

# Research Article Visualization of Gas Diffusion-Sorption in Coal: A Study Based on Synchrotron Radiation Nano-CT

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Gas diffusion-sorption is a critical step in coalbed methane (CBM) exploitation and carbon dioxide sequestration. Because of the particularity of gas physical properties, it is difficult to visualize the gas diffusion-sorption process in coal by experimental methods. Due to the limitation of experimental approaches to image the three-dimensional coal pore structure, it is impossible to obtain the three-dimensional pore structure images of coal. As a result, the visualization of gas diffusion-sorption in coal pore structure by numerical ways is impossible. In this study, gas diffusion coefficients were firstly estimated by experiments. Then, a gas diffusion-sorption coupled model was developed which can be applied to the nanoscale geometry imaged by synchrotron radiation nano-CT. The dynamic process of gas diffusion and ad-/desorption in the nanoscale microstructure of coal was visualized by the developed gas diffusion-adsorption coupled model and the numerical simulation based on MATLAB. The simulation results show a good agreement with the experimental results. The gas diffusion-sorption coupled model and provides a possibility to investigate the multiscale gas transportation and adsorption in coal pore-fracture system.

## 1. Introduction

Coal, as a porous medium, exhibits high gas adsorption affinity [1]. As a result, coal is not only a methane reservoir but also can be considered as a potential place for carbon dioxide storage [2, 3]. The recoverable coalbed methane (CBM) is between 500 and  $3000 \times 1012$  scf (14.2 to  $84.9 \times 1012$  m3) in the world [4]. Carbon dioxide storage capabilities in deep coal seam are nearly 150 Gt in the world [5]. During coalbed methane (CBM) production, the gas needs to diffuse through the coal matrix and finally flows to the producing well [6–8]. When carbon dioxide sequestration is considered, carbon dioxide is physically adsorbed on the pore surface of coal through a reverse process [9]. Therefore, gas diffusion is an indispensable step in both CBM production and carbon dioxide sequestration. A significant amount of researches

has been conducted to study gas diffusion behavior in coal by experimental and numerical methods. Experimental research is focused on the factors that affect gas diffusion behavior, such as particle size [10], temperature [11], and gas pressure [12, 13]. Numerical methods are mainly used to calculate the gas diffusion coefficient by the bidisperse diffusion model [14]. Currently, widely implemented methods for diffusion coefficient calculation are the unipore model assuming a uniform pore size distribution [15, 16] and bidisperse model assuming bimodal pore size distribution [17]. Compared to bidisperse model, the unipore model is much easier in mathematical calculations. Some researchers found that the unipore model is sufficient to model the experimental data [11, 18-20], while other researchers found that bidisperse model is needed to achieve satisfactory accuracy [21-24].



FIGURE 1: Photographs of the instruments for synchrotron radiation nano-CT imaging. (a) Instruments for placing the sample particle on the tip of a pin. (b) Sample turntable for clipping the pin. (c) Transmission X-ray microscopy (TXM) instrument. (d) Instruments for mounting gold particle on the sample.

Among the factors of reparticle size, temperature, and pressure that affect gas diffusion behavior, pressure attracts relatively more attention. Because the gas pressure in coal matrix is continuously changing during gas production and carbon dioxide sequestration [13]. As for the relationship between gas diffusivity and gas pressure, there are two opposite results in prior studies. One conclusion is that diffusivity increased with the increase of pressure [25], while other results show that diffusivity drops with increasing pressure [13].

Previous researches on gas diffusion behavior can only provide macro (statistical) diffusion characteristics, such as diffusion coefficient, and are incapable of providing the real-time gas distribution in coal three-dimensional microstructure which is caused by the limitations of pore structure imaging approaches, especially in nanoscale [26–28]. In this paper, the synchrotron-based nano-CT at the Beijing Synchrotron Radiation Facility (BSRF) is applied to obtain the image of coal microstructure. Benefiting from a monochromatic beam and high X-ray coherency, synchrotronbased nano-CT can achieve nanometer-scale resolution with very good data quality [29].

In this study, methane and carbon dioxide diffusion coefficients during the adsorption and desorption process were measured and comprehensively analyzed. Based on an experimental study, a gas diffusion-sorption coupled model was developed. Finally, real-time gas diffusion- sorption process in coal was visualized by the combination of nanoscale microstructure and the coupled model of gas diffusionsorption.

