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## Release of methane from nanochannels through displacement using CO<sub>2</sub>

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In this work, we investigate the release of methane in quartz nanochannels through the method of displacement using carbon dioxide. Molecular dynamics (MD) simulations and theoretical analysis are performed to obtain the release percentage of methane for nanochannels of various diameters. It is found that both the pressure of CO<sub>2</sub> and the channel size affect the release percentage of methane, which increases with increasing pressure of CO<sub>2</sub> and channel diameter. Without CO<sub>2</sub>, the majority of methane molecules are adsorbed by the channel surface. When CO<sub>2</sub> is injected into the channel, CO<sub>2</sub> molecules replace many methane molecules due to the relatively strong molecular interactions between CO<sub>2</sub> and the channel, which leads to the desorption of methane, reduces the energy barrier for the transport of methane, and consequently increases the release rate. Theoretical predictions using the kinetic energy of methane and the energy barrier inside the channel are also conducted, which are in good agreement with the MD simulations.

### 1. Introduction

In the past decades, the rapid increase of energy consumption has posed a challenge to the growth of the worldwide economy, which has motivated the exploration of new energy sources. Among various alternatives, shale gas has become a promising source for solving the potential energy crisis.<sup>1</sup> Compared with the traditional fossil fuels, shale gas is eco-friendly due to its low carbon emission.<sup>2,3</sup> For the exploitation of shale gas, the combination of hydraulic fracturing and horizontal drilling is the most widely used technology for mass production.<sup>4</sup> However, this technology consumes a large amount of water and has potential contamination of underground water.<sup>5-7</sup> Moreover, the output of a typical shale gas well usually experiences a significant drop after three years.<sup>8,9</sup> Therefore, it is important to find new methods to exploit shale gas.

Shale gas mainly contains methane, which is trapped in nanoscale pores of shale.<sup>10,11</sup> The strong confinements of the nanopores make the release of shale gas a nontrivial process. In the literature, many efforts have been made to study the adsorption and desorption of methane molecules in nanopores through experiments and simulations. Rexer *et al.*<sup>12</sup> examined the adsorption of methane in shale samples through experiments by varying the temperature and pressure according to various geological conditions of shale gas. They measured and modeled the methane excess uptake and isosteric enthalpy,

which provide useful information for understanding the storage mechanisms of shale gas. Lithoxoos *et al.*<sup>13</sup> numerically investigated the capacity of single-wall carbon nanotubes (SWCNTs) for methane storage at room temperature under different pressures and the results were confirmed by experiments. They obtained the density distributions of different gases and found that almost all the gas molecules were adsorbed by the interior surface of the pores. Zhu and Zhao<sup>14</sup> explored the mechanisms of methane adsorption in CNTs through molecular dynamics (MD) simulations and proposed an equation of state for the adsorbed phase of methane molecules. Their equation can predict most of the adsorption phenomena observed in their simulations. Furthermore, they found that the adsorption behavior in nanopores was affected by the size and curvature of the pores. As a consequence, there exists an optimal CNT diameter that maximizes the adsorption of methane. Wu *et al.*<sup>15</sup> also studied the mechanisms of methane adsorption and displacement processes in carbon nanochannels through MD simulations and obtained similar results to those of Zhu and Zhao.<sup>14</sup> It was found that when the external pressure reaches 5 MPa, the adsorption isotherms for bulk methane is about 1.5 mmol cm<sup>-3</sup>, whereas it is about 10 mmol cm<sup>-3</sup> in nanopores. Bartus *et al.*<sup>16</sup> studied the behavior of methane molecules inside rigid and flexible carbon nanotubes (CNTs) at room temperature through classical MD simulations and obtained that the diffusion coefficient in rigid and flexible CNTs are similar. Mahdizadeh *et al.*<sup>17</sup> used grand canonical Monte Carlo (GCMC) simulations to investigate the methane adsorption in single-walled carbon nanotubes (SWCNTs) and their results indicate that SWCNTs can be stylized for methane adsorption. Liu *et al.*<sup>18</sup> explored the diffusion of methane at room

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temperature under various pressures in dry and wetted CNTs with different diameters through MD simulations. They reported that the diffusion coefficient of methane molecules reduces dramatically in wetted CNTs compared with that in dry CNTs because the low solubility of  $\text{CH}_4$ , especially in thin CNTs.

In addition, there are some studies comparing the adsorption of  $\text{CH}_4$  and  $\text{CO}_2$  in nanoconfinements. Huang *et al.*<sup>19</sup> used GCMC simulations to examine the adsorption behavior of an equimolar  $\text{CO}_2/\text{CH}_4$  mixture in CNTs by considering the effects of pressure, temperature, and CNT diameter. They found that the adsorption of  $\text{CO}_2$  is much stronger than that of  $\text{CH}_4$  and the influences of temperature and pressure are minor in small CNTs and the CNT size affects the adsorption of  $\text{CO}_2$  more significantly than that of  $\text{CH}_4$ . Lu *et al.*<sup>20</sup> compared the selectivity of several nanostructures for  $\text{CO}_2/\text{CH}_4$  mixtures through GCMC simulations and found that CNTs have the highest selectivity. Liu *et al.*<sup>21</sup> reported a comparison of the adsorption of  $\text{CO}_2/\text{CH}_4$  mixtures of three different types of carbon nanopores at different temperatures and observed that the selectivity of these carbon nanopores decreases with increasing temperature and the (7, 7) CNT has the highest selectivity of  $\text{CO}_2$ . Cao *et al.*<sup>22</sup> changed the hydrophilicity of CNTs by changing the number of -CO groups and found that the selectivity of  $\text{CO}_2$  increases with increasing hydrophilicity. Moreover, Hong *et al.*<sup>23</sup> investigated the adsorption capacity of open-ended SWCNTs for various gases, especially CO, and found that under the conditions of room temperature and 1 atm, the (8, 8) open-ended SWCNT presents a high adsorption capacity for CO.

