Hydrate-Based Carbon Dioxide Capture Technology in the Ocean: Research Advances and Challenges

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Abstract. The urgent need for emission reduction due to climate change has spurred the development of carbon capture and storage (CCS) technologies, with carbon dioxide (CO₂) hydrates emerging as a promising option due to their high storage capacity and cost-effectiveness. This paper provides an overview of the characteristics and formation mechanisms of CO₂ hydrates, along with an exploration of mechanical and chemical methods to enhance CO₂ hydrate formation. Thermodynamic additives are beneficial for reducing the formation pressure of CO₂ hydrate, while mechanical methods and kinetic promoters play a positive role in improving kinetic parameters, especially when both are combined. To investigate the effectiveness of kinetic and thermodynamic promoters, this study explores the impact of various promoters on induction time, formation rate, phase equilibrium, and gas consumption. Additionally, the existing challenges of CO₂ hydrate method of CO₂ capture technology is expected to assume a crucial role in marine carbon capture technology.

Keywords: Carbon capture and storage; Hydrate-based CO₂ capture; Mechanical methods; Thermodynamic promotion; Kinetic promotion.

1. Introduction

Carbon capture and storage (CCS) is employed as a measure to mitigate climate change [1]. The carbon dioxide (CO₂) ocean storage technology utilizes the hydrate method for CO₂ storage due to its advantages, including stable seabed conditions, low fluid disturbance risk, and low leakage risk, ensuring long-term stable storage [2–4].

Mechanical methods like stirring, bubbling, and ultrasonic techniques enhance hydrate formation rates. Stirring and ultrasonic methods reduce gas induction time [5, 6], while bubbling enhances heat transfer and gas dissolution capacity, promoting gas hydrate formation [7].

For cost-effective applications, chemical promoters are widely used, including surfactants like sodium dodecyl sulfate (SDS) and dodecyl trimethylammonium chloride (DTAC)[8], improving CO₂ hydrate formation kinetics [9]. Additionally, porous media and amino acids can also promote the kinetic formation of CO₂ hydrate [10]. Currently, scholars have studied various thermodynamic promoters, including tetrahydrofuran (THF), cyclopentane (CP), propane (C₃H₈), and tetrabutylammonium bromide (TBAB). THF exhibits the most outstanding promoting effect [11]. The coexistence of THF and SDS results in shorter induction times and better CO₂ consumption [12]. Under conditions of 279~283K, TBAB and CP at freezing point 266.0K show good stability for hydrates [16]. Combining kinetic and thermodynamic promoters achieves complementary thermodynamics and kinetics [11].

In summary, as shown in Fig. 1, this paper provides a comprehensive exposition of the characteristics and formation mechanisms of CO_2 gas hydrates. It explores three CO_2 hydrate capture technologies, as well as the effects of thermodynamic and kinetic promoters on CO_2 hydrate formation. Finally, building on previous research, this paper identifies the challenges and future development prospects of CO_2 hydrate capture technology in the ocean, providing guidance for further improvement and application of carbon capture and storage technology.



Fig. 1 Contents graphic of aspects reviewed in this paper

2. CO₂ Hydrate





Fig. 2 Characteristics and configurations of gas hydrate crystal cages [15] Gas hydrates are crystalline inclusion compounds formed when small gas molecules (guests) are encapsulated within water molecules (hosts) held together by hydrogen bonds. These solid hydrates exist under specific conditions of low temperature and high pressure [16]. Fig. 2 shows the typical cages and structures of gas hydrates. The CO₂ hydrate formation is governed by two distinct structures: Structure I, suitable for small gas molecules like CO₂ and methane (CH4), and Structure II (SII), formed by larger molecules and suitable for larger gases like nitrogen (N₂) and C₃H₈ [17]. When CO₂ hydrate, a small non-polar hydrocarbon, interacts with water molecules at temperatures below the equilibrium temperature and above the equilibrium pressure, it gives rise to silica hydrates, denoted by the molecular formula CO₂ \cdot nH₂O (N145.75) [16].It belongs to Structure I and consists of 2 small cages and 6 large cages, composed of a total of 46 water molecules [11]. Upon dissociation, 1 m³ of CO₂ hydrate can release 175 m³ of CO₂ gas under standard temperature and pressure conditions.

