Study of the Effect of Porous Particles on Vapor-Liquid Equilibrium Using the Headspace Gas Chromatography

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The effect of certain porous particles on vapor-liquid equilibrium (VLE) of ethanol + water, ethanol + ethyl acetate, acetic acid + ethyl acetate, and n-hexane + n-heptane systems was investigated using the headspace gas chromatography (HSGC) at 60, 50, 50, and 50°C, respectively. Four kinds of porous particles were studied: molecular sieves (3 Å, 4 Å, 5 Å, and 13 X), activated carbons (columnar activated carbon, powdered activated carbon), activated alumina balls, and nonpolar adsorption resins (D4006, D4020). Good agreement was noticed when the experimental results in the absence of porous particles were compared with the NRTL model's predictions. These results added to the validity of using the HSGC in studying the VLE of binary systems. The results obtained showed that the VLE of these four kinds of binary mixtures in the presence of molecular sieves and activated alumina balls was altered considerably. The presence of activated carbons had no effect on the VLE of these binary systems, but the VLE of n-hexane + n-heptane system was altered in the presence of D4006 or D4020 nonpolar adsorption resin. Other factors, such as pore size, type, weight, properties of porous particles, and solvents were also investigated. The results showed that the alteration in the VLE of a given binary solution was a function of the pore size, type, weight, properties of porous particles and the properties of solvents. In addition, the mechanism of the porous particles altering the VLE was also analyzed accordingly. © 2015 American Institute of Chemical Engineers *AIChE J*, 62: 256–263, 2016

Keywords: vapor-liquid equilibrium, porous particles, binary mixture, headspace gas chromatography, mechanism

Introduction

Binary mixtures with close boiling points or systems that have azeotropic points are often encountered in the process of the distillation separation. It is difficult to separate the low relative volatility mixtures and azeotropic mixtures by means of the conventional distillation methods. Thus, some innovative methods such as reactive distillation, extractive distillation, salt distillation, vacuum distillation, membrane distillation, pervaporation, adsorptive distillation, and capillary distillation[1–3] come out to separate azeotropic mixtures. To obtain the final product from the mixtures separated by distillation, accurate vapor-liquid equilibrium (VLE) data are essential for the design of distillation columns and separation processes. In fact, only few VLE data of binary mixtures can be directly obtained from the related handbooks. Most VLE data need to be determined by experimental methods. The headspace gas chromatography (HSGC) method is a relatively new technique to measure the VLE of binary or ternary mixtures.[4,5] It is simpler, faster, and more accurate than other measurement methods.[6]

The basic principle of the HSGC method and many useful technologies can be found in the textbooks[6–9] and corresponding articles.[10–15] Chen et al.[13] measured the VLE of *o*-xylene + styrene mixture at 40, 60, 80, 100, and 120°C using the HSGC and validated the reliability of these VLE data obtained. Ma et al.[16] investigated the isothermal VLE data of methanol + dimethyl carbonate + dimethyl oxalate at different temperatures using the headspace gas chromatograph apparatus. Takamatsu and Ohe[17] studied the effect of inorganic salts on vapor-liquid equilibria for ethyl acetate + ethanol system using the HSGC method, and discovered that the azeptropic point was observed to shift to the ethyl acetate-rich region in $CaCl_2$ and that LiCl broke the azeotrope. Banat et al. studied the VLE of acetone + water,[18] ethanol + water,[19,20] and 1-propanol + water[21] systems with 3 Å, 4 Å molecular sieves using the HSGC technique, and discovered that both the VLE and azeotropic points of these systems were apparently altered in the presence of molecular sieves. Additionally, they attributed the alteration of VLE to the force field created between the solids and the liquids and the curvature of the gas-liquid interface inside the pore.

The objective of this work is to explain further what leads to the alteration of the VLE of binary systems in the presence of certain porous particles. In addition, a few affecting factors on VLE alteration, such as the properties of solvent (i.e., polarity) and porous particles (i.e., amount, pore size, and surface area of porous particles) are also studied accordingly.

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Table 1. Purities and Properties of Pure Components

Chemicals	Purity (wt %)	Boiling Point (K)	Density (20°C, g/cm^3)	Molecular Critical Size[a] (nm)
Ethanol	99.7	351.50	0.789	0.47
Ethyl acetate	99.5	350.25	0.902	1.40
Acetic acid	99.5	391.05	1.049	0.51
n-Hexane	98.0	341.90	0.660	0.49
n-Heptane	98.5	371.60	0.684	0.49

[a] Data from Ref. 22.