## 2. Experimental

2.1. Sample. Coal samples were collected from Xinzhouyao coal mine and Tangshan coal mine and were named as sam-

ple XZY and sample TS in the following sections of this paper. Because the true density of coal samples will be used in the following numerical study, the true density was measured. The true density of two samples is  $1.3502 \text{ g/cm}^3$  (sample XZY) and  $1.5355 \text{ g/cm}^3$  (sample TS), respectively.

For synchrotron radiation nano-CT imaging, the first step is to pulverize the coal samples, and then the particle with size close to  $10 \,\mu$ m was selected and placed on the tip of a pin by the instruments shown in Figure 1(a). Figure 1(b) shows the turntable with the pin. Using the instruments shown in Figure 1(c), the gold particle was placed on the sample to facilitate the images alignment.

For gas diffusivity test, in order to eliminate the cracks and macropores, which have impacts on the test results, the coal sample size is 60-80 mesh ( $180-250 \mu$ m). Prior to tests, samples were degassed for 24 h at 303 K.

2.2. 3D Nanoscale Microstructure of Coal. The 3D nanoscale microstructure of coal was imaged by the synchrotron radiation nano-CT at BSRF. For more details about the nano-CT and imaging method, refer to the paper [29]. Before numerical investigation, the nano-CT images were processed in the following three steps: region of interest (ROI) selection, noise filtration [30], and images segmentation [31]. For more details about the nano-CT images processing, refer to the paper [32]. Figure 2 shows the flowchart of the images processing, and the processed synchrotron radiation nano-CT images were used for subsequent numerical investigation.

2.3. Gas Diffusivity Setup. Diffusion coefficient tests are similar to sorption isotherm measurements both in setup and experimental procedures. In diffusion measurements, the time of adsorption and desorption is recorded [13]. The gas diffusivity tests were completed by H-Sorb 2600 adsorption analyzer (Gold APP Instruments Corporation, China). For



FIGURE 2: Flowchart of synchrotron radiation nano-CT images processing. ROI size is  $200 \times 200 \times 200$  voxels. Voxel size is  $0.01459 \times 0.01459 \times 0.01459 \mu m$ . XZY represents sample from Xinzhouyao coal mine, and TS represents sample from Tangshan coal mine.



FIGURE 3: Gas sorption amount variation with time during the adsorption and desorption period.

more details about H-Sorb 2600 adsorption analyzer, refer to Sun et al. [33]. The gas pressure is up to 8 MPa for methane and is up to 5 MPa for carbon dioxide in diffusivity teste at the temperature 303 K. Figure 3 shows the test procedure. It can be found from Figure 3 that there are more significant leaps of the amount of adsorbed  $CO_2$  at the initial stage of each pressure level than that of  $CH_4$ . There are also more significant leaps in sample XZY than that in sample TS. It is because of the difference in gas diffusivity characteristics discussed in the following section. The experimental and Langmuir isotherms are shown in Figure 4, and the Langmuir parameters are listed in Table 1.

2.4. Estimation of Diffusion Coefficients and Discussion. According to the prior studies, there are two widely-used models to estimate the diffusion coefficient of coal, unipore model, and bidisperse model [5]. Compared to the bidisperse model, the unipore model is relatively simple in the mathematical calculation [12]. The unipore model was used to estimate the gas diffusion coefficient in this study.

According to Fick's second law,

$$\frac{M_t}{M_{\infty}} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left[-\frac{Dn^2 \pi^2 t}{r_p^2}\right]$$
(1)

For the convenience of calculation, equation (1) can also be written as,

$$\frac{V_t}{V_{\infty}} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left[-\frac{Dn^2 \pi^2 t}{r_p^2}\right]$$
(2)

According to equation (2) [34], the diffusion coefficients of  $CH_4$  and  $CO_2$  were calculated, as shown in Figures 5(a)-5(d).

It can be found in Figure 5 that the diffusion coefficients are in the range of  $10^{-13}$  to  $10^{-11}m^2/s$ , which is at the same magnitude as the results obtained by other researchers [11].