2.2 Formation Mechanism



Dissolved Guest Blob Amorphous Clathrate Cry Fig. 3 Microscopic nucleation mechanism [20]

The nucleation and growth mechanism of CO₂ hydrates is similar to that of methane hydrates and other hydrocarbon gas hydrates. Under high pressure and low temperature conditions, critical nucleus formation initiates the nucleation process, continuously increasing [18]. Jacobson et al. [19] combined the theories of unstable cluster nucleation and localized structure nucleation, naming it the cluster nucleation theory. This theory proposes that the nucleation process is as shown in Figure 1. From Figure 1, it can be seen that gas molecules dissolved in water (Fig. 3a) aggregate into clusters of various sizes (Fig. 3b). Gas molecules dissolved in water aggregate into clusters of various sizes, then separate into primary complexes, which continuously nucleate, dissolve, and disappear until reaching the critical size to transform into amorphous hydrate nuclei (Fig. 3c), eventually developing into crystalline hydrate (Fig. 3d). Once hydrate nucleation occurs, it grows rapidly.

3. Hydrate-based CO₂ capture technology

3.1 Stirring



Fig.4 Effect of Different Stirring Speeds on CO₂ Hydrate. (a) effect on total mole fraction of CO₂[21] (b) effect on induction time [5].

Stirring, as a mechanical method, enhances gas dissolution in water by agitating the reactor, updating the gas-liquid interface, and facilitating prompt heat transfer during CO₂ hydrate formation. Studies by Li [5] and Linga [22] showed that gas-inducing agitated reactors effectively promote stable CO₂ hydrate formation through mechanical agitation, gas recycling during CO₂ dissolution and nucleation stages. Hassan et al. [21] investigated four stirring samples for CO₂ hydrate (CO₂·6H₂O) formation. As shown in Fig. 4(a), at 275 K and 36 bar, a maximum stirring speed of 7000 rpm (Method 4) resulted in absorbing about 3.9 millimoles of CO₂ gas per gram of H₂O. As depicted in Fig. 4(b), increasing stirring speed reduced the induction time from 261 minutes to 24 minutes, effectively shortening CO₂ hydrate nucleation time [5].

3.2 Bubbling



Fig. 5 Variations in CO₂ Concentration and gas consumption with bubble size and gas flow rate in the residual gas phase (a) change with bubble size (b) change with gas flow rate [23].

The bubbling method is used in a reaction vessel where gas is introduced through a bubble generator, initiating the hydrate reaction The hydrate shells on bubble surfaces act as barriers, preventing direct contact between guest molecules and the aqueous phase while hindering water permeation into the bubbles [24]. Xu et al. [31, 32] found that hydrate shells may hinder further formation inside the bubbles. To enhance CO₂ hydrate formation, Xu et al. [23] proposed using smaller bubbles and higher flow rates. As shown in Fig. 5, at 274.15 K, with a 50 mm bubble size and a gas flow rate of 6.75 ml/min/L, the optimal CO₂ concentration for gas consumption was achieved.

3.3 Ultrasound



Fig. 6 Gas consumption volume in case of 0 W and 150 W at a subcooling temperature of 0.5 K [26]

The generation process of CO₂ hydrates is influenced by ultrasound in two ways. Firstly, ultrasound induces cavitation bubbles, serving as nucleation points and increasing the probability of hydrate formation. Secondly, it enhances mass transfer, gas dissolution rate, and CO₂ solubility in water, leading to higher supersaturation, promoting hydrate nucleation, and reducing induction time [27]. Sun et al. [28], demonstrated that ultrasound facilitates significant CO₂ hydrate generation, with a pressure difference of approximately 0.8 MPa, and achieves optimal hydrate formation under subcooling temperature of 0.5 K and 150 W power, consuming four times more gas than at 0 W power condition [26]. Combining ultrasound with micro-nano bubbles can be a promising low-cost technology for rapid hydrate formation. Fig. 6 indicates that the amount of gas consumed at 150 W is four times higher than that observed under the 0 W power condition.