Table 2. Detector and Capillary Column Used for Analyzing These Systems

Detector	Capillary Column	Analyte
FID	HP INNOWAX (30 m × 0.25 mm × 0.25 μm)	Ethanol + Ethyl acetate Acetic acid + Ethyl acetate
FID	HP-5 (30 m × 0.32 mm × 0.25 μm)	*n*-Hexane + *n*-Heptane
TCD	HP INNOWAX (30 m × 0.25 mm × 0.25 μm)	Ethanol + Water

Experimental

Materials

Ethanol, ethyl acetate, acetic acid, *n*-hexane, and *n*-heptane used in this work were of analytical commercial grade of purity, obtained from Tianjin Jiangtian Chemical Reagents Factory. The purities and properties of these chemical reagents are listed in Table 1.

All the chemicals were used directly without further purification. The 3 Å molecular sieves, 4 Å molecular sieves, 5 Å molecular sieves, 13 X molecular sieves were purchased from Tianjin Nankai Catalyst Factory. Columnar activated carbon and powdered activated carbon were supplied by Tianjin Kermel Chemical Reagent Factory. Activated Alumina balls were provided by Tianjin Bo-Hong Resin Technology Co. in China. Distilled water came from the Basic Experimental Center of Tianjin University.

Apparatus and procedures

The VLE for all the binary systems were measured using the HSGC method. The HSGC measurement apparatus is composed of a gas chromatography (Agilent 7890A) and a headspace autosampler (Agilent G1888), which has an electropneumatic sampling system and a precision thermostat with accuracy of ±0.1 K. Figure 1 depicts an overview of the headspace gas chromatograph measurement apparatus. Specifications for detector and capillary column were used for analysis in the experimental process. They are listed in Table 2.

Before measuring the isothermal VLE of these binary systems in the absence and presence of porous particles, the parameters of headspace autosampler and GC needed to be determined.[23] Among these parameters, the equilibration time was an especially important parameter.[23] To obtain the equilibrium time, vials with different sample concentrations were prepared. The vials (ca. 20 cm^3) were filled with 5 mL of liquid samples. These sample vials were kept in the headspace oven for different time intervals at a constant temperature. When the peak areas obtained kept constant, the phase equilibrium was assumed to be reached. In addition to the equilibration time and equilibration temperature, other parameters, such as loop equilibrium time, loop fill time, injection time, loop temperature, transmission line temperature, vial pressure, oven temperature, injector temperature, and detector temperature must be optimized before measuring the VLE data.[23,24] A summary of these parameters used in the experiments are shown in Tables 3 and 4.

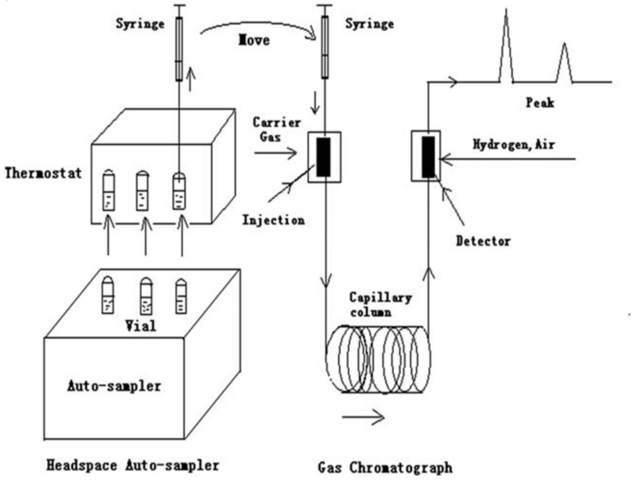


Figure 1. Experimental setup of the headspace gas chromatography technique.

The sample preparation and measurement procedures were as follows: sample mixtures with different concentrations were prepared first in several 250-mL flasks at room temperature. Each sample mixture was prepared accurately using Mettler AE163 model digital analytical balance with an accuracy of ±0.0001 g, according to calculated mole ratio. Then, they were stirred 10 min by means of an ultrasonic cleaning machine and directly analyzed using the GC to get the relative molar correction factors of these prepared samples with known composition. We weighed an exact amount of porous particles and added them into a set of 20-mL empty glass vials. Then, respectively, pipette 5-mL samples of known liquid composition into each vial and seal properly with a 20-mm aluminum lid and a rubber septum to guarantee that the headspace gases do not escape. The sample vials were placed in the headspace 70-sampler rotating tray and automatically moved into the oven of the headspace autosampler. The sample vials were heated to the equilibrium temperature and gently shaken until the equilibrium between vapor and liquid phases was reached. After reaching the equilibrium, each vial was raised onto the needle, and the vapor sample was withdrawn and analyzed in the GC. The peak areas of the GC analysis were recorded by a HP7900 computer with the software package Agilent ChemStation. The liquid-phase composition in equilibrium with the vapor phase can be determined from the original liquid composition.[25] To ensure the reproducibility, at least three samples were prepared for each composition. The average values are presented in the experimental data.

