Author(s): L.W. Wang, S.J. Metcalf, R.E. Critoph, R. Thorpe, Z. Tamainot-Telto
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Development of thermal conductive consolidated activated carbon for adsorption refrigeration

L.W. Wang[a,b*], S.J. Metcalf[b], R.E. Critoph[b], R. Thorpe[b], Z. Tamainot-Telto[b]

[a] Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai, 200240, China;

[b] School of Engineering, University of Warwick, Coventry CV4 7AL, UK.

Abstract

A new type consolidated composite activated carbon (AC) was developed with the host matrix of the expanded natural graphite treated with sulphuric acid (ENG-TSA). The samples with different density, different grain size of AC, and different proportion of AC were produced, and the thermal conductivity, permeability, specific heat capacity and adsorption performance were tested. Results show that the highest thermal conductivity, effective thermal conductivity, and thermal diffusivity of consolidated composite AC were 34.15 W $m^{-1}K^{-1}$, 20.3 W $m^{-1}K^{-1}$, and 2.44×10^{-5} m^2 s^{-1}, which were improved by 150 times, 88 times and 45 times, respectively, if compared with the data of granular AC. The permeability of adsorbents ranged between 1.24×10^{-14} m^2 to 7.81×10^{-10} m^2 while the density ranged between 215 to 448 kg m^{-3}. Under some conditions the permeability increased with the increasing bulk density of AC mainly because that the AC grain disconnected the connections among ENG-TSA micro layers. The adsorption performance for composite AC and granular AC was tested and compared, and the equilibrium D-A equations were fitted by the experimental data. Results show that the additive of

* Corresponding author. Fax: +86-21-34206814. E-mail address: : lwwang@sjtu.edu.cn

ENG-TSA didn't influence the equilibrium adsorption performance of granular AC, and two types of adsorbents had similar adsorption performance.

1 Introduction

As a type of physical adsorbent for refrigeration, activated carbon (AC) has the advantages of high mass transfer performance, stable adsorption performance, and no problems of corrosion with metal containers compared with chemical adsorbents such as chlorides. Meanwhile AC also has the disadvantage of small cycle adsorption quantity [1]. On the adsorption with ammonia and methanol as refrigerants, the highest adsorption quantity of AC is about 0.4-0.5 and normally the cycle adsorption quantity is only about 0.2 [1]. The refrigerating power of adsorption refrigeration related with the cycle adsorption quantity is [2]:

$$W_{ref} = \frac{Q_{ev}}{t_c} = \frac{m_{ac} \times \Delta x \times \left[L_{ev} - C_{pL} \times \left(T_c - T_e \right) \right]}{t_c} \tag{1}$$

where W_{ref} is the refrigerating power (kW), Q_{ev} is the refrigerating capacity (kJ), m_{ac} is the mass of adsorbent in adsorber (kg), Δx is the cycle adsorption quantity (kg kg^{-1}), L_{ev} is the latent heat of refrigerant (kJ kg^{-1}), C_{pL} is the specific heat capacity of refrigerant (kJ kg^{-1}K^{-1}), T_{c} and T_{e} are condensing and evaporating temperature (K), respectively, and t_{c} is the cycle time (s).

Just as the eq.(1) shows, for the adsorbent with fixed value of mass and small Δx in a refrigeration system the only method to improve W_{ref} is to decrease t_{c}, i.e. to make the adsorption and desorption process faster by improving the thermal conductive and mass transfer performance of adsorbents.

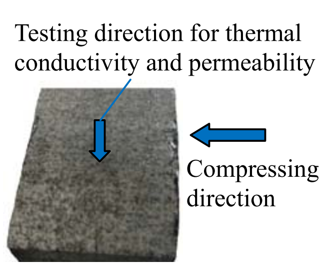
In order to improve the thermal conductivity of AC the consolidated and composite adsorbents, which have higher thermal conductivity, have been investigated by various researchers, e.g. Critoph[3], Spinner[4] and Wang[5]. Consolidated adsorbents of AC for refrigeration were mainly developed by mixing AC with various chemical binders. For example Critoph et al. utilizing the 208C precursor for treatment of monolithic activated carbon and the thermal conductivity is about 0.44W $m^{-1}K^{-1}$ [6], Wang et al utilized the acrylic latex adhesive to consolidate the AC and got the thermal conductivity of 0.34 W $m^{-1}K^{-1}$ [5], and Cacciola utilized PTFE as a binder got the effective thermal conductivity of 0.2 W $m^{-1}K^{-1}$ for AC[7]. For such materials the mass transfer performance tends to be reduced by adhesive or binder. On the utilization for refrigeration in order to develop a type of consolidated adsorbent with better heat transfer performance and meanwhile not to deteriorate the mass transfer performance, the simple composite consolidated adsorbent of AC and expanded natural graphite (ENG), which is a type of matrix with low heat and mass transfer resistance [8-11], had been developed, and the thermal conductivity has been improved to about 2.5 W $m^{-1}K^{-1}$ [11]. Py and Spinner et al. had proposed a type of new method to improve the thermal conductivity [4,12-14], and it is a little complex because it needed to mix together with the precursor and the activation agent for composite preparation for AC and ENG, i.e. the direct contact of agents, coating by an activation salt, impregnation and the forced convection of an activation gas. Such a method could get the highest thermal conductivity as high as about 32 W $m^{-1}K^{-1}$ [12,13], but it only had been proved for CO_2 adsorption for gas purification [14], not for refrigeration. Different from the method from Py et al, in this paper a new type ENG that was treated by sulfuric graphite (ENG-TSA) is proposed for the matrix of common AC for adsorption refrigeration, and the similar high thermal conductivity of 34 W $m^{-1}K^{-1}$ have been gotten by simple developing method.