Another approach for developing shale gas is to replace it by other species. Some studies have been conducted to investigate the performance of this method. Yu *et al.*<sup>24</sup> built an experimental apparatus to obtain the transport characteristics of

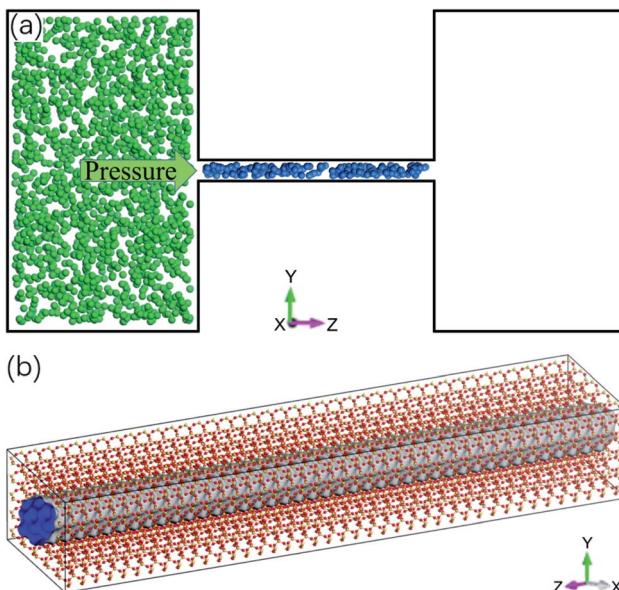


Fig. 1 Molecular dynamics simulation system. (a) Schematic of the system: a quartz nanochannel with two reservoirs at the ends (blue and green spheres are methane and  $\text{CO}_2$  molecules). (b) Atomic structure of quartz nanochannel.

Table 1 Potential parameters for the force field

Bond stretch parameters			
Bond type	$K_0$ (kcal mol $^{-1}$ Å $^{-2}$ )	$R_0$ (Å)	
C-H	700	1.09	
Si-O	700	1.587	
C-O	1400	1.152	
Bond angle bend parameters			
Bond type	$K_0$ (kcal mol $^{-1}$ Å $^{-2}$ )	$\theta_0$	
H-C-H	100	109.471°	
Si-O-Si	100	104.51°	
O-Si-O	100	109.471°	
O-C-O	100	180	
Torsional parameters			
Torsion type	$B_0$ (kcal mol $^{-1}$ )	$d_0$	$n_0$
O-Si-O-Si	2	-1	3
Lennard-Jones parameters			
Interaction type	$\sigma$ (Å)	$\epsilon$ (kcal mol $^{-1}$ )	
H-H	3.195	0.015	
C-C	3.898	0.095	
H-C	3.547	0.038	
H-O	3.3	0.038	
H-Si	3.733	0.069	
C-O	3.651	0.095	
C-Si	4.084	0.172	
O-O	3.405	0.096	
O-Si	3.838	0.173	
Electrostatic parameters			
Element type	Charge (e)		
C in methane	-0.4		
C in carbon dioxide	0.572		
H	0.1		
O in carbon dioxide	-0.286		
O in quartz	-0.445		
Si	0.89		

methane in nanopores and found that carbon dioxide is easier to be adsorbed by the pore surface than methane. Bhowmik *et al.*<sup>25</sup> investigated the displacement behavior of methane by pure carbon dioxide in dry, powdered, bituminous Indian coals. It was also found that carbon dioxide is preferentially adsorbed by silt pores compared with methane. However, most of the previous experimental work is mainly focused on macroscopic studies. Only a few studies have been performed to understand the replacement of methane in nanopores perhaps because nanoscale studies are experimentally challenging. Huo *et al.*<sup>26</sup> collected 4 shale samples in Jiaoshiba area of Sichuan basin, China and investigated the displacement behavior of methane by carbon dioxide. It was found that the injection pressure of



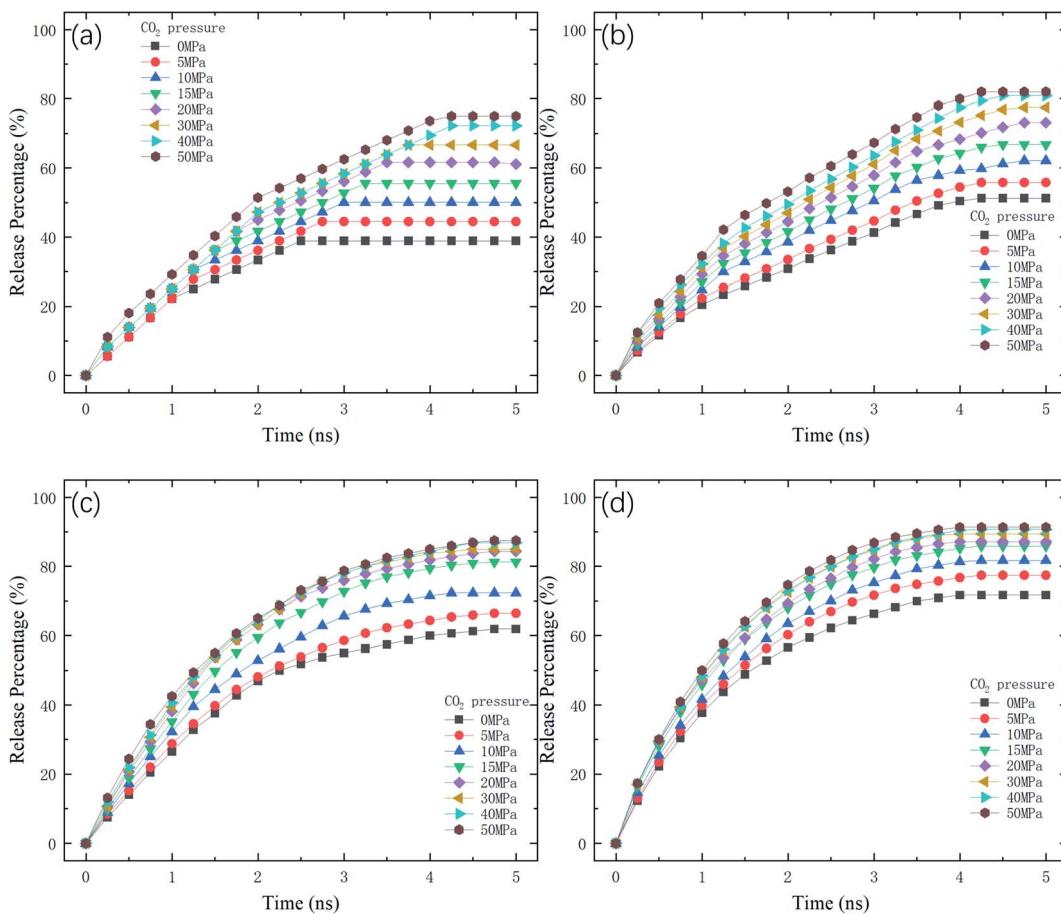


Fig. 2 Release percentage of methane as a function of time at different  $\text{CO}_2$  pressures in channels with various diameters  $D$ . (a)  $D = 1 \text{ nm}$ . (b)  $D = 1.5 \text{ nm}$ . (c)  $D = 2 \text{ nm}$ . (d)  $D = 2.5 \text{ nm}$ .

carbon dioxide strongly affects the displacement process. The release rate of methane increases with increasing injection pressure of carbon dioxide. Their investigations provide preliminary knowledge for carbon dioxide sequestration in shale reservoirs.