Results and Discussion

The isothermal VLE data for ethanol + water, ethanol + ethyl acetate, acetic acid + ethyl acetate, and *n*-hexane + *n*-heptane mixtures have been determined in the absence and presence of porous particles at 60, 50, 50, and 50°C using the HSGC apparatus, respectively.

Table 3. Parameters Used for Ethanol + Water and Acetic Acid + Ethyl Acetate Mixtures

		Ethanol + Water	Acetic Acid + Ethyl Acetate
Headspace autosampler	Oven temp. (°C)	60	50
	Vial eq. (time/min)	960	120
	Loop fill (time/min)	0.2	0.5
	Loop eq. (time/min)	0.1	0.1
	Inject (time/min)	1	0.04
	Loop temp. (°C)	140	70
	Tr. Line temp. (°C)	150	95
Gas chromatograph	Column temp. (°C)	70	62°C (held 3 min), then was ramped to 120°C and held for 9 min
	Injector temp. (°C)	180	180
	Detector temp. (°C)	200	200

Validity of the HSGC method

The experimental, compared with NRTL model, isothermal VLE data for ethanol + water, ethanol + ethyl acetate, acetic acid + ethyl acetate, and *n*-hexane + *n*-heptane systems without porous particles at the temperature of 60, 50, 50, and 50°C are shown in Figure 2. These figures show obviously that the experimental results are in close agreement with those calculated using the NRTL model. These results prove the validity of using the HSGC method to study the effect of porous particles on the VLE of binary systems. As shown in Figure 2, ethanol + water and ethanol + ethyl acetate have azeotropic points, acetic acid + ethyl acetate and *n*-hexane + *n*-heptane systems do not have azeotropic points.

VLE of binary mixtures in the presence of porous particles

The isothermal VLE data for ethanol + water, ethanol + ethyl acetate, acetic acid + ethyl acetate, and *n*-hexane + *n*-heptane systems in the presence of porous particles are determined at 60, 50, 50, and 50°C using the HSGC technique, separately. For the convenience of handling experimental data, these systems with porous particles are approximately treated as quasi-binary systems. The experimental results are presented in Figure 3.

As can be seen from Figure 3, the VLE data of ethanol + water, ethanol + ethyl acetate, acetic acid + ethyl acetate, and *n*-hexane + *n*-heptane systems do not change in the presence of activated carbons, but those of ethanol + water, ethanol + ethyl acetate, and acetic acid + ethyl acetate systems have been altered in the presence of molecular sieves and activated alumina balls. The azeotropic point of ethanol + ethyl acetate in the presence of certain porous particles has been shifted to the ethyl acetate-rich region and that of ethanol + water with certain porous particles is broke. But the VLE of *n*-hexane + *n*-heptane system is not altered in the presence of molecular sieves or activated alumina balls. However, the VLE of *n*-hexane + *n*-heptane system is altered obviously in the presence of nonpolar adsorption resin. But nonpolar adsorption resin does not affect the VLE of ethanol + water, ethanol + ethyl acetate, and acetic acid + ethyl acetate systems.

Table 4. Parameters Used for Ethanol + Ethyl Acetate and *n*-Hexane + *n*-Heptane Mixtures

		Ethanol + Ethyl Acetate	*n*-Hexane + *n*-Heptane
Headspace autosampler	Oven temp. (°C)	50	50
	Vial eq. (time/min)	120	120
	Loop fill (time/min)	0.5	0.5
	Loop eq. (time/min)	0.1	0.1
	Inject (time/min)	0.04	0.04
	Loop temp. (°C)	70	70
	Tr. Line temp. (°C)	95	95
Gas chromatograph	Column temp. (°C)	60	70
	Injector temp. (°C)	180	180
	Detector temp. (°C)	200	200

A few affecting factors on VLE alteration include the properties of solvent and porous particles are discussed as follows.