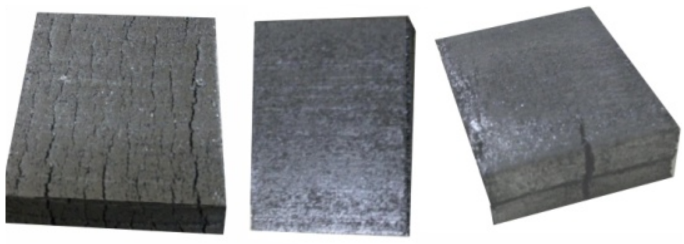
2 Development of adsorbents

Considering the anisotropic thermal conductivity and permeability of consolidated expanded graphite matrix [15], the plate samples, for which the thermal conductive and mass transferring direction is perpendicular with the compressing direction (Fig.1a), were developed for the experiments.

The whole process was firstly mixing AC, water and ENG-TSA, and then compressing the composite adsorbent by pressing machine. Two types of composite adsorbents were developed, one type was the composite adsorbents with large grain size of AC (30-40 mesh), and another type was the composite adsorbents with smaller size of AC (80-100 mesh), both two types of AC were from Chemviron.

The density of flake ENG-TSA is only about 6kg m^{-3}, and is very different from bulk granular AC, which is over than 300kg m^{-3}.This leads to a difficult mixing and consolidating process, and experiments showed that the adsorbent was difficult to be mixed evenly and to be compressed effectively with large AC grain size. Experiments showed that the cracks easily occurred for the sample with smaller density or larger density, or larger grain of AC, especially for the larger proportion of AC. For example, the samples with the ratio between AC and ESATNG of 2:1 for the AC of 80-100 mesh are shown in Fig.1. Results show that the cracks occurred for the sample with the density about 250 kg m^{-3}, and the cracks also existed for the density of about 450kg m^{-3}.





(a) (b) (c) (d)

Fig.1 Consolidated composite adsorbents, (a) Compressing direction and testing direction (b) density of 249kg m^{-3}, (c) density of 388 kg m^{-3}, (d) density of 448 kg m^{-3}

In the experiments 27 composite samples with different ratio and different density were developed, and the parameters are shown in Table 1.

The bulk density of granular AC of 80-100 mesh is 369 kg m^{-3}, and the bulk density of granular AC of 30-40 mesh is 306 kg m^{-3}. The bulk density of AC was calculated by dividing the total volume of composite adsorbents with the mass of AC in composite adsorbents. The relation between bulk density of AC, density of composite adsorbent, and ratio of AC is shown in Fig.2. The maximum bulk density of AC was 298 kg m^{-3} while the percentage of AC was 67% and the density of composite adsorbent was 448 kg m^{-3}. The bulk density of AC decreased when the percentage of AC and the density of composite adsorbent decreased. The smallest bulk density of AC in the experiments was 93 kg m^{-3} when the percentage of AC was 34% and the density of composite adsorbent was 278 kg m^{-3}.

Table 1 Parameters of the samples developed for the research

Serial No.	Ratio of AC	Grain size of AC (mesh)	Density of sample 1 (kg m^{-3})	Density of sample 2 (kg m^{-3})	Density of sample 3 (kg m^{-3})	Density of sample 4 (kg m^{-3})	Density of sample 5 (kg m^{-3})
1	33%	80-100	278	374	430		
2	40%	80-100	215	260	322	419	
3	50%	80-100	264	289	302	412	500
4	60%	80-100	231	315	401	467	

5	67%	80-100	250	308	388	448
6	71%	80-100	190	255	335	372
7	50%	30-40	244	303	356	

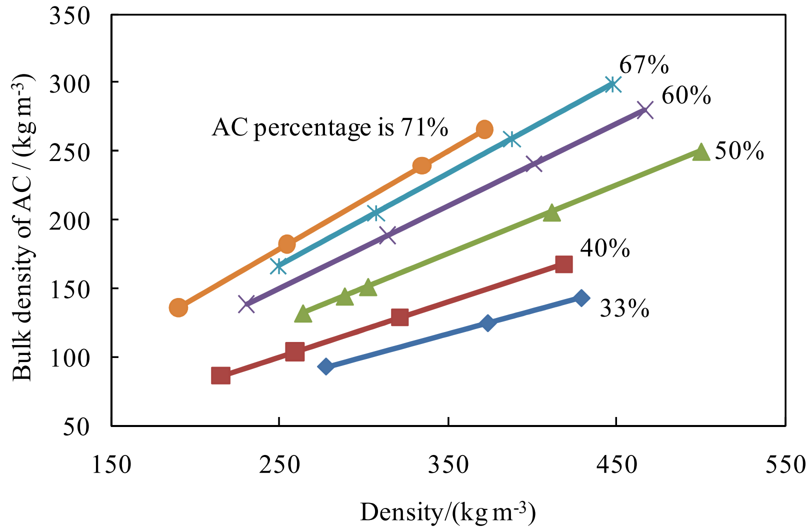


Fig.2 Relation between bulk density of AC, percentage of AC, and density of composite adsorbents

3 Study on the thermal conductivity

3.1 Thermal conductivity of composite adsorbents

Thermal conductivity was measured by an Anter Quickline-10 using the ASTM E1530 guarded thermal flow meter method [15]. Before the thermal conductivity of composite adsorbents was tested, the calibration experiments were preceded. Three calibration samples were: a steel disk sample with Ø50.8×12.7 mm thickness and two Vespel™ disks with Ø50.8×3.175 mm thickness and Ø50.8×6.35mm thickness. The calibration results are shown in Fig.3, in which point A is the steel sample, point B is the Vespel sample with thickness of 3.175 mm, and point C is the Vespel sample with thickness of 6.35 mm.