As an alternative approach, numerical simulations have been conducted to probe the replacement process of shale gas in nanopores. Shi *et al.*<sup>27</sup> proposed a shale model using organic-inorganic composites and used Grand Canonical Monte Carlo (GCMC) and MD simulations to study the dynamics of methane driven by carbon dioxide. It was found that the amount of methane in the shale decreases dramatically as the injection pressure of carbon dioxide rises from 0 to 30 MPa. However, when the pressure of carbon dioxide is higher than 30 MPa, there is no further increase in the release rate of methane due to the  $\text{CO}_2$  saturation in the pores. Zhang *et al.*<sup>28</sup> employed GCMC simulations to study the displacement of shale gas at different geological depths up to 4 km, they varied the geological conditions by changing the pressure and temperature of the system. The results indicate that carbon dioxide can displace methane molecules efficiently under the geological depth of 1 km. However, the displacement amount of methane decreases significantly when the geological depth is further increased.

Sun *et al.*<sup>29</sup> investigated the microscopic adsorption and diffusion of methane and carbon dioxide in kerogen shale pores and studied the replacement of methane by carbon dioxide through MD simulations. It was revealed that methane can be replaced

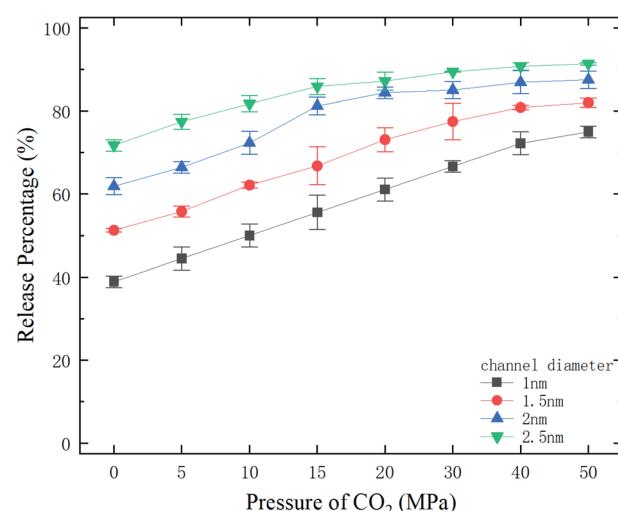


Fig. 3 The final release percentages of methane as a function of  $\text{CO}_2$  pressure.

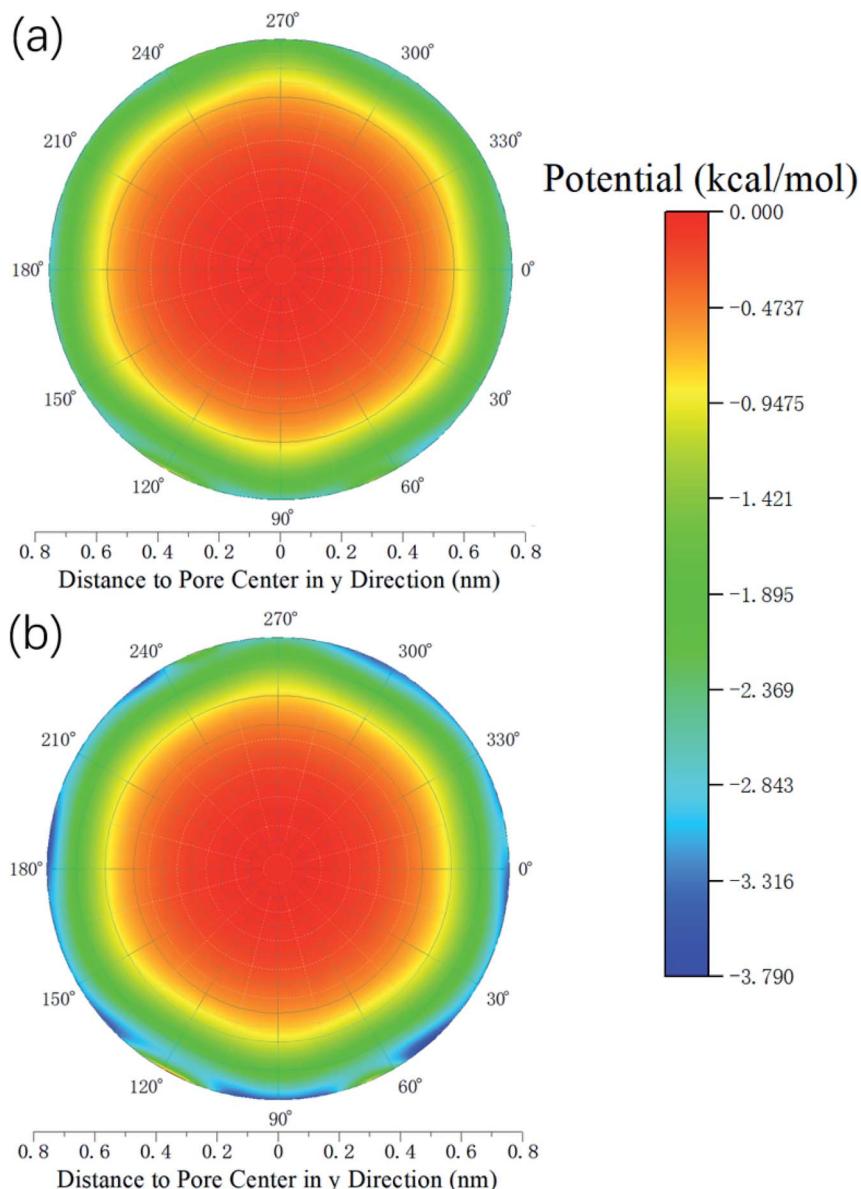


Fig. 4 Potential distribution inside the 2 nm-diameter channel in a plane perpendicular to the channel axis. (a) Methane (b)  $\text{CO}_2$ .