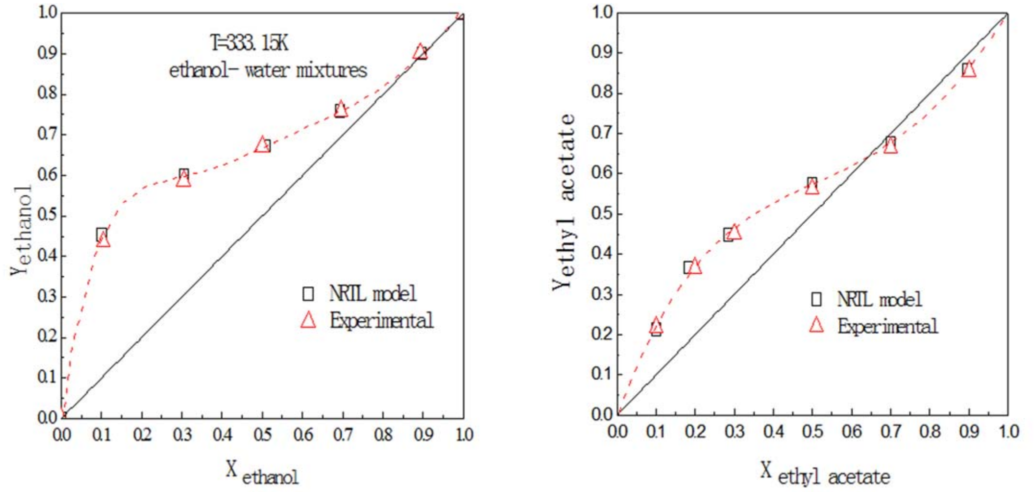
Effect of polarity of the solvents and porous particles

To discuss the effect of polarity of the solvents and porous particles on the VLE, four kinds of binary mixtures in the presence of porous particles are studied, respectively. Table 5 lists the relative permittivity of the experimental solvents. The results, shown in Figure 3, show that the VLE of ethanol + water, ethanol + ethyl acetate, and acetic acid + ethyl acetate is altered in the presence of molecular sieves and activated alumina balls. However, the VLE of *n*-hexane + *n*-heptane mixture is only altered in the presence of nonpolar adsorption resin. These results indicate that the polarity of the solvents and porous particles have an important effect on the VLE of the binary mixtures. The alteration of VLE is due to the force field created by the porous particles on the solvents, which is a function of the polarity of each component. The intermolecular interactions between the polar particles and the more polar component in the liquid phase will be greater than those between the molecular sieves and the component of less polarity, and the adsorption equilibrium constants between porous particles and the component with strong polarity would be increased. Thus, the composition of the more polar component in the vapor phase will be less than that in the absence of the polar particle.[21] Similarly, in the *n*-hexane + *n*-heptane system, nonpolar adsorption resin can adsorp *n*-hexane selectively, and the adsorption equilibrium constants between nonpolar adsorption resin and *n*-hexane would be increased. So, the *n*-heptane in the vapor phase will be less than that in the absence of the particles.

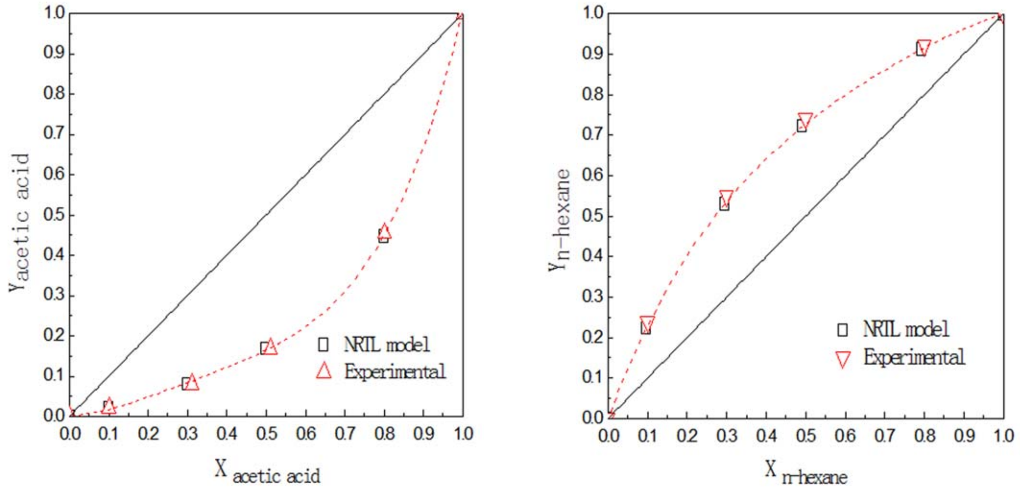
Effect of the surface area of particles

As can be seen from Figure 3, the VLE of ethanol + water, ethanol + ethyl acetate, acetic acid + ethyl acetate systems in the presence of molecular sieves and activated alumina balls is altered. However, the alteration of VLE data is different in the presence of different kinds of porous particles. The results might be explained with the help of the properties of porous particles. The properties of certain porous particles are shown in Tables 6 and 7.