According to the results by other researchers, there is a positive relationship between gas diffusion coefficient and adsorbed gas volume [12]. The gas diffusion coefficient in sample XZY is higher than that in sample TS (Figure 5), which can be explained by the difference in the gas adsorption capacity. In this work, the gas adsorption capacity was quantified by the adsorbed gas amount on unit pore surface area, which can be obtained from the ad-/desorption isotherms in Figure 4, when the pore surface area of unit mass was obtained. The pore surface area in unit mass was calculated by the following equation (3).

$$F = \frac{f}{N_{solid} V_{voxel} \rho_{true}}$$
(3)

The ratio of pore surface area of two samples was estimated,

$$\frac{F_{XZY}}{F_{TS}} = \frac{f_{XZY}}{f_{TS}} \cdot \frac{N_{solid,TS}}{N_{solid,XZY}} \cdot \frac{\rho_{true,TS}}{\rho_{true,XZY}} = 0.7809 < 1$$
(4)

As shown in equation (4), the pore surface area in unit mass of sample XZY is less than that of sample TS, while the adsorbed gas amount on unit mass in sample XZY is higher, as shown in Figure 4, which indicates that the gas adsorption capacity of sample XZY is higher. It verifies that there is a positive relationship between the gas diffusion coefficient and adsorbed gas volume.

During the adsorption period,  $CH_4$  diffusion coefficient peaks at the inflection-point pressure of adsorption isotherm (7.15 MPa for sample XZY and 5.12 MPa for sample TS) where capillary condensation begins (Figures 4(a), 4(b), and 5(a)). When capillary condensation begins, the gas



FIGURE 4: Experimental and Langmuir isotherms for adsorption and desorption of two coal samples.

TABLE 1: Langmuir constants.

	Adsorption				Desorption			
Gas	XZY		TS		XZY		TS	
	$V_L (ml/g)$	P <sub>L</sub> (MPa)	$V_L (ml/g)$	P <sub>L</sub> (MPa)	$V_L (ml/g)$	P <sub>L</sub> (MPa)	$V_L$ (ml/g)	P <sub>L</sub> (MPa)
CH <sub>4</sub>	12.41	2.31	11.55	5.35	11.45	1.44	7.94	1.01
$CO_2$	27.80	1.46	25.71	2.03	26.36	1.04	22.87	1.12

adsorption rate significantly increases. According to the positive correlation between gas diffusion coefficients and adsorbed gas volume [12], the increase of gas adsorption rate facilitates gas diffusion. Because there is no capillary condensation in  $CO_2$  diffusion tests, which may be caused by the smaller test gas pressure range in  $CO_2$  diffusion tests,  $CO_2$ diffusion coefficients calculated from the adsorption stage are relatively constant although there is a fluctuation with gas pressure (Figure 5(c)). The reasons why the diffusion coefficient is relatively constant during the adsorption period except at the gas pressure where capillary condensation begins needs further research.

During the desorption period, as shown in Figures 5(b) and 5(d), there is a U-shape relationship between gas pressure and diffusion coefficients. At the low-pressure regime, the amount of adsorbed gas is small and the effect of adsorbed gas is small. According to the Lennard–Jones fluid model (Figure 6(a)) [35], there is a negative relationship between gas diffusion coefficient and gas pressure (Figures 5(b) and 5(d)). Subsequently, with the increase of



FIGURE 5: Gas diffusion coefficient variation with gas pressure.



FIGURE 6: Pressure-related parameters of gas. (a) The relationship between self-diffusivities and pressure [35]. (b) The relationship between compressibility factor and pressure.

gas pressure, the impact of adsorbed gas becomes stronger, which causes the positive relationship between diffusion coefficient and gas pressure (Figures 5(b) and 5(d)) [13]. The different laws presented in adsorption and desorption needs further investigation.

Moreover, it can be found that  $CO_2$  diffusivity is consistently higher than that of  $CH_4$ , which has also been found by some other researchers [12], because the kinetic diameter of carbon dioxide is smaller ( $CO_2$ : 0.33 nm;  $CH_4$ : 0.38 nm) [10].

#### 3. Visualization of Gas Diffusion-Sorption

3.1. Coupled Model of Gas Diffusion-Sorption. In current researches on gas transport behavior in coal, insufficient attentions have been paid to the visualization of dynamic gas diffusion-sorption process in the real geometrical morphology of coal microstructure. In this work, gas diffusionsorption visualization in the real coal microstructure was achieved by the combination of high-resolution images of coal microstructure and the coupled model of gas diffusion and adsorption.