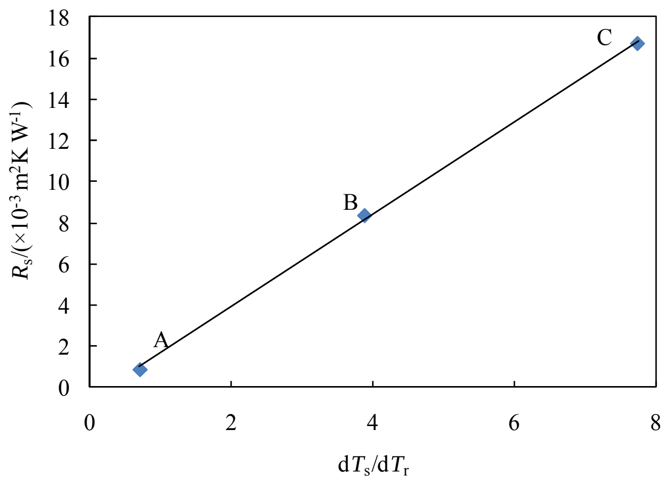


Fig.3 Characteristic line for calibration samples

Then the thermal conductivity of the samples was tested and calculated.

$$R_s = \frac{d}{\lambda} = F(\Delta T_s / \Delta T_r) - R_{\text{int}} \tag{2}$$

where R_{int} is the interfacial thermal resistance ($m^2K\ W^{-1}$) between the surface of sample and plates; F is the reference thermal resistance ($m^2K\ W^{-1}$); ΔT_s is the temperature difference across the sample (K), and ΔT_r is the temperature difference across the referenced sample (K).

In eq. (2) ΔT_s and ΔT_r could be tested by the Anter Quickline-10. The values of F and R_{int} in eq.2 were calculated by the results of calibration in Fig.3, and they were 2.26×10^{-3} $m^2K\ W^{-1}$ and 5.99×10^{-4} $m^2K\ W^{-1}$, respectively. For the testing results to be accurate, the thermal resistance obtained must fall within the range of samples used during the calibration, which are from 8.7434×10^{-4} to 1.6759×10^{-2} $m^2K\ W^{-1}$.

The thermal conductivity of samples was tested, and the relation between thermal conductivity and the bulk density of AC is shown in Fig.4, in which the serial number of each sample is shown in Table 1.

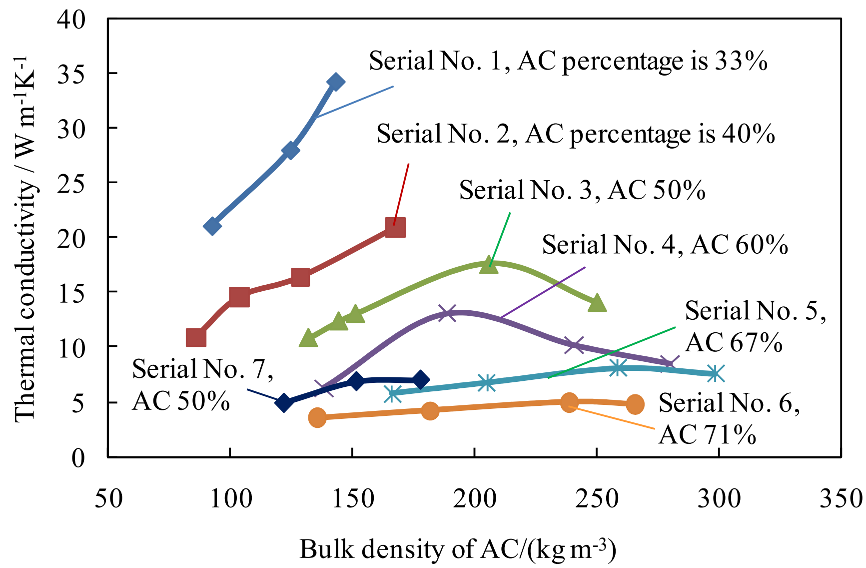


Fig.4 Thermal conductivity vs. bulk density of AC for consolidated composite adsorbents

Fig.4 shows that for the same bulk density of AC, the thermal conductivity always increases while the ratio of AC decreases. For the same ratio, generally the thermal conductivity increases while the bulk density of AC increases. For some samples, such as the samples for serial No.3 and serial No.4, the thermal conductivity decreases while the bulk density of AC is too high mainly because the cracks occur for such samples. The highest thermal conductivity of the consolidated composite adsorbent is as high as 34.15 W $m^{-1}K^{-1}$, which is improved about by 150 times if compared with the data of granular AC, which is 0.23 W $m^{-1}K^{-1}$.

Fig.4 also shows that the adsorbents with smaller size of AC have much better performances than that with larger size of AC. For example, while the ratio of AC is 50%, and the bulk density of AC is around 150 kg m^{-3}, the composite adsorbent with AC of 30-40 mesh has the thermal conductivity of 6.84 W $m^{-1}K^{-1}$, and the composite adsorbent with AC of 80-100 mesh has the thermal conductivity of 13.02 W $m^{-1}K^{-1}$. The data of the sample with AC of 80-100 mesh has been improved by over than 90% if compared with the data of the sample with AC of 30-40 mesh.

3.2 Effective thermal conductivity for heat transfer

In an adsorber, the adsorption and desorption heat is transferred from/to the solid adsorbent by means of a heat exchanging process and the involved heat flux meets two types of thermal resistance related to the solid adsorbent side (Fig.5).