As indicated in Figure 3 and Tables 6 and 7, the alteration of polar binary systems in the presence of molecular sieves is



2-a T=333.15K, Ethanol+ Water system 2-b T=323.15K, Ethanol+ Ethyl acetate system



2-c T=323.15K, Acetic acid + Ethyl acetate system 2-d T=323.15K, N-hexane + N-heptane system

Figure 2. Experimental vapor-liquid equilibrium data for binary systems.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

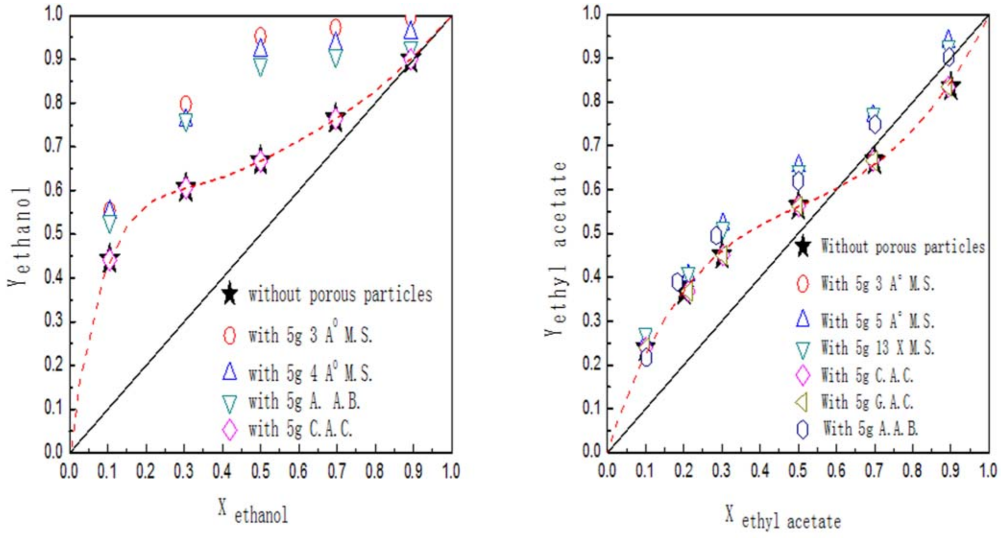
greater than those in the presence of activated alumina balls. It is because that although both of the molecular sieves and activated alumina balls are polar particles, the specific surface area of molecular sieves is bigger. The adsorption of solvents molecular on molecular sieves is greater than activated alumina balls.

Effect of the pore size

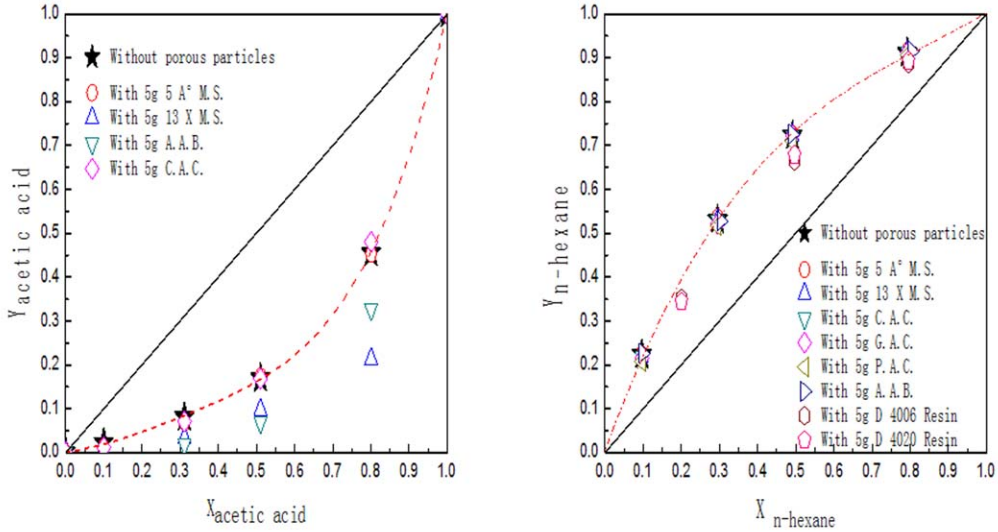
As shown in Figure 3, the VLE data of ethanol + water, ethanol + ethyl acetate, acetic acid + ethyl acetate, and *n*-hexane + *n*-heptane systems do not change in the presence of activated carbons, but the VLE of *n*-hexane + *n*-heptane system in the presence of nonpolar adsorption resins is altered. As indicated in Figure 3 and Tables 1 and 7, the VLE of these binary systems investigated in the presence of activated carbons does not alter, this may be attributed to the pore size of powdered activated carbon and its nonpolarity. The pore size of powdered activated carbon is much smaller than molecular critical size of water, ethanol, ethyl acetate, acetic acid, *n*-hexane, or *n*-heptane, so the solvent molecules cannot enter the pores of activated carbon, activated carbon cannot adsorp solvent molecules selectively. In contrast, the pore size of nonpolar adsorption resins is bigger than molecular critical size of *n*-hexane, so *n*-hexane molecular can enter the pores of nonpolar adsorption resins.

