temperature was controlled at -20 °C. Fig.6. (b) shows the

5 desorption performance when the condensation temperature was set at -10 °C. When

6 80% of convertible ammonia in the chemical reaction desorbed from the SrCl₂-ENG

7 under 1.91 bar restricted pressure (-20 °C condenser temperature), the required

8 generation time is 34 minutes under 90 °C heat source temperature and 21.6 minutes

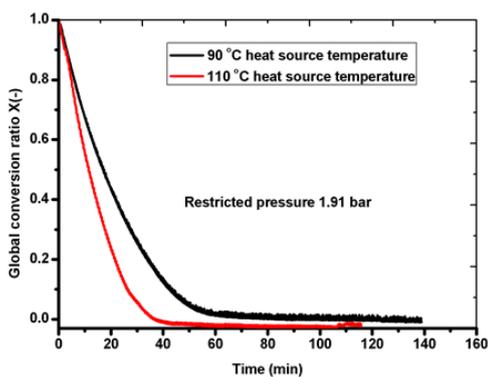
9 under 110 °C generating temperature. When the restricted pressure is changed to 2.89

10 bar (-10 °C condenser temperature), the regeneration time of the SrCl₂-ENG under the

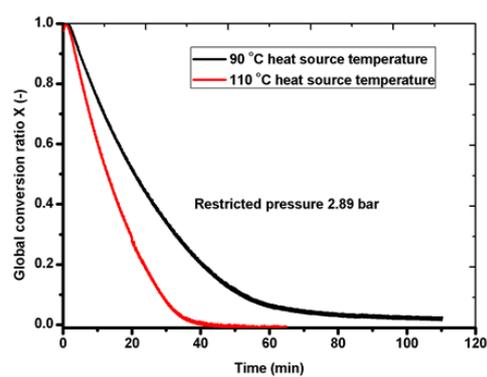
11 same heat source temperatures are extended as illustrated in Fig.6. (b). When the

12 global conversion ratio is at 0.2, the regeneration time of the SrCl₂-ENG under 90 °C

13 and 110 °C heat source temperature is 40.0 and 23.3minutes, respectively.



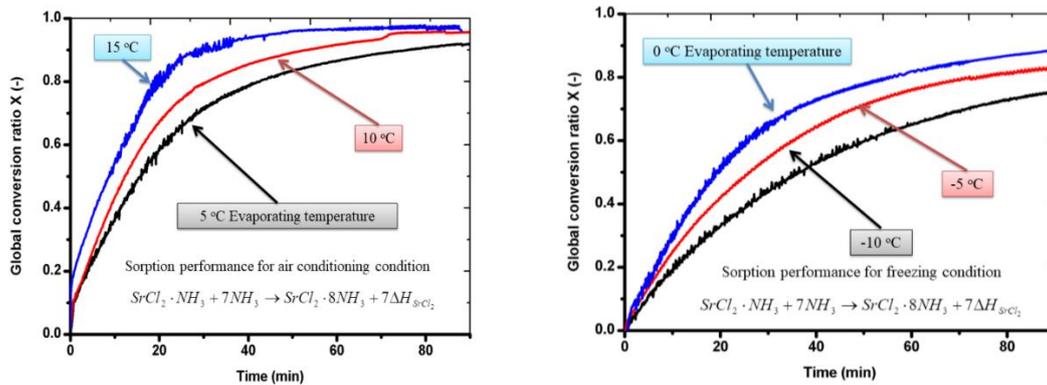
(a) the condenser was at -20 °C



(b) the condenser was at -10 °C

Fig.6. The desorption performance of SrCl₂ consolidated sorbent

1 The adsorption performance was experimentally tested under six different working
 2 conditions to simulate different refrigeration conditions. The adsorbent bed was
 3 controlled at 20 °C to release the chemical reaction heat into the environment during
 4 the adsorption process. Results indicate that the SrCl₂-ENG rapidly absorbed
 5 ammonia within around 20 minutes and then slowed the reaction rate down after 20
 6 minutes as shown in Fig.7. (a), when controlling the evaporator at 5, 10 and 15 °C for
 7 air conditioning applications. When the global conversion ratio was 0.7, the reaction
 8 duration for 5, 10 and 15 °C evaporation temperature is respectively 29.2, 21.8 and
 9 15.8 minutes. Adsorption performance of SrCl₂-ENG for freezing condition (under
 10 zero Celsius) has been tested, and the results are plotted in Fig.7. (b). When the
 11 freezing temperature was set at -10 °C, it requires around 71 minutes for SrCl₂-ENG
 12 to reach the global conversion ratio at 0.7. For the other two freezing conditions, the
 13 reaction time is 48.1 minutes for -5 °C and 35.5 minutes for 0 °C under the global
 14 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

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

14 The global conversion ratio of ammonia and the adsorption amount dropped with the
15 evaporation temperature decrease, which indicated that a higher evaporation
16 temperature would lead to more evaporated ammonia, and thus more ammonia was
17 adsorbed by the sorbent, producing a higher cooling effect.