by carbon dioxide because carbon dioxide has stronger interaction with pore walls than methane. It was also observed that a small portion of methane molecules were hard to be replaced through carbon dioxide injection. Ho *et al.*<sup>30</sup> probed the release of  $\text{CH}_4$  and  $\text{CO}_2$  in kerogen and CNTs through MD simulations. It was found that the diffusion coefficient of  $\text{CH}_4$  is higher than that of  $\text{CO}_2$ , which indicates that  $\text{CO}_2$  is more difficult to be released from kerogen and CNTs than  $\text{CH}_4$ . Moreover, the impacts of water on the release of methane with and without the presence of  $\text{CO}_2$  were also explored. Due to the relatively high solubility,  $\text{CO}_2$  can be preferentially adsorbed in kerogen, leading to the release of methane. Yuan *et al.*<sup>31</sup> investigated the enhanced recovery of confined  $\text{CH}_4$  with  $\text{CO}_2$  by MD simulations and found that there exists an optimal CNT size for  $\text{CH}_4$  displacement. Yang *et al.*<sup>32</sup> studied the adsorption and diffusion properties of  $\text{CH}_4$  and  $\text{CO}_2$  in CNTs with preabsorbed water at

room temperature with different pressures. They found that the presence of water enhances the adsorption of  $\text{CO}_2$  due to the  $\text{CO}_2\text{-H}_2\text{O}$  interaction and the adsorption selectivity of  $\text{CO}_2/\text{CH}_4$  increases with increasing pressure. Although the displacement phenomena of methane has been observed in experiments and simulations, the microscopic mechanism of shale gas replacement in nanopores is still unclear, which requires extensive investigations.

In this work, we investigate the displacement of methane by carbon dioxide through MD simulations. The methane release percentage is obtained at various carbon dioxide injection pressures for different pore diameters. Quartz nanochannels with tetrahedral structure, which have been widely used for gas storage,<sup>33,34</sup> are employed to model shale pores. It is found that the release percentage of methane rises as the injection pressure of carbon dioxide is increased due to the relatively strong



molecular interactions between carbon dioxide and channel walls. Furthermore, the release percentage of methane is theoretically predicted using the kinetic energy of methane molecules and the energy barrier inside the channel, which is in good agreement with MD simulations.

## 2. Molecular dynamics simulation

Molecular dynamics simulations are conducted using Material Studio. The simulation system contains a cylindrical quartz (silicon dioxide) nanochannel with two reservoirs at the ends, as illustrated in Fig. 1a. The structure of the channel is tetrahedral (Fig. 1b) and the diameter of the nanochannel ranges from 1 to 2.5 nm. The length of the nanochannel is 20 nm and the lengths of the two reservoirs are 15 nm, 25 nm, and 10 nm in the *x*, *y*, and *z* directions, respectively. The Berendsen thermostat and Parrinello–Rahman barostat are used to control the temperature and pressure of the system at 350 K and 20 MPa, which are similar to the real geological conditions of shale gas reservoirs.<sup>35–37</sup> Under these conditions, the density of methane is

119.41 kg m<sup>−3</sup>,<sup>38</sup> which is used to initially store methane molecules in the nanochannel. The left reservoir is filled with a certain number of CO<sub>2</sub> molecules, ranging from 4600 to 45 400, which generates a pressure in the reservoir from 5 to 50 MPa.<sup>39</sup> A special case without CO<sub>2</sub> injection is also studied, for which, there are no CO<sub>2</sub> molecules in the reservoir.

The DREIDING force field<sup>40</sup> is employed to describe the quartz channel, methane, and methane–channel interactions. The general potential for these interactions is given by

$$U = \sum_{\text{bonds}} \frac{K_b}{2} (r_{ij} - R_0)^2 + \sum_{\text{angles}} \frac{K_a}{2} (\theta - \theta_0)^2 + \sum_{\text{torsions}} \frac{B_0}{2} (1 - d_0 \cos(n_0 \phi)) + \sum_{i < j} 4\epsilon_{ij} \left( \left( \frac{\sigma_{ij}}{r_{ij}} \right)^{12} - \left( \frac{\sigma_{ij}}{r_{ij}} \right)^6 \right) + \sum_{i < j} \frac{q_i q_j}{r_{ij}} \quad (1)$$

where  $K_b$  is a force constant,  $R_0$  and  $\theta_0$  are the equilibrium bond distance and angle,  $B_0$  is the barrier height,  $d_0$  is the phase