According to the continuum equation,

$$\frac{\partial C}{\partial t} + \nabla J = S \tag{5}$$

Gas flow in the coal matrix can be described by the Fick's first law [36],

$$J = -D\nabla C \tag{6}$$

Substituting the equation (6) to the equation (5), Fick's second law containing the source term S is derived,

$$\frac{\partial C}{\partial t} - D\Delta C = S$$

$$S = -\frac{\partial C_{ad}}{\partial t}$$
(7)

Cad can be formulated as equation (8),

$$C_{ad} = \frac{n_{ad}}{V_e} = \frac{sv/V_m}{V_e} = \frac{sv}{V_eV_m}$$
(8)

Because the internal pore surface is the place where gas adsorbs, the identification equation of the internal pore surface was built,

$$\begin{cases} g(x, y, z) - g(x + 1, y, z) = -1, \text{ or} \\ g(x, y, z) - g(x, y + 1, z) = -1, \text{ or} \\ g(x, y, z) - g(x, y, z + 1) = -1, \text{ or} \\ g(x - 1, y, z) - g(x, y, z) = 1, \text{ or} \\ g(x, y - 1, z) - g(x, y, z) = 1, \text{ or} \\ g(x, y, z - 1) - g(x, y, z) = 1 \end{cases}$$
(9)



FIGURE 7: Variation of the gas sorption amount with time in numerical simulation.

In this study, the grey value of solid and pore is 0 and 1, respectively.

The amount of adsorbed gas on unit pore surface area can be estimated by equation (10).

$$v = \frac{V}{F} \tag{10}$$

Gas adsorption here follows Langmuir isotherm model by equation (11) [37],

$$V = \frac{PV_L}{P + P_L} \tag{11}$$

Figure 4 shows the Langmuir isotherms, and the Langmuir parameters are listed in Table 1.

The coupled model of gas diffusion and sorption is developed as,

$$\frac{\partial C}{\partial t} - D\Delta C = -\frac{\partial}{\partial t} \left[ \frac{sPV_L}{1000V_m FV_e(P + P_L)} \right]$$
(12)

The gas state equation is,

$$C = \frac{n}{V} = \frac{P}{ZRT}$$

$$Z = f(T, P)$$
(13)

Figure 6(b) shows the gas compressibility factor [38]. Now, equation (14) can be written as,

$$\frac{\partial P}{\partial t} - D\Delta P = -ZRT \frac{\partial}{\partial t} \left[ \frac{sPV_L}{1000V_m FV_e(P + P_L)} \right]$$
(14)

The visualization of gas diffusion-sorption in coal can be achieved by solving equation (14).

Geofluids



FIGURE 8: The gas pressure and adsorbed gas distribution during the process of adsorption and desorption.

3.2. Parameters Determination. In the simulation, the equilibrium pressure is 1 MPa. A cube from sample XZY was used as the simulation geometry. The size of the cube is  $200 \times 200 \times 200 \times 200$  voxels, and the voxel size is  $0.01459 \times 0.01459 \times 0.01459 \ \mu$ m (Figure 2). Adsorption and desorption stage were both investigated in numerical study. At the stage of adsorption and desorption, the pressure on the simulation geometry surface is 1 MPa and 0 MPa, respectively.

Gas diffusion in coal is mainly impacted by pore structure, matrix, gas molecular, and the characteristics of sorption [12]. Gas transport mechanism in pores can be determined by Knudsen number described by equation (15) [39].

$$K_n = \frac{\lambda}{D_p} \tag{15}$$

$$\lambda = \frac{k_B T}{\sqrt{2\pi}\delta^2 P} \tag{16}$$

Gas transport can be divided into different flow patterns by Knudsen number, and for each flow regime, gas transport follows different control equations [40].

As the methane pressure is equal to 1 MPa, the Knudsen number in sample XZY is calculated to be 0.07. Moreover, as shown in Figure 5(a), at the low-pressure regime, the trend of  $CH_4$  diffusion coefficients complies with Lennard–Jones fluid model (Figure 6(a)) [35], which indicates the gas diffusion can be approximately treated as bulk diffusion. Therefore, in the simulations, the value from Lennard–Jones model (Figure 6(a)) was set as the diffusion coefficient in pores.