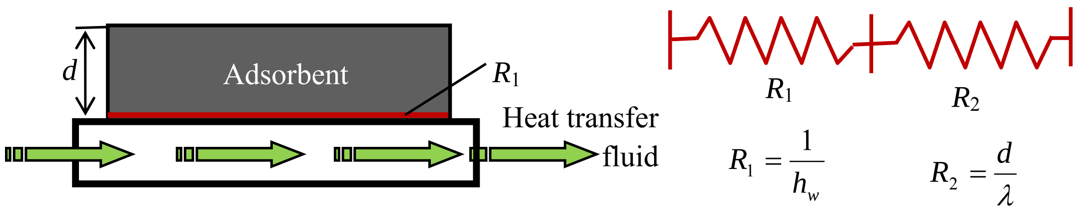


Fig.5 Scheme of the thermal resistance involved in heat transfer within an adsorber

Fig.5 shows that two types of thermal resistance are involved, one is the interfacial thermal resistance of R_1, and another, i.e. R_2, is the thermal resistance caused by the thermal conductivity of adsorbent. Combined the interfacial thermal resistance with the sample thermal resistance, the effective thermal conductivity (λ_{eff}) for the thickness (d in Fig.5) of 15mm was calculated, and the equation is:

$$\lambda_{eff} = \frac{d}{R_1 + R_2} = \frac{d}{\frac{R_{int}}{2} + \frac{d}{\lambda}} \qquad (3)$$

In the experiments the interfacial thermal resistance tested by the Anter Quickline-10 involved both surfaces of one sample of adsorbent, thus the value of R_1 was half of the value of R_{int}. The effective thermal conductivity is shown in Fig.6.

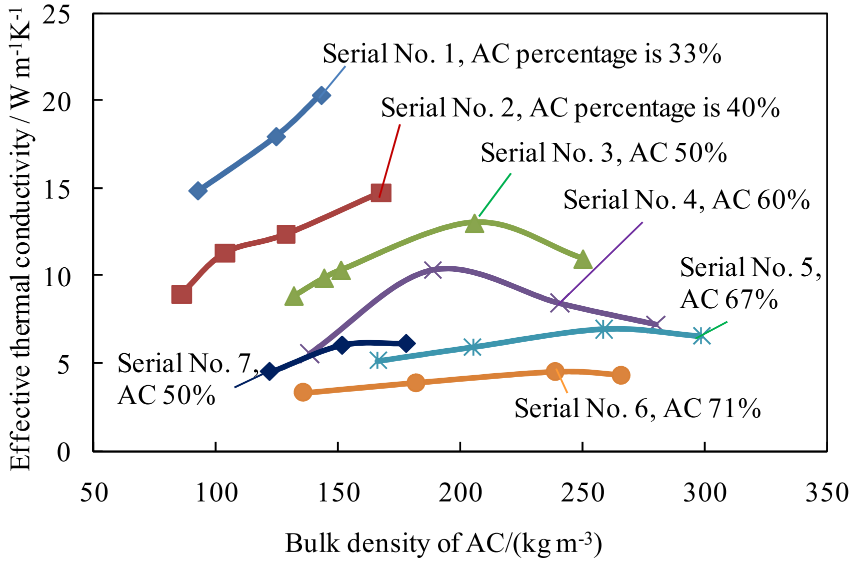


Fig.6 Effective thermal conductivity vs. bulk density of AC for consolidated composite adsorbents

Fig.6 shows that the interfacial thermal resistance doesn't influence the results of thermal conductivity very much while the thermal conductivity is small. For example for the sample of serial No.6, while the bulk density of AC is 136 kg m^{-3}, the thermal conductivity and effective thermal conductivity of adsorbent are 3.54 and 3.31 W m-1K-1, respectively, and the effective thermal conductivity only 6.9% decreased by the interfacial thermal resistance. The effective thermal conductivity is much different from the thermal conductivity of the adsorbent while the thermal conductivity is high. The highest effective thermal conductivity is for the sample of serial No. 1 with bulk density of AC of 143 kg m^{-3}, and the value is 20.3 W m^{-1} K^{-1}, and it is decreased by 40.6% if compared with the thermal conductivity of the sample.

In Fig.6 for the similar parameters of samples with different grain size of AC, for example, while the ratio of AC is 50%, and the bulk density of AC is around 150 kg m^{-3}, the composite adsorbent with AC of 30-40 mesh has the effective thermal conductivity of

6.02 W $m^{-1}K^{-1}$, and the composite adsorbent with AC of 80-100 mesh has the thermal conductivity of 10.33 W $m^{-1}K^{-1}$. The data of the sample with AC of 80-100 mesh has been improved by 72% if compared with the data of the sample with AC of 30-40 mesh.

Considering the thermal conductivity for the AC of 80-100 mesh is much better than that of 30-40 mesh, only the composite adsorbents with the AC of 80-100 mesh were tested in the following experiments for the specific heat capacity, permeability and adsorption performance.

4 Study on the thermal diffusivity of adsorbents

The specific heat capacity of AC and ENG-TSA were tested using a Seteram SENSYS DSC, and the specific heat capacity of consolidated composite adsorbent was calculated for 1 kg AC in the adsorbent, and the equation is:

$$C_p = \frac{1}{r} \times \left[r \times C_{p,\mathrm{AC}} + (1-r) \times C_{\mathrm{p,ENG-TSA}} \right] \qquad (4)$$

where C_p is the specific heat capacity for the consolidated composite adsorbent with 1 kg AC (J $kg^{-1}K^{-1}$), r is the ratio of AC inside the composite adsorbents, $C_{p,\mathrm{AC}}$ and $C_{p,\mathrm{ENG-TSA}}$ are the specific heat capacity of AC and ENG-TSA (J $kg^{-1}K^{-1}$), respectively.