The effect of pore size of the molecular sieves on the VLE of the ethanol + water and ethanol + ethyl acetate systems is shown in Figure 4. As can be seen from Figure 4 and Table 6, the molecular sieves have a significant effect on the VLE of ethanol + water and ethanol + ethyl acetate systems in the following order: 3 Å molecular sieves, >4 Å molecular sieves, and 5 Å molecular sieves, >13 X molecular sieves. These experimental results are in good agreement with those reported in the literature.[18,19,21] This may be due to two factors as follows[18,19,21]:

1. The intermolecular interactions between the particles and the solvents are inversely proportional to the pore size.



3-a T=333.15K, Ethanol+ Water system 3-b T=323.15K, Ethanol+ Ethyl acetate system



3-c T=323.15K, Acetic acid + Ethyl acetate system 3-d T=323.15K, N-hexane + N-heptane system

Figure 3. Experimental vapor-liquid equilibrium data with porous particles.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

2. The vapor pressure of the pure components reduces in the presence of molecular sieves, and the reduction of the vapor pressure is inversely proportional to the pore size.

Table 5. The Relative Permittivity of Experimental Solvents

Binary mixtures	Solvent	Polarity Relative Permittivity[a]	Temperature (K)
Ethanol + Water	Ethanol	25.70	293.15
	Water	80.40	293.15
Ethanol + Ethyl acetate	Ethanol	25.70	293.15
	Ethyl acetate	6.40	293.15
Acetic acid + Ethyl acetate	Acetic acid	6.17	293.15
	Ethyl acetate	6.40	293.15
n-Hexane + *n*-Heptane	*n*-Hexane	1.91	293.15
	n-Heptane	1.93	293.15

[a] Data from Ref. 26.

Effect of the amount of molecular sieves and activated alumina balls

To point out the alteration of VLE of binary mixtures in the presence of different weights of molecular sieves and activated alumina balls, the effects of molecular sieves and activated alumina balls at different amount levels, that is, 2, 4, 6, 8, 10, 12, 13, and 16 g are studied at 60 and 50°C, respectively. The experimental results are plotted in Figure 5. When increasing the amount of molecular sieves and activated alumina balls, as shown in Figure 5, the vapor mole fraction of less polar component of ethanol + water and ethanol + ethyl acetate mixtures increases initially and then levels out. In addition, it also can be seen in Figure 5 that the optimum amount of 3 Å molecular sieves, 4 Å molecular sieves, and activated alumina balls for the studied binary mixtures (ethanol + water and ethanol + ethyl acetate) are 6 and 13 g, respectively. That is to say, when the amount of molecular sieves and activated

Table 6. Properties and Pore Sizes of Molecular Sieves

Type	Bases	Cation	Surface Area (m^2/g)	Pore Volume (cm^3/g)	Pore Diameter (nm)
3Å	Alumina-Silicate	Potassium	573	0.10	0.30
4Å	Alumina-Silicate	Sodium	600	0.15	0.42
5Å	Alumina-Silicate	Calcium	650	0.18	0.50
13X	Alumina-Silicate	Sodium	724	0.36	0.90

alumina balls is less than the optimum amount, increasing the amount of particles can alert the VLE of binary mixtures greater, but when the optimum amount of molecular sieves and activated alumina balls has been reached, no further improvement on the VLE could be achieved by increasing the amount of the particles. This is because when the amount of particles is less than the optimum amount, the height of the bed of the particles is not enough to prevent vapor molecules escaping without coming in contact with the particles. At the optimum amount, a bed height was reached where no vapor molecules could escape without coming in contact with the particles.[18,19,21]

Mechanism analysis of altering the VLE

According to the above experimental results, the change of the isothermal VLE of binary mixtures in the presence of porous particles may be attributed to adsorption effect between the porous particles and the liquids. In another word, the interfacial molecular forces between the solids and the liquids, for example, the London force dispersion interactions and the induction force polar interactions of the liquids may alter the VLE of the binary mixtures.[19]

At equilibrium, the fugacity of any solute must be equal in the vapor, liquid, and solid phases, namely[27]

$$f_i^{\mathrm{L}}=f_i^{\mathrm{S}} \tag{1}$$

$$f_i^{V}=f_i^{\mathrm{L}} \tag{2}$$

The fugacity of component i in the adsorbed phase is defined as follows[28]

$$f_i^{\mathrm{S}}=p_i^{\theta}\gamma_i^{\mathrm{S}}x_i^{\mathrm{S}}\exp\left(\frac{-A\left(\sigma-\sigma_i^0\right)}{m_iRT}\right) \tag{3}$$