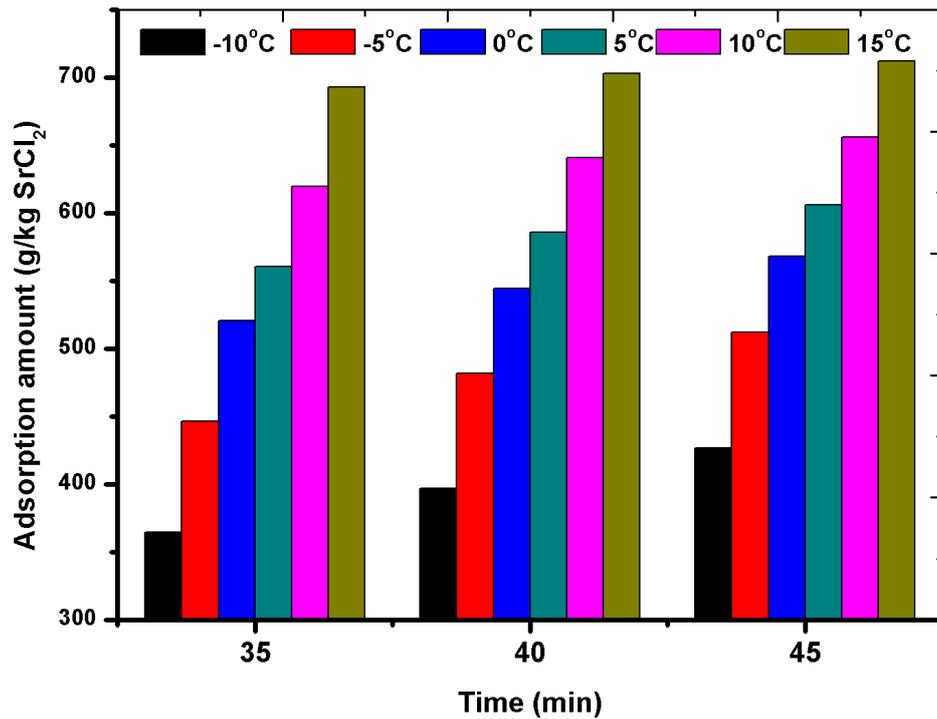


Fig.8. The adsorption capacity of SrCl₂-ENG under different reaction time for refrigeration application

1 ***3.4 Short discussion for the performance of SrCl₂-ENG compared***
2 ***with other adsorbents***

3 Results indicated by adding ENG to SrCl₂ can effectively improve the thermal
4 conductivity of pure SrCl₂. The thermal conductivity of the commonly used salts is
5 ranging from 0.3 to 0.5 W/(m·K) [3, 32], while the thermal conductivity of
6 SrCl₂-ENG ranges from 1.25 to 3.07 W/(m·K). The highest thermal conductivity of
7 the consolidated composite activated carbon adsorbent reported by Wang et al. is 2.47
8 W/(m·K) [33], which is lower than the maximum value obtained from the developed
9 SrCl₂-ENG in this study. The gas permeability of other commonly used composite
10 adsorbents including graphite–CaCl₂·nNH₃ (n=8, 4, 2), BaCl₂·nNH₃ (n=8, 0) and

1 $\text{MnCl}_2 \cdot n\text{NH}_3$ ($n=6, 2$) range from $5.0 \times 10^{-16} - 10^{-12} \text{ m}^2$ [8], which is lower than the
2 results obtaining from this work ranging from 9.37×10^{-14} to $9.51 \times 10^{-10} \text{ m}^2$. The
3 sorption performance results reported by Jiang et al. [17] using $\text{CaCl}_2/\text{ENG-TSA}$ as
4 the composite adsorbent range from 364 g/kg to 449.2 g/kg under the evaporation
5 temperature set from -10 to $15 \text{ }^\circ\text{C}$. The reported results in this paper using
6 $\text{SrCl}_2\text{-ENG}$ under the evaporation temperature at $0 \text{ }^\circ\text{C}$ can potentially achieve higher
7 adsorption capacity compared to that of $\text{CaCl}_2/\text{ENG-TSA}$ after 35 min reaction time.

8 ***4. Conclusions***

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

- 16 • The composite sorbents $\text{SrCl}_2\text{-ENG}$ under various densities ($400 - 600 \text{ kg/m}^3$)
17 and mass ratios of salt (50% - 83%), the thermal conductivity ranges from
18 1.25 to $3.07 \text{ W/(m}\cdot\text{K)}$. The highest thermal conductivity is achieved at 3.07
19 $\text{W/(m}\cdot\text{K)}$, retrieving from the sample with a density of 600 kg/m^3 and the
20 SrCl_2 mass ratio of 50 %.

- 1 • The permeability of the tested samples ranges from 9.51×10^{-10} to 9.37×10^{-14}
2 m². The largest value of permeability is obtained from the sample under the
3 density of 400 kg/m³ and salt mass ratio of 83%.
- 4 • When the sorbent desorbed 80% of convertible ammonia, the generation time
5 was 34 minutes at 90 °C and 21.6 minutes at 100 °C under the restricted
6 pressure at 1.91 bar. When the restricted pressure was set at 2.89 bar, in order
7 to reach 80% global conversion ratio, it required 40.0 and 23.3 minutes under
8 the desorption temperature at 90 °C and 100 °C, respectively.
- 9 • The results of adsorption performance analysis from six cases shown that the
10 reaction duration for -10, -5, 0, 5, 10 and 15 °C evaporation temperature to
11 reach 0.7 global conversion ratio is respectively around 71, 48.1, 35.5, 29.2,
12 21.8 and 15.8 minutes under 20 °C adsorbent temperature.
- 13 • The sorption capacity of the tested samples was analysed with different
14 reaction times and refrigeration temperatures. The highest sorption capacity
15 obtained in this study is 736.8 g/kg SrCl₂.

16 In summary, the quantitative data provide valuable thermophysical parameters of
17 the SrCl₂·ENG composite adsorbents, which are critical and important to build
18 simulation models for sorption systems.

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