The results are shown in Fig.7. The specific heat capacity increases while the ratio of AC decreases. The heat capacity of consolidated composite adsorbent with the AC ratio of 33% is about two times of that of pure AC while the mass of AC in both materials is 1kg.

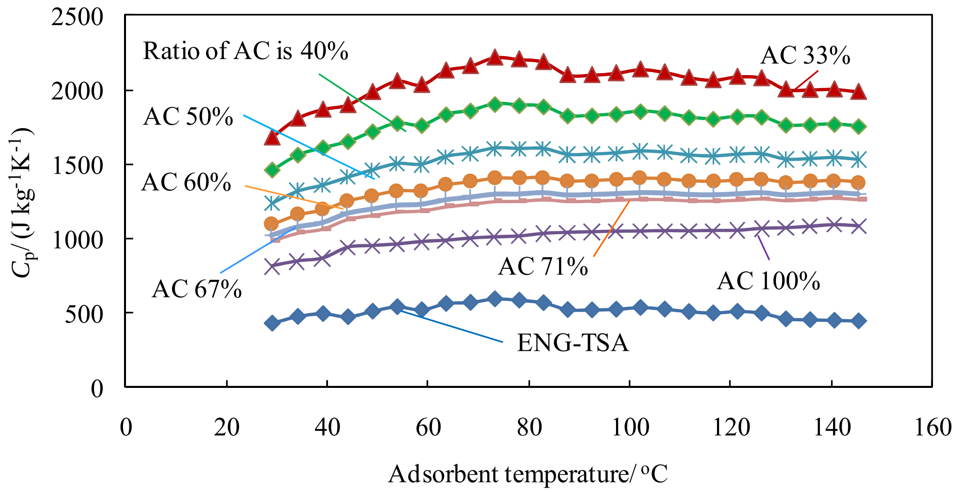


Fig.7 The specific heat capacity of adsorbents

In order to evaluate different consolidated composite adsorbents concerning the specific heat capacity and thermal conductivity, the thermal diffusivity for the consolidated composite adsorbents was analyzed based on the density of composite adsorbent and the specific heat capacity for the composite adsorbent with 1 kg AC, and the equation is:

$$\alpha = \frac{\lambda_{eff}}{\rho \times C_{p,ave}} \tag{5}$$

where α is the thermal diffusivity (m^2 s^{-1}), ρ is the density of consolidated composite adsorbent (kg m^{-3}). $C_{p,ave}$ is the average value of C_p for the temperature range between 27-140 °C.

The results of thermal diffusivity are shown in Fig. 8. Fig.8 shows that the trends of thermal diffusivity are different from the trend of thermal conductivity because the density and the heat capacity of adsorbents are considered. Because the heat capacity of consolidated samples decreases significantly while the ratio of AC increases, combining the influence of thermal conductivity, the difference of thermal diffusivity of the samples with serial number of 1, 2, and 3 are not very large under the condition of similar bulk density of AC. For the sample with the AC ratio of 60% and bulk density of AC of 189 kg m^{-3}, the thermal diffusivity of the sample is similar with the largest value of the sample with serial No.1, and it is 2.44×10^{-5} m^2 s^{-1}. It is also the optimum value because its bulk density of AC is much larger than the optimal point for the sample of Serial No.1.

For the granular AC the thermal diffusivity was calculated, and it was 0.054×10^{-5} m^2 s^{-1}. The highest thermal diffusivity of consolidated composite adsorbent has been improved by 45 times if compared with that of granular AC.

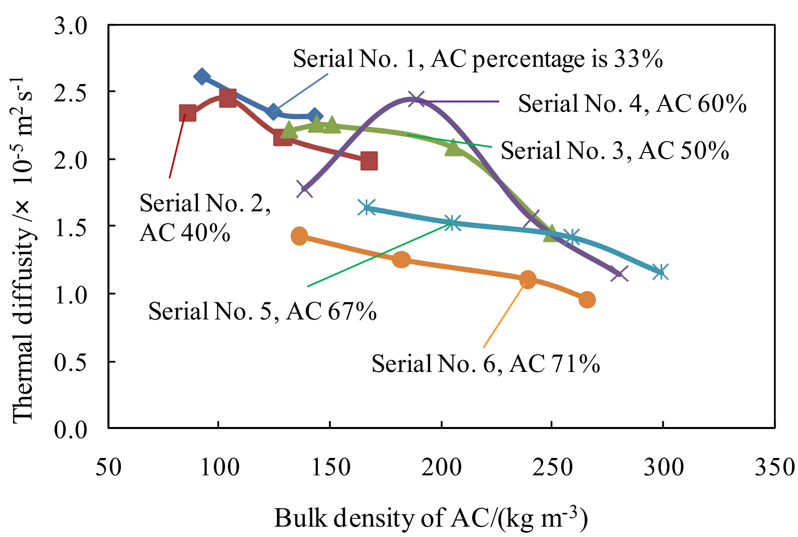


Fig.8 Thermal diffusivity of consolidated composite adsorbents

4 Study on the permeability

The permeability of the samples was tested by using a specially designed test unit shown in reference [15]. Since the samples to be tested are porous media with very low gas velocities, the Ergun model was applied in the research [15].

The results of permeability are shown in table 2. Table 2 shows that the permeability decreases while the ratio of AC in the sample decreases. The value is generally equal to or higher than 10^{-11} while the ratio of AC is larger than 40%, and it decreases seriously while the ratio of AC is 33%.