The fugacity of component i in liquid phase, f_i^{L} and in vapor phase, f_i^{V} at atmospheric or subatmospheric pressure can be expressed as[27]

$$f_i^{\mathrm{V}}=py_i\hat{\phi}_i^{\mathrm{V}} \tag{4}$$

$$f_i^{\mathrm{L}}=p_i^{\theta}\phi_i^{\theta}\gamma_ix_i\exp\left(\frac{V_i^{\mathrm{L}}\left(p-p_i^{\theta}\right)}{RT}\right) \tag{5}$$

Equations 1 and 2 are rearranged as

$$x_i^{\mathrm{S}}=\frac{p_i^{\theta}\phi_i^{\theta}\gamma_i\exp\left(\frac{V_i^{\mathrm{L}}\left(p-p_i^{\theta}\right)}{RT}\right)}{p_i^{\theta}\gamma_i^{\mathrm{S}}\exp\left(\frac{-\left(\Omega-\Omega_i^0\right)}{\Gamma_iRT}\right)}x_i=K_{\mathrm{S,L},i}x_i \tag{6}$$

$$y_i=\frac{p_i^{\theta}\phi_i^{\theta}\gamma_i\exp\left(\frac{V_i^{\mathrm{L}}\left(p-p_i^{\theta}\right)}{RT}\right)}{p\hat{\phi}_i^{\mathrm{V}}}x_i=K_{\mathrm{V,L},i}x_i \tag{7}$$

The composition in the liquid phase containing the porous particles can be written as[29]

$$X_i=\varphi x_i+(1-\varphi)x_i^{\mathrm{S}} \tag{8}$$

The relative volatility between Component 2 and Component 1 is defined as

$$\alpha_{21}=\frac{y_2X_1}{y_2X_2}=\frac{K_{\mathrm{V,L,2}}\left[\varphi+(1-\varphi)K_{\mathrm{S,L,1}}\right]}{K_{\mathrm{V,L,1}}\left[\varphi+(1-\varphi)K_{\mathrm{S,L,2}}\right]}=\alpha_{21}^0\frac{\left[\varphi+(1-\varphi)K_{\mathrm{S,L,1}}\right]}{\left[\varphi+(1-\varphi)K_{\mathrm{S,L,2}}\right]} \tag{9}$$

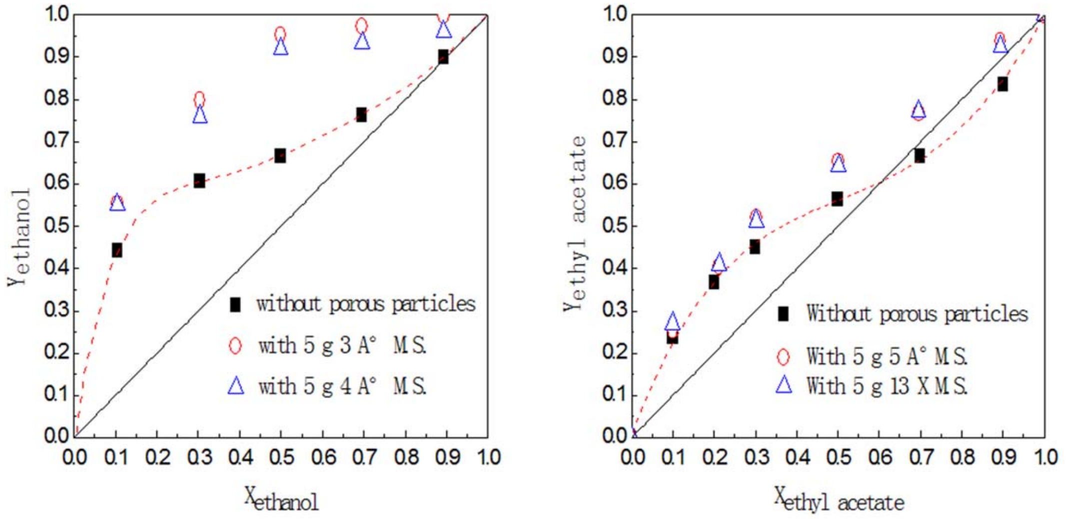
where α_{21}^0 is the relative volatility in the absence of porous particles, φ is the mole fraction of free liquid phase in the overall liquid phase, $K_{\mathrm{S,L,1}}$ is the solid-liquid adsorption equilibrium constant between Component 1 and porous particles, $K_{\mathrm{S,L,2}}$ is the solid-liquid adsorption equilibrium constant between Component 2 and porous particles.