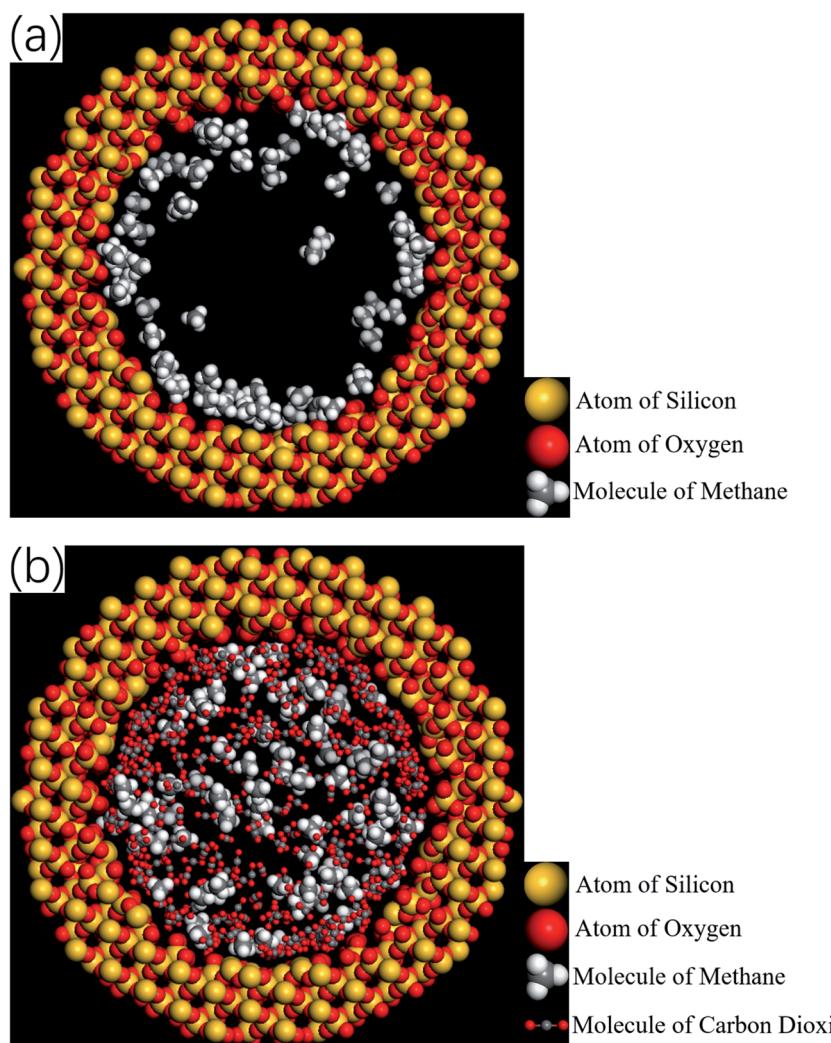


Fig. 5 Snapshots of simulations showing the spatial distributions of methane and CO<sub>2</sub> molecules. (a) Before the injection of CO<sub>2</sub> (the majority of methane molecules are adsorbed by the channel wall). (b) After the injection of CO<sub>2</sub> (some adsorbed methane molecules are replaced by CO<sub>2</sub> molecules and driven into the inner area of the channel).



factor,  $n_0$  is the periodicity,  $\varepsilon$  is the binding energy and  $\sigma$  is the collision diameter,  $r_{ij}$  is the separation between molecules/atoms  $i$  and  $j$ ,  $\theta$  is the bond angle,  $\phi$  is the bond torsion angle, and  $q$  is the charge. The values of relevant parameters for various interactions are listed in Table 1, where the bond stretch, bond angle bend, torsional, and Lennard-Jones parameters are adopted from the original DREIDING potential.<sup>40</sup> However, the charges for the electrostatic potential are estimated using the Gasterier method,<sup>41</sup> which have been confirmed by previous work.<sup>31,42</sup>

The cut-off distance for the potential is set at 10.5 Å and the time step is 1 fs. Initially, the reservoirs and the nanochannel are not connected (they are separated by a wall) and the system is relaxed for 200 ps in the ( $N, V, T$ ) ensemble. After the relaxation, the walls between the reservoirs and the nanochannel are removed so that CO<sub>2</sub> molecules can infiltrate into the channel. At the same time, the system is performed in the ( $N, V, E$ ) ensemble to calculate the release percentage of methane molecules.

### 3. Results and discussion

By varying the pressure of CO<sub>2</sub> and the channel diameter, the number of methane molecules expelled from the channel is obtained and the release percentage of methane is computed as

$$P_r = \frac{N}{N_0} \times 100\%, \quad (2)$$

where  $N$  is the number of methane molecules released from the channel, *i.e.*, the number of methane molecules in the reservoirs, and  $N_0$  is the total number of methane molecules in the system. Fig. 2 shows the release percentage as a function of time for different channel diameters under various CO<sub>2</sub> pressures. It is seen that  $P_r$  approaches constant values in 5 ns regardless of the channel size and CO<sub>2</sub> pressure. The final release percentage is depicted in Fig. 3. It is found that  $P_r$  increases as the pressure of CO<sub>2</sub> is raised. At zero CO<sub>2</sub> pressure, *i.e.*, initially no CO<sub>2</sub> in the left reservoir,  $P_r$  is about 40% for 1 nm-diameter channel, while it is about 70% for 2.5 nm diameter channel. This is because the reservoirs initially are vacuum and the high methane pressure inside the channel drives some methane molecules into the reservoirs. For 1 and 1.5 nm-diameter channels,  $P_r$  increases and eventually reaches about 80% and 85%, respectively, as the pressure of CO<sub>2</sub> increases, which indicates that the method of displacement using CO<sub>2</sub> works well. In 2 nm and 2.5 nm diameter channels, as the storage capacity of the channels for methane is weak, even if there is no CO<sub>2</sub> injection,  $P_r$  is over 60%. With CO<sub>2</sub> injection,  $P_r$  reaches about 90% and 95%, which demonstrates that the method of displacement is still useful for relatively large diameters.

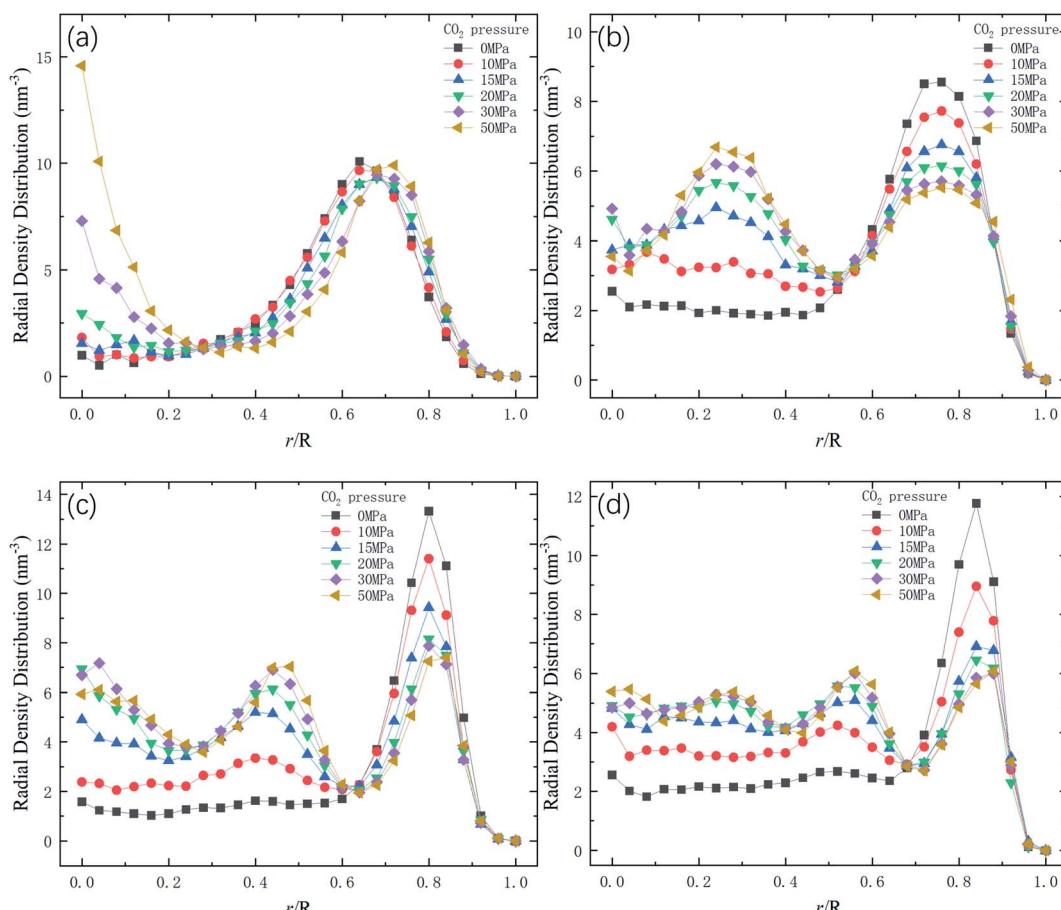


Fig. 6 Radial density distribution of methane in channels of different diameters  $D$ .  $R$  is the radius of the channel. (a)  $D = 1$  nm. (b)  $D = 1.5$  nm. (c)  $D = 2$  nm. (d)  $D = 2.5$  nm.