The pore radius from the synchrotron-based nano-CT in this study is in the range of 9-279 nm. According to the prior test results by NMR cryoporometry, the pore volume of pores with radius in the range of 0.84-9 nm account for 43% of the total pore volume in the range of 0.84-250 nm [41]. Coal matrix and pores out of nano-CT detection coverage account for the majority of the coal. Therefore, the gas diffusion coefficient in matrix was from the value measured in experimental study (Figure 5). Through pores range (9-288 nm) detected in this paper do not cover the entire pore size range, gas adsorbed on these pores surfaces can proportionally reflect the dynamic process of adsorbed gas distribution and the gas pressure distribution in this simulation can relatively accurately reflect the free gas distribution in real situation.

3.3. Numerical Simulation Results and Discussion. Figure 7 shows the total amount of adsorbed gas varies with time during the adsorption and desorption period. It can be found that adsorption and desorption rate is significantly faster at the initial stage of adsorption and desorption, and the amount of adsorbed gas becomes steady eventually after a certain time, which is the same as the experimental data in Figure 3. There is a contradiction between resolution and sample size in CT imaging, and the sample size needs to be small enough to meet the resolution requirements. In the synchrotron radiation nano-CT imaging, the sample size is less than  $10 \,\mu\text{m}$ , while the sample mass needs to achieve a certain amount to ensure the accuracy of experimental measurement in gas ad-/desorption. Therefore, the geometric scale of experiments and simulations is not at the same scale. Moreover, there is the diffusion in the space between the coal particles in experiments. As a result, it is not comparable between the experimental and numerical results in the sorption-time coordinate system. In the future, the numerical method for investigating the gas diffusion-sorption considering the effect of scale and the diffusion in the space between the coal particles should be studied.

In Figure 8, the dynamic process of gas diffusion-sorption during the adsorption process is visualized in the rows 1 and



FIGURE 9: The comparison between simulation and experiment results.

2, and the dynamic process of gas diffusion-sorption during the process of desorption is visualized in the rows 3 and 4. The nano-CT image slices were numbered 1-200 from top to bottom. The first column is the slices numbered 2, 5, 10, and 100. The dynamic gas pressure evolution over time is presented in rows 1 and 3. The dynamic adsorbed gas evolution over time is presented in rows 2 and 4. It can be found that gas diffusion dominates the gas adsorption. When gas diffuses to a pore, there can be gas adsorption on the surface of the pore. Moreover, gas pressure determines the amount of gas adsorbed and the amount of adsorbed gas is higher when the gas pressure is higher.

Because of the particularity of gas physical properties, it is difficult to visualize the gas diffusion-sorption process in coal by experimental methods. Due to the limitation of previous means to characterize coal pore structure, it is impossible to obtain the three-dimensional pore structure images of coal. As a result, it is not possible to realize the visualization of

gas diffusion-sorption process based on the real threedimensional microstructure by numerical means. In the previous study of gas transportation in coal by numerical method, only one parameter (porosity) was given to characterize the effect of pore structure on gas transportation in coal [42, 43], which cannot precisely investigate the influence of pore structure on gas transportation, because the size and spatial distribution of pore structure was not considered. In this study, based on the nanoscale microstructure, the simulation visualizes the dynamic process of gas diffusionsorption in coal microstructure and obtains the variation of total adsorbed gas amount with time. Besides, various numerical methods have been developed to generate porous media [44-46]. The coupled model of gas diffusion and sorption and the numerical method for simulating gas diffusion and sorption in 3D porous media, which are developed in this paper, provides an option for further researches on the impact of microstructure on the gas diffusion and sorption.

Although there is adsorption-swelling effect [47], this study intends to develop the method to visualize gas diffusion and sorption in coal, so the adsorption-swelling effect was not investigated, but the improved model will be developed in the future.