Equation 9 shows that the relative volatility between Component 2 and Component 1 would be increased when the porous particles could adsorb the Component 1. That is to say, if the $K_{\mathrm{S,L,1}}$ is improved, the relative volatility between Component 2 and Component 1 will also be increased. Thus, when the polar molecule of binary mixtures contacts the porous particle with similar polarity more, the component with strong polarity could go into the pores of the porous particles. Then, adsorption occurs in pores, the adsorption equilibrium constants between porous particles and the component with strong

Table 7. Properties of Certain Porous Particles[a]

	Unit	Powered Activated Carbon	Columnar Activated Carbon
Surface area	m^2/g	1202	39.84
Pore volume	mL/g	0.5416	0.01744
Pore size	nm	0.4875	0.4775
	Unit	D4006 Nonpolar Adsorption Resin	D4020 Nonpolar Adsorption Resin
Surface area	m^2/g	400–440	540–580
Pore volume	mL/g	0.73–0.77	2.88–2.92
Pore size	nm	0.65–0.75	1–1.05
	Unit	Activated Alumina Balls	
Surface area	m^2/g	315.9	
Pore volume	mL/g	0.1192	
Pore size	nm	0.5625	

[a] Data from analysis using the Quantachrome Automated Gas Sorption System.



4-a T=333.15K, Ethanol+ Water mixtures 4-b T=323.15K, Ethanol+ Ethyl acetate mixtures

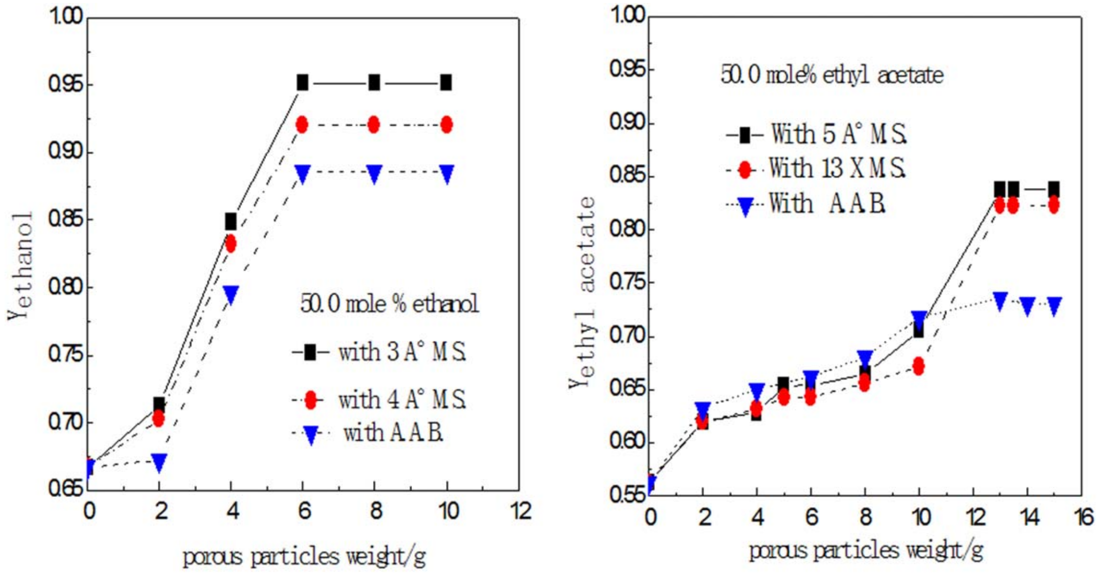
Figure 4. Effect of molecular sieves pore sizes on the vapor mole fraction.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

polarity would increase. It makes the volatile of component with weak polarity more relative. Thus, the vapor mole fraction of more polar component will be less than that in the absence of the porous particles under the same conditions.

Conclusions

The VLE of the ethanol + water, ethanol + ethyl acetate, acetic acid + ethyl acetate, and *n*-hexane + *n*-heptane systems under nonporous particles condition and in the presence of porous particles is studied at 60, 50, 50, and 50°C using the HSGC technique, respectively. The experimental results obtained prove the validity of using the HSGC method to study the isothermal VLE of binary mixtures in the absence and presence of porous particles. Only activated carbons have no effect on the VLE of binary mixtures among these porous particles considered in this work. Molecular sieves, activated alumina balls, and nonpolar adsorption resins all have a significant effect on the VLE. Moreover, some factors, such as the properties of solvent (i.e., polarity) and porous particles (i.e., amount, pore size, and surface area of porous particles) are also investigated. The experimental results show that the alteration in the VLE of a given binary mixture is a function of the properties of solvents and porous particles. In addition, the alteration in the VLE of binary systems in the presence of certain porous particles is attributed to the adsorption effect.



5-a T=333.15K, Ethanol-Water 5-b T=323.15K, Ethanol-Ethyl acetate

Figure 5. Effect of porous particles weight on the vapor mole composition.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

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