Whether a methane molecule can be released from the channel or not mainly depends on the kinetic energy  $E$  of the methane molecule and the energy barrier  $\Delta G$  in the channel.<sup>43–45</sup>  $E$  is mainly determined by the temperature  $T$  and  $\Delta G$  is governed by the methane–quartz molecular interaction and the pore structure.  $\Delta G$  is the potential difference between the maximum and minimum potential points in the channel. If the kinetic energy of a methane molecule is sufficiently high, it can overcome the energy barrier and can be released from the channel. The probability for the methane molecules to escape from the attraction of the channel is proportional to  $\exp(-\Delta G/E)$ , as will be discussed later.

Therefore, the release percentage of methane can be enhanced by either increasing the kinetic energy  $E$  of methane molecules or reducing the energy barrier  $\Delta G$  of the channel. In previous work,<sup>46,47</sup> we explored the method of increasing the kinetic energy  $E$  by heating or applying an external force on the channel to release methane from nanopores. Herein, by injecting  $\text{CO}_2$ , we expect to decrease the energy barrier  $\Delta G$  in the channel through the displacement of methane molecules to increase the release percentage of methane. Fig. 4a and b show the potential distribution of methane and carbon dioxide, respectively, inside the 2 nm-diameter channel in a plane perpendicular to the channel axis. In Fig. 4a, it is seen that the

potential energy of methane next to the wall is low and that at the center area is high. The low potential close to the wall is caused by strong methane–wall interactions, which lead to the adsorption of methane molecules on the channel surface, as demonstrated in Fig. 5a. As  $\text{CO}_2$  molecules are injected into the channel,  $\text{CO}_2$  molecules replace methane molecules on the adsorption sites of the channel wall because the  $\text{CO}_2$ –wall intermolecular interaction is stronger than that between methane and the wall, as indicated by the potential distribution in Fig. 4 (the potential energy of methane next to the wall is about 3 kcal mol<sup>−1</sup> while that of carbon dioxide is about 3.8 kcal mol<sup>−1</sup>). Consequently, some methane molecules are replaced by carbon dioxide molecules and freed from adsorption, as shown in Fig. 5b, which makes them easier to be released from the channel because the energy barrier to be overcome becomes smaller, as will be shown later. The replacement of methane molecules by  $\text{CO}_2$  molecules can be manifested by the density distribution of methane in the channel as the pressure of  $\text{CO}_2$  is varied, as depicted in Fig. 6. It is seen that the density of methane next to the wall decreases while the density around the center area increases as the  $\text{CO}_2$  pressure is increased due to the adsorption of  $\text{CO}_2$  on the channel surface and the replacement of methane by  $\text{CO}_2$ . Fig. 7 shows the density distribution of  $\text{CO}_2$  in the channel. It is clear

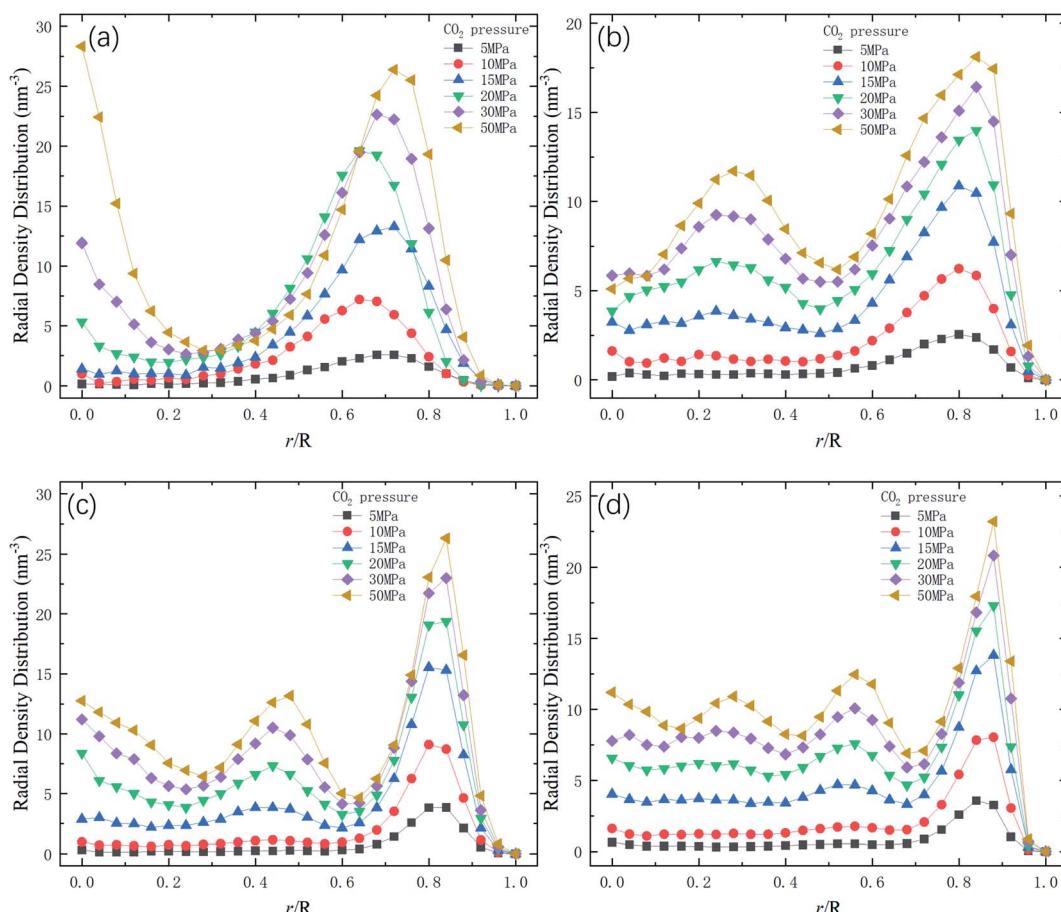


Fig. 7 Radial density distribution of carbon dioxide in channels of different diameters  $D$ .  $R$  is the radius of nanochannels. (a)  $D = 1$  nm. (b)  $D = 1.5$  nm. (c)  $D = 2$  nm. (d)  $D = 2.5$  nm.