3.4 Kinetic Promoters

Table 1 Mavantageous effects of knette promoters on eog nyurate formation								
Promoter(s)	Con T _{eq} (K)	ditions P _{eq} (MPa)	Advantages of kinetic promoters	Ref				
SDS (1000, 1500 and 3000ppm)	277.15	3.5	Water conversion :90%Gas consumption: 85% (at 1500 ppm)	[31, 37]				
Polyurethane (PU) foam, C ₃ H ₈ (2.5 mol%)	274.2	6.0	 Water conversion: 54% Induction period: <3.67 min (at 6.0 MPa). The standardized rate of hydrate formation: 64.48 (±3.82) mol·min⁻¹·m⁻³ 	[31]				
Pumice	274	3.0	 Water conversion: 46 mol% The lower height of the pumice bed, the higher kinetics. 	[10]				
L-methionine (0.2 w t%)	273.2	3.3	 Weight capacity of CO₂ hydrate : 356 mg·g⁻¹ (within 1000 minutes) 	[32]				
L-tryptophan (300ppm)	273.65	3.4	 Water conversion: 78%. 275.65K showed shorter induction times and better gas absorption. 	[33]				
	s		Gas budratos					

Table 1 Advantageous effects of kinetic promoters on CO₂ hydrate formation



Fig. 7 Gas hydrate process in the presence of SDS [34]

Dynamics promoter is mainly a surfactant, which can increase the hydration rate, but it itself does not participate in the formation of hydrates. In addition to surfactants, porous media and amino acids can also affect the kinetics of CO₂ hydrate formation. Table 1 summarizes the dynamic promoting effects of surfactant SDS, porous media, and amino acids in pure CO₂ systems.

Fig. 7 illustrates the gas hydrate process with SDS [34]. The hydrate kinetics are effectively improved by surfactants, reducing interfacial tension and gas diffusion resistance. Extensive SDS use may adversely affect the environment, causing pollution. In addition, porous structures enhance complete contact with dissolved CO₂, promoting gas hydrate formation intensely. Yang et al. [35] revealed that reducing the pore size of porous media makes CO₂ hydrate formation conditions more stringent, thus lowering the driving force. Hence, the utilization of porous media with appropriate pore and particle sizes can significantly enhance the kinetics of CO₂ hydrate formation. Porous media serve as alternative kinetic promoters, reducing energy consumption. Formed hydrates with amino acids typically exhibit porous properties. These channels transport mother solution via capillary suction through porous hydrate structure, enhancing gas-liquid contact and gas diffusion. Pandey et al. [36] and Handerval et al. [33] found hydrophobic amino acids to better promote gas hydrate kinetics than pure water and hydrophilic amino acids. L-lysine and L-tryptophan significantly promote CO₂ hydrate kinetics. Biodegradable amino acids are preferred kinetic promoters for gas hydrate-based applications due to their cleaning characteristics.

3.5 Thermodynamic Promoters

Table 2 Advan	ntageous effects of the	ermodynamic promoters on CO2 hydrate equilibriu	m
Promoter(s)	Conditions	Advantages of thermodynamic promoters	Ref

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	$T_{eq}(K)$	P _{eq} (MPa)		
THF (1.5 mol%)	274.15	1.5	 The THF concentration reduces the equilibrium pressure of CO₂ hydrates, the driving force decreases with increasing pressure. The lower pressure, the THF concentration more affects the formation. 	[37]
THF (5 mol%), SDS)(5, 100 and 500 ppm)	274.1	3.0	 P_{eq:} 3.0 → 0.9 MPa (5 mol% TBAB) Storage capacity: 121% (with 500-ppm SDS and 5 mol%-THF), 37% (with 500-ppm SDS0 	[38]
TBAB (0.29, 0.61, 3.6, 9.4 mol%)	279.3- 290.9	3.5-122	 Peq: 14.36 → 0.84 Mpa (0.29 mol% TBAB) No impact on the hydrate crystallization pressure. 	[39]
TBAB (0.3, 1.0, 1.5, 2.0, 3.0 mol%)	279.2	6.0	 Equilibrium temperature: 284.5 K (1.5 mol%), 278.5 K (0.3 mol%) The highest total gas consumption is at 0.3 mol%. The highest hydrate growth rate was in the 1.0 mol%. 	[40]
CP (5 vol%)	273.7- 275.3	3.06	 Reaching equilibrium pressure: 5 vol% Induction time: <0.2 hours Hydrate growth time: <2 hours 	[41]
CP (15 ml)	275.7	6.0	 Reducing the equilibrium pressure and temperature Gas uptake: 0.0338 moles/mole_{water} CO₂ Composition: 90.36 mol% 	[42]

At present, thermodynamic research mainly focuses on temperature and pressure parameters. In practical applications, pure CO_2 hydrates require high-pressure conditions. The thermodynamic promoters can adjust the formation conditions of CO_2 hydrates, which actively influence the formation of CO_2 hydrates by regulating their composition. Table 2 summarizes the effects of various thermodynamic promoting agents on the equilibrium and kinetic formation of CO_2 hydrates.