Although it is not comparable between the experimental and numerical results in the adsorption-time coordinate system as mentioned above, it is comparable between the experimental and numerical results in the adsorption isotherm, because the effect of scale and the diffusion in the space between the coal particles is ignorable when the adsorption reaches equilibrium. In order to validate the numerical method to visualize the dynamic process of gas diffusion and ad-/desorption in coal microstructure, the adsorption isotherms from numerical simulations are compared with the experimental results. As shown in Figure 9, adsorption isotherms from numerical simulations are consistent with the experimental results, which validate the numerical method. The application of nano-CT and the coupled model of gas diffusion and adsorption developed in this paper make it possible to investigate the dynamic process of pressure distribution and adsorbed gas distribution during the adsorption and desorption period. Moreover, the pore-scale model in this study can be combined with the fracturescale models, such as discrete fracture model (DFM) [48], to investigate the multiscale gas transportation and adsorption in coal reservoir.

## 4. Conclusions

Visualization of gas diffusion-sorption in coal is very important for investigating the impact of pore structure on gas diffusion-sorption and multiscale gas transportation and adsorption in coal pore-fracture system. In this study, based on the nanoscale images of coal pore structure, the dynamic process of gas diffusion-sorption in coal was visualized. Before the visualization of gas diffusion-sorption in coal, methane and carbon dioxide diffusion coefficients during the adsorption and desorption processes in two coal samples were tested and comprehensively analyzed. Coal with higher gas adsorption capacity presents higher diffusivity. The smaller kinetic diameter of CO<sub>2</sub> causes the diffusivity of CO<sub>2</sub> is higher than that of CH<sub>4</sub>. During the adsorption process, gas diffusion coefficient peaks at the gas pressure where capillary condensation begins. There is a U-shape relationship between gas diffusion coefficient and gas pressure during the desorption process. In order to investigate the dynamic process of gas diffusion and ad-/desorption in coal, a gas diffusion-sorption coupled model was developed. Based on the nanoscale microstructure, the dynamic process of gas diffusion and ad-/desorption in coal nanoscale microstructure was visualized. The numerical simulation results show a good agreement with the experimental results. The gas diffusionadsorption coupled model and numerical method can help to investigate the influence of microstructure on gas diffusion and ad-/desorption and provides a possibility to investigate the multiscale gas transportation and adsorption in coal pore-fracture system.

#### Nomenclature

$M_{\cdot}$ :	Total desorbed gas mass in time $t(g)$		
$M_{aa}$ :	Total desorbed gas mass in infinite time (g)		
D:	Diffusion coefficient $(m^2/s)$		
r.:	Diffusion path length (m)		
$V^{p}$ .	Total volume of gas ad/de-sorbed in time $t$ (ml)		
$V^{t}$ .	volume of gas ad/de-sorbed in infinite time (ml)		
$f \cdot \infty$	Total pore surface area in ROI $(m^2)$		
N	Total number of solid voxel in ROI		
V :	Volume of per voxel $(m^3)$		
voxel	True density $(g/cm^3)$		
$Y \cdot true$	Coal sample collected from Xinzhouyao coal mine		
TS.	Coal sample collected from Tangshan coal mine		
C:	Gas concentration $(mol/m^3)$		
I:	Diffusion flux $(mol/(m^2 \cdot s))$		
S:	Source term $(mol/(m^3 \cdot s))$		
$C_{ad}$ :	Gas concentration impacted by gas adsorption		
ии	(mol/m <sup>3</sup> )		
$n_{ad}$ :	Amount of adsorbed gas (mol)		
$V_e$ :	Volume of mesh element in numerical calculation		
	(m <sup>3</sup> )		
<i>s</i> :	Pore surface area in the element $(m^2)$		
<i>v</i> :	Adsorbed gas amount on unit pore surface area		
	$(ml/m^2)$		
$V_m$ :	Molar volume of gas (22.4 <i>L/mol</i> , STP)		
g(x, y, z):	The grey value in the location $(x, y, z)$		
V:	Volume of gas adsorbed on unit mass of coal		
	(ml/g)		
F:	Pore surface area in unit mass of coal $(m^2/g)$		
P:	Gas pressure (Pa)		
$V_L$ :	Langmuir volume (ml/g)		
$P_L$ :	Langmuir pressure (MPa)		
Z:	Gas compressibility factor		
$D_{\rm p}$ :	Mean diameter of the pore (m)		
λ:	Mean free path of gas molecules (m)		
$k_B$ :	Boltzmann constant $(1.3805 \times 10^{-23} \text{J/K})$		
T:	Temperature (K)		
δ:	Collision diameter (m).		

#### **Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

### **Conflicts of Interest**

The authors declare that there is no conflict of interest regarding the publication of this paper.

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