that many  $\text{CO}_2$  molecules are adsorbed by the channel surface and the adsorption is enhanced by the pressure. Fig. 7 confirms that  $\text{CO}_2$  molecules can replace methane molecules efficiently. Fig. 8 shows the fraction of methane molecules as a function of potential energy in nanochannels. It is seen that the number of methane molecules with low potential energy decreases as the pressure of  $\text{CO}_2$  is increased, which reduces the energy barrier for methane molecules, as will be shown later, and consequently increase the release percentage of methane.

As mentioned previously, the release percentage of methane molecules can be theoretically predicted using  $E$  and  $\Delta G$ . Similar to the velocity, the kinetic energy of methane molecules follows the Maxwell–Boltzmann distribution,

$$f(E) = 2\sqrt{\frac{E}{\pi}} \left(\frac{1}{k_B T}\right)^{3/2} e^{\left(\frac{-E}{k_B T}\right)}, \quad (3)$$

where  $k_B$  is the Boltzmann constant. If the potential energy barrier in the quartz nanochannels is denoted as  $\Delta G$ , the release percentage can be theoretically predicted as

$$P^* = 1 - \int_0^{\Delta G} 2\sqrt{\frac{E}{\pi}} \left(\frac{1}{k_B T}\right)^{3/2} e^{\left(\frac{-E}{k_B T}\right)} dE \quad (4)$$

The results of eqn (4) is proportional to  $\exp(-\Delta G/k_B T)$ , i.e.,  $P^* \propto \exp(-\Delta G/k_B T)$ . As  $\Delta G$  is governed by the potential distribution inside the channels, and the potential  $U$  depends on the nature of atoms and position of molecules in the channels, the average potential  $U_{\text{avg}}(z)$  along the axis of the channels is employed to obtain  $\Delta G$ .  $U_{\text{avg}}(z)$  is calculated through

$$U_{\text{avg}}(z) = \frac{\iint_s U(x, y, z) e^{-\beta U(x, y, z)} ds}{\iint_s e^{-\beta U(x, y, z)} ds}, \quad (5)$$

where  $s$  is the area of adsorption site of methane molecules (for the cases without  $\text{CO}_2$  injection and at low  $\text{CO}_2$  pressures,  $s$  is the an interior surface next to the channel; at high  $\text{CO}_2$  injection pressures,  $s$  is the whole inner space of the channel, i.e.,  $r/R = 0\text{--}0.65$ , where  $R$  is the radius of channel) and  $\beta = 1/k_B T$ .  $\Delta G$  is calculated as the potential difference between the point where  $U_{\text{avg}}(z)$  is the highest and the point where  $U_{\text{avg}}(z)$  is the minimum.

Fig. 9 shows the potential energy barrier  $\Delta G$  for methane as a function of  $\text{CO}_2$  pressure in different nanochannels. It is seen that  $\Delta G$  in small-diameter channels is higher than that in large-diameter channels. This is why the release percentage in small channels is relatively low, as shown in Fig. 3. Furthermore,  $\Delta G$  decreases with increasing  $\text{CO}_2$  pressure due to the displacement of methane by  $\text{CO}_2$ . On the basis of the  $\Delta G$  values in Fig. 9, the

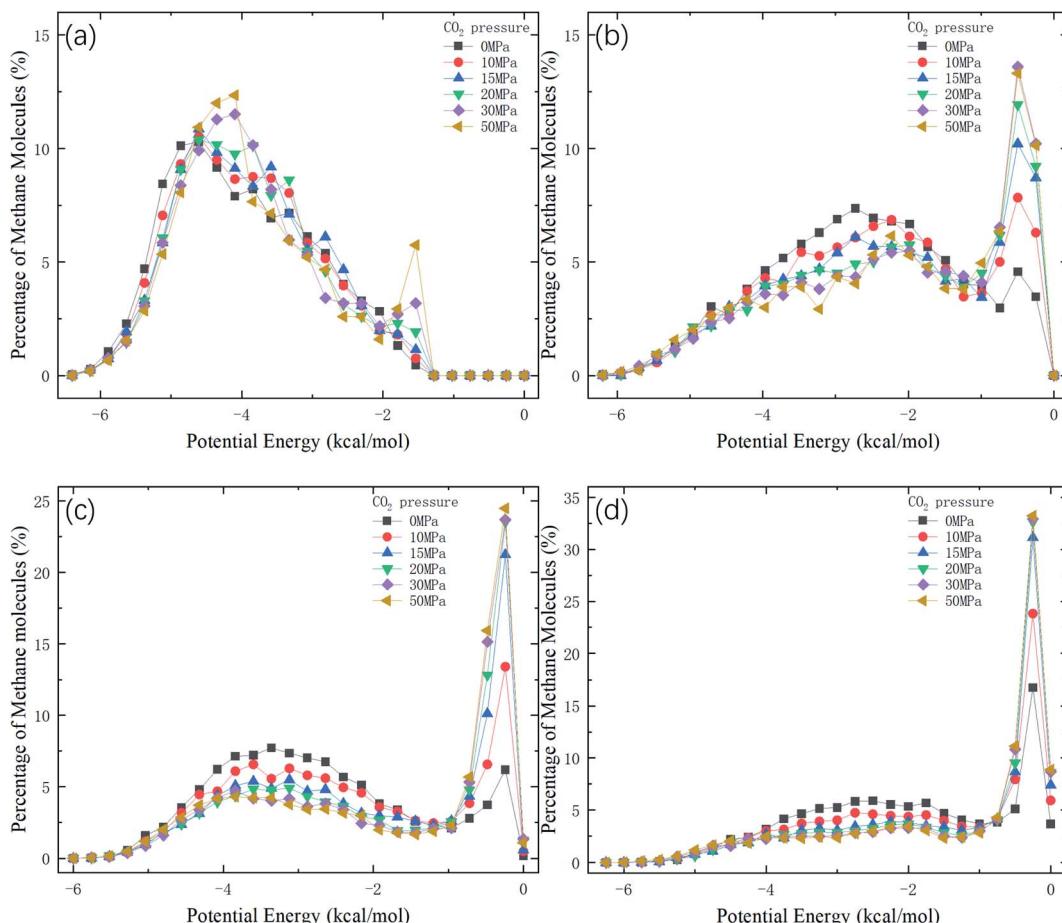
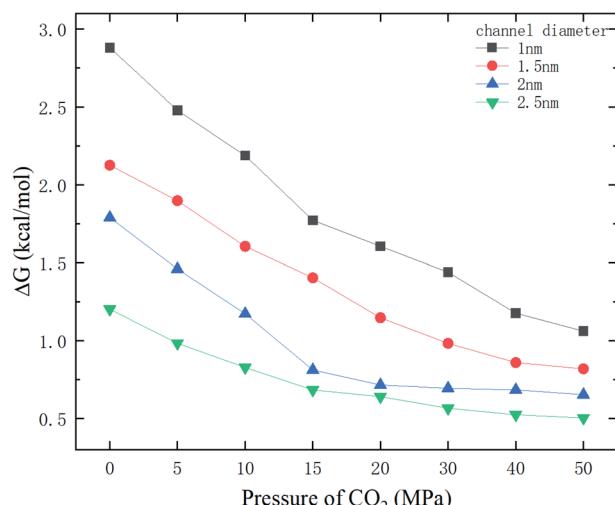