Table 2 Permeability of consolidated composite adsorbents

Ratio of AC	Sample 1		Sample 2		Sample 3		Sample 4	
	ρ (kg m^{-3})	K (m^2)	ρ (kg m^{-3})	K (m^2)	ρ (kg m^{-3})	K (m^2)	ρ (kg m^{-3})	K (m^2)
33%	278	1.24×10^{-14}	374	3.03×10^{-14}	430	3.6×10^{-14}		
40%	215	1.89×10^{-11}	260	1.50×10^{-11}	322	1.33×10^{-11}		
50%	264	9.89×10^{-11}	302	9.29×10^{-11}	412	3.30×10^{-11}		
60%	231	1.05×10^{-10}	315	9.03×10^{-11}	401	4.44×10^{-10}		
67%	250	1.43×10^{-10}	308	1.21×10^{-10}	388	6.57×10^{-11}	448	7.81×10^{-10}
71%	255	1.68×10^{-10}	335	1.1×10^{-10}	372	1.44×10^{-10}		

Table 2 also shows that somehow the permeability increases while the density of sample increases, and it is different from the results had gotten from the compact ENG [14]. In order to get a general understanding for such a phenomenon, the relation between the permeability and the bulk density of AC was analyzed, and results are shown in Fig.9. Fig.9 shows that while the permeability is very low, i.e. for the AC percentage of 33%, the permeability increases slightly when the bulk density of AC increases. It is mainly because the continuous structure of ENG-TSA had been destroyed by the AC, and such a phenomenon will be helpful for the improvement of the mass transfer process. While the percentage of AC is equal to or larger than 40%, the permeability of composite adsorbent is improved significantly. For such a situation the permeability firstly decreases while the bulk density of AC is smaller because the tightly connection between AC and ENG-TSA had prevented the gas transfer process. With the increasing of bulk density of AC, the permeability will increase because the AC cannot be compressed very much and it will resist the compressing process of ENG-TSA, and the resisting force will destroy the continuous structure of ENG-TSA. Such a result was analyzed by the SEM pictures of the adsorbents.

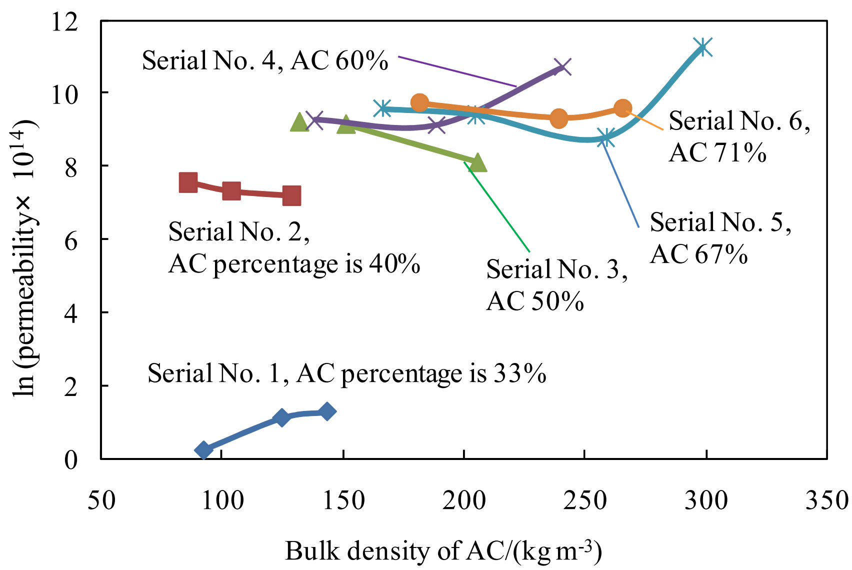
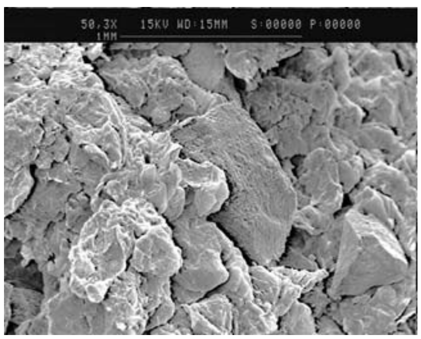


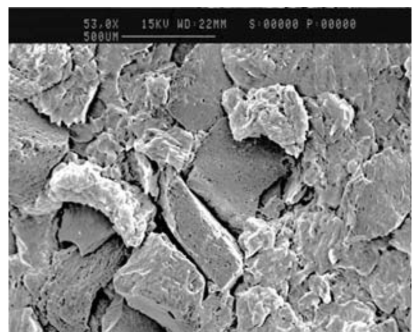
Fig.9 Permeability of composite adsorbents

5 SEM pictures of consolidated composite adsorbents

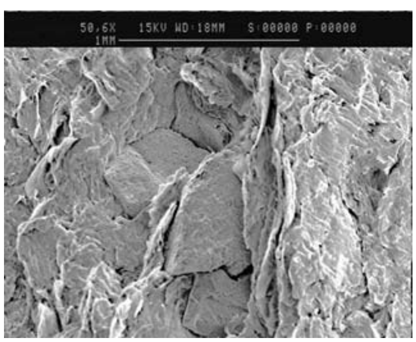
The SEM pictures were observed, and results are shown in Fig.8. For consolidated composite adsorbents, the grains of AC are embedded in the ENG-TSA. The structure of ENG-TSA likes worm while the density of the samples is small (Fig.8a and 8b), while it just distributes as organized layers while the density is larger (Fig.8c and Fig.8b).