Fig. 8 Distribution of potential energy of methane in channels of different diameters  $D$ . (a)  $D = 1$  nm. (b)  $D = 1.5$  nm. (c)  $D = 2$  nm. (d)  $D = 2.5$  nm.



Fig. 9 Energy barrier  $\Delta G$  as a function of  $\text{CO}_2$  pressure.

release percentages predicted by eqn (4) are shown in Fig. 10. It is seen that the theoretical predictions are in good agreement with the MD results. The discrepancy is caused by the estimation of  $\Delta G$ , which is obtained using the average potential in the channels.

With the  $\Delta G$  data in Fig. 9, the variation of the release percentage in Fig. 3 can be explained. For a small-diameter nanochannel, when  $\text{CO}_2$  is injected into the channel,  $\text{CO}_2$  molecules occupy most of the space next to the channel wall and drive the methane molecules to the center area, which greatly reduces  $\Delta G$  and increases the release percentage of methane (Fig. 3). In large nanochannels,  $\Delta G$  is relatively small and is not sensitive to the  $\text{CO}_2$  pressure (Fig. 8). This is why the release percentage of methane is high, even at low  $\text{CO}_2$  pressures.

## 4. Conclusions

The displacement of methane molecules by carbon dioxide in nanochannels of different pore sizes has been studied through MD simulations. As the intermolecular interaction between carbon dioxide and the quartz nanochannel is stronger than the methane–channel interaction, some methane molecules are replaced by carbon dioxide molecules and expelled to the center area of the channel, where reduces the energy barrier for the transport of methane and consequently enhances the release percentage of methane. Theoretical predictions for the methane release percentage using the kinetic energy of methane and the energy barrier in the channel are also calculated, which are in good agreement with MD simulations.

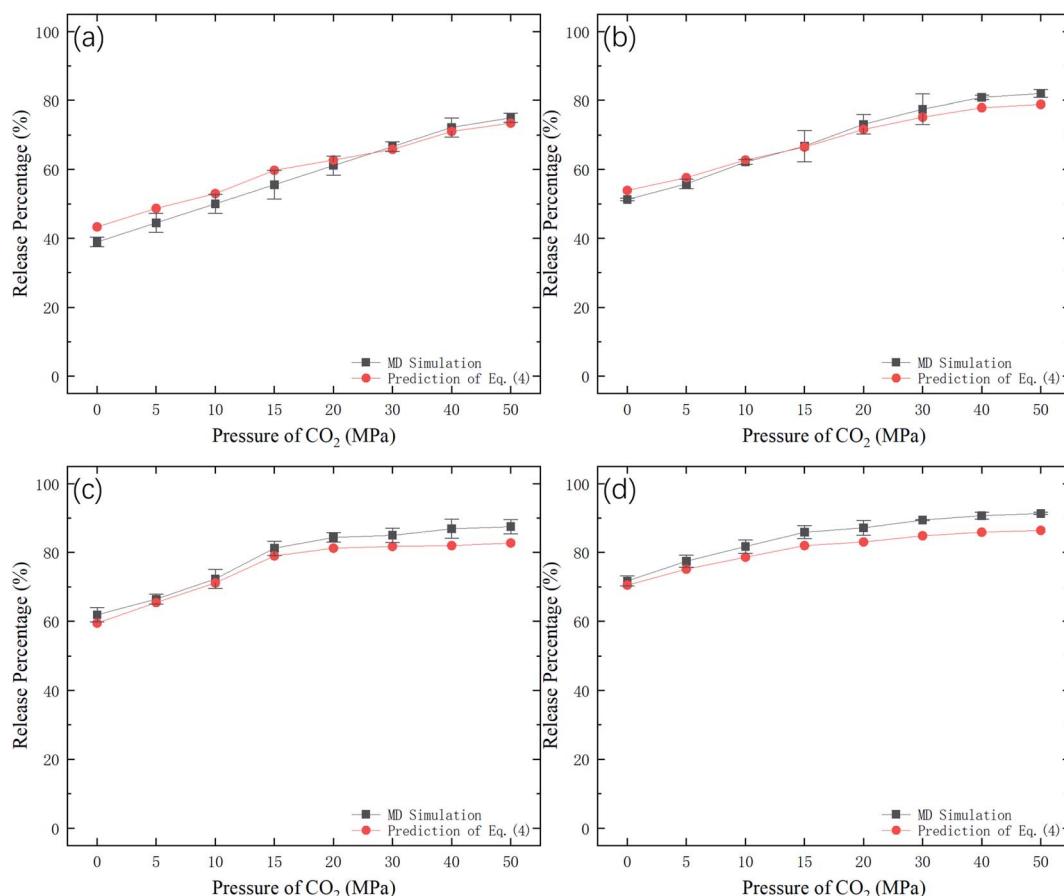


Fig. 10 Methane release percentage from MD simulations and theoretical predictions of eqn (4).



## Conflicts of interest

There are no conflicts of interest to declare.

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