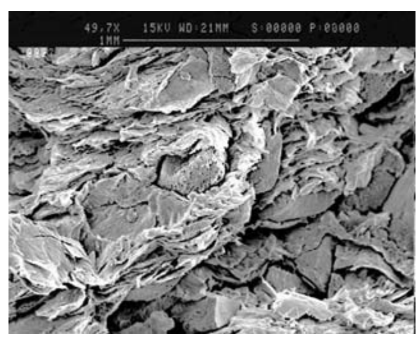
Inside the consolidated samples with larger value of density, the thermal conductivity increases while the density increases because of that the structure of ENG-TSA is much more organized for larger density. But if the density is too high the larger bulk density of AC will influence the thermal conductivity because more grains of AC in a fixed volume will cause a larger thermal resistance for the heat transfer process. Inversely for some samples larger bulk density of AC will be helpful for the mass transfer process, especially for the samples with smaller proportion of AC. It is mainly because of that more AC grains disconnect more connections among ENG-TSA layers, and makes the micro mass transfer channels larger inside the samples.





6(b)





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(d)

Fig.10 SEM pictures of consolidated composite adsorbents. (a) AC percentage of 33%, 278 kg m^{-3}, 50.3X; (b) AC percentage of 67%, 250 kg m^{-3}, 53X; (c) AC percentage of 33%, 430 kg m^{-3}, 50.6X; (d)AC percentage of 67%, 448 kg m^{-3}, 49.7X

6 Equilibrium adsorption performances test

The ENG-TSA had been treated by the sulfuric acid. In order to make sure if such a treatment will influence the adsorption performance of adsorbents on refrigerant, the adsorption performance of granular AC and composite adsorbent of AC was tested and compared using a magnetic suspension balances (Rubotherm). The test unit is shown in Fig. 11. The adsorbent was contained in a sample basket surrounded by a thermostatically controlled jacket and the volume around the basket linked to an ammonia vessel that controlled the pressure. With both pressure and temperature of the surrounding ammonia controlled the mass and hence concentration was measured by the magnetic suspension balance.

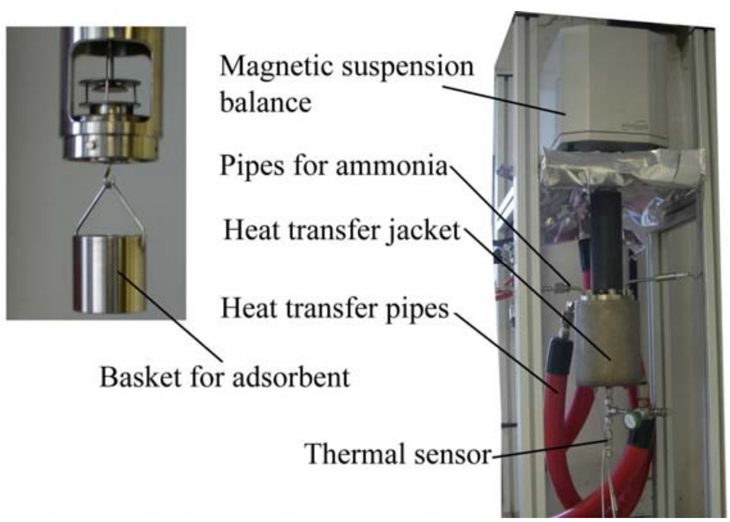

Fig.11 The Rubotherm for adsorption performance test

For the adsorption working pair with AC-ammonia as working pair, the D-A equation [16,17] is applicable, and it is as follows

$$x = x_0 \exp[-K(\frac{T}{T_s} - 1)^n] \tag{6}$$

where x is the adsorption quantity (kg kg^{-1}), T is the temperature of adsorbent (K), T_s is the saturated temperature of refrigerant (K), x_0 is the maximum adsorption quantity, K and n are coefficients.

The equilibrium adsorption performance was tested, and the relation between adsorption quantity x and (T/T_{sat}-1) is shown in Fig.12. Results shows that the performance of composite adsorbent isn't influenced by the addition of ENG-TSA, and it is similar with granular AC.

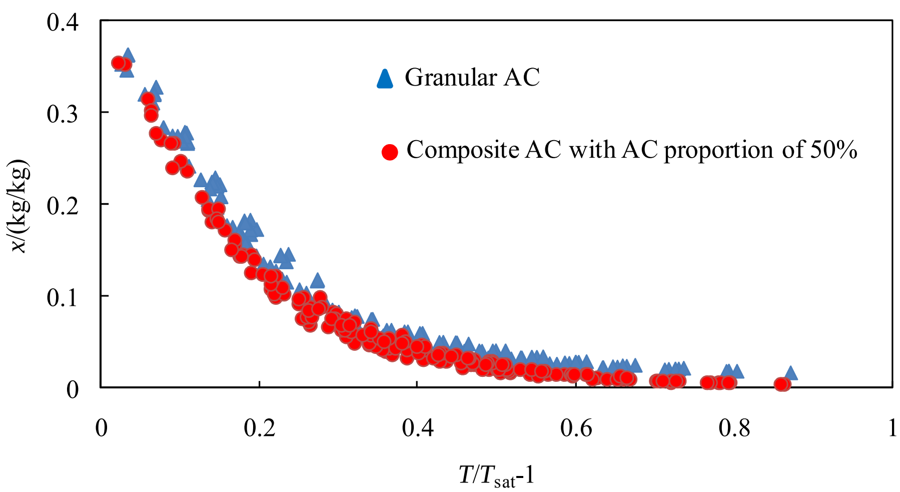

Fig.12 The adsorption performance of granular AC and composite adsorbent of AC

The performance of AC and composite adsorbent of AC was fitted by the exponential equations, which are as follows:

$$x = 0.4655 \times \exp\left[-4.282 \times (\frac{T}{T_{sat}} - 1)^{0.81}\right], R^2=0.9698 \quad \text{Granular AC} \tag{7}$$

$$x = 0.4703 \times \exp\left[-5.551 \times (\frac{T}{T_{sat}} - 1)^{0.89}\right], R^2 = 0.9872 \quad \text{Composite AC} \tag{8}$$

The coefficient of determination (R^2) in Eqs.(7) and (8) are 0.9698 and 0.9872, respectively, for granular AC and composite AC, and it means the data gotten from composite AC has slightly higher precision. It is mainly because of the higher heat transfer performance for the composite adsorbent. The thermal conductivity of granular AC is much lower than composite adsorbent of AC, and then the temperature difference between granular AC and the heat source will be slightly larger than that of composite adsorbent of AC. Such a phenomenon somehow will cause the slightly higher error between the experimental data and the real data. Actually because the mass of sample inside the Ruberthem is less than 1g, and the heat transfer process is very fast, the error caused by heat transfer is very small and can be neglected. Just as Fig.12 shows, the relative difference between the data of granular AC and composite AC in is less than 9%.

Conclusions

The consolidated composite AC was developed with the host matrix of ENG-TSA under the conditions of different density, different grain size of AC and different proportion of AC. The conclusions are mainly as follows:

(1) For the development of consolidated composite adsorbents, the samples with AC of small grain size had much higher thermal conductivity and were also much easier to be developed if compared with the sample with AC of larger grain size. Between AC of 80-100 mesh and AC of 30-40 mesh researches showed that the cracks easily happened on the composite adsorbent with AC of 30-40 mesh. The experiments on thermal conductivity showed that while the ratio of AC was 50% and the density was around 300 kg m^{-3} the composite adsorbent with AC of 30-40 mesh had the thermal conductivity of 6.84 W $m^{-1}K^{-1}$, whereas the composite adsorbent with AC of 80-100 mesh had the thermal

conductivity of 13.02 W $m^{-1}K^{-1}$. The data of the sample with AC of 80-100 mesh has been improved by over than 90% if compared with the data of the sample with AC of 30-40 mesh.

(2) For the AC of 80-100 mesh researches showed that for the sample bulk density of AC the thermal conductivity always increased while the ratio of AC decreased. For the same ratio, generally the thermal conductivity increased while the bulk density of AC increased. For some samples, such as the samples for serial No.3 and serial No.4, the thermal conductivity decreased while the bulk density of AC was too high mainly because the cracks occurred for such samples. The highest thermal conductivity of the consolidated composite adsorbent was as high as 34.15 W $m^{-1}K^{-1}$, which was improved about by 150 times if compared with the data of granular AC, which was 0.23 W $m^{-1}K^{-1}$.

(3) Considering the interfacial thermal resistance the effective thermal conductivity was calculated. Results showed that the interfacial thermal resistance didn't influence thermal conductivity very much while the thermal conductivity was small. For some samples the effective thermal conductivity was only 6.9% decreased by the interfacial thermal resistance. The effective thermal conductivity was much different from the thermal conductivity of the adsorbent while the thermal conductivity was high. For example the highest effective thermal conductivity was 20.3 W $m^{-1}K^{-1}$, and it was decreased by 40.6% if compared with the thermal conductivity of the sample.

(4) The thermal capacity was tested and the thermal diffusivity was calculated, results showed that the trends of thermal diffusivity were different from the trends of thermal conductivity because the density and the heat capacity of adsorbents were considered. The optimal thermal diffusivity of different samples was 2.44×10^{-5} m^2 s^{-1}, which was improved by 45 times if compared with that of granular AC.

(5) The permeability of consolidated composite AC decreased while the ratio of AC in the sample decreased. The value was generally equal to or higher than 10^{-11} while the ratio of AC was larger than 40%, and it decreased seriously while the ratio of AC was 33%. For some samples the permeability increased slightly when the bulk density of AC increased because the continuous structure of ENG-TSA had been destroyed by increasing AC grains in fixed volume, which was helpful for the improvement of the mass transfer process.

(6) The adsorption performance of consolidated composite AC and granular AC was tested, and the equilibrium D-A equations were fitted. Results showed that the equilibrium adsorption performance of consolidated composite AC wasn't influenced by the additive of ENG-TSA, and it was similar with the adsorption performance of pure granular AC.

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Captions for Figures and Tables

Fig.1 Consolidated composite adsorbents, (a) Compressing direction and testing direction (b) density of 249kg m^{-3}, (c) density of 388 kg m^{-3}, (d) density of 448 kg m^{-3}

Fig.2 Relation between bulk density of AC, percentage of AC, and density of composite adsorbents

Fig.3 Characteristic line for calibration samples

Fig.4 Thermal conductivity vs. bulk density of AC for consolidated composite adsorbents

Fig.5 Scheme of the thermal resistance involved in heat transfer within an adsorber

Fig.6 Effective thermal conductivity vs. bulk density of AC for consolidated composite adsorbents

Fig.7 The specific heat capacity of adsorbents

Fig.8 Thermal diffusivity of consolidated composite adsorbents

Fig.9 Permeability of composite adsorbents

Fig.10 SEM pictures of consolidated composite adsorbents. (a) AC percentage of 33%, 278 kg m^{-3}, 50.3X; (b) AC percentage of 67%, 250 kg m^{-3}, 53X; (c) AC percentage of 33%, 430 kg m^{-3}, 50.6X; (d)AC percentage of 67%, 448 kg m^{-3}, 49.7X

Fig.11 The Rubotherm for adsorption performance test

Fig.12 The adsorption performance of granular AC and composite adsorbent of AC

Table 1 Parameters of the samples developed for the research

Table 2 Permeability of consolidated composite adsorbents