THF is extensively studied as a chemical additive in CO₂ hydrate capture technology, inducing the formation of SII hydrates in flue gas [43]. Increasing THF concentration significantly reduces fuel gas mixture hydrate equilibrium conditions [43], thus lowering hydrate formation pressure. However, excessively high THF concentrations may decrease the formation rate. What's more, CP can form SII hydrates, occupying large cages at temperatures near 280 K and atmospheric pressure [44]. CP/water emulsion significantly enhances hydrate formation rate [41]. Unlike THF, CO₂ hydrate formation with CP is independent of its concentration, possibly because CP is immiscible with water. Gas must diffuse through the CP layer to the water interface, posing challenges when scaling up the process. Tetrabutylammonium bromide (TBAB) consists of an environmentally friendly TBA+ ionic liquid. TBAB forms semi-clathrate (SC) hydrates, differing from other promoters [45]. At low TBAB concentrations, water arrangement at the gas-liquid interface hinders water molecule rearrangement. However, at high concentrations, as shown in Fig.8(a) [46], the additive's presence enhances the local hydrogen bonding network among water molecules, promoting CO₂ hydrate nucleation. Increasing TBAB concentration reduces equilibrium hydrate formation pressure and increases formation temperature, enhancing the effects of other cage-forming hydrate promoters like THF and CP [47].



Fig. 8 Promotion mechanism of CO2 hydrate nucleation[46]

4. Challenges and Prospects

By employing efficient thermodynamic promoters, it becomes possible to reduce the phase equilibrium pressure of CO₂ hydrates, thereby facilitating hydrate formation at lower pressures. However, low driving forces are unfavorable for mass transfer, and as dense hydrates form, mass transfer resistance increases. The use of kinetic promoting agents has not fully addressed this issue.

Currently, additives have limitations in promoting effects, and excessive use may cause irreversible harm to the environment. To deeply investigate the impact of additives, this work conduct research in the following three aspects. Firstly, emphasis should be placed on studying composite additives, exploring the combination of different kinetic promoting agents, the synergistic effects between thermodynamic and kinetic additives, and the influence of additive-field coupling. Secondly, it is imperative to acquire a profound comprehension of the promotion mechanisms exhibited by diverse additives in order to ascertain suitable enhancement strategies and achieve the desired promoting effects. Lastly, further exploration of environmentally friendly novel additives and their feasibility is needed.

5. Conclusion

This paper reviews the carbon capture technology of CO_2 gas based on the hydrate method in the ocean and focuses on discussing the promoting mechanisms of mechanical methods and chemical promoters for CO_2 hydrate formation. Firstly, this work provides an overview of the characteristics and formation mechanism of CO_2 hydrates. Secondly, this paper mainly explains the mechanical methods that promote CO_2 hydrate formation from the perspectives of induction time, gas consumption, and hydrate formation rate. This study explores the promoting mechanisms of different types of kinetic promoters and thermodynamic promoters for CO_2 hydrate formation from both kinetic and thermodynamic aspects. The carbon capture method based on CO_2 hydrates faces challenges, as promoting agents commonly used have high pollution risks, and mechanical methods have high energy consumption. By combining chemical and mechanical methods, the efficiency and economic benefits of hydrate formation can be improved.

In the future, this work proposes to develop environmentally friendly and efficient thermodynamic promoters for hydrates to accelerate the rate of CO_2 hydrate formation. Additionally, comprehensive and systematic research is needed to further evaluate the environmental impact and economic benefits of CO_2 hydrate technology to better promote the application and development of this technology.

References

- H. Wang et al. Molecular Dynamics of Carbon Sequestration via Forming CO2 Hydrate in a Marine Environment. Energy Fuels. Vol. 37 (2023). No. 13, p. 9309–9317.
- [2] J. Zheng, Z. R. Chong, M. F. Qureshi, et al. Carbon Dioxide Sequestration via Gas Hydrates: A Potential Pathway toward Decarbonization. Energy Fuels, Vol. 34 (2020). No. 9, p. 10529–10546.
- [3] J. Gabitto, D. Riestenberg, S. Lee, L. Liang, et al. Ocean Disposal of CO 2 : Conditions for Producing Sinking CO2 Hydrate. J. Dispers. Sci. Technol. Vol. 25 (2005). No. 5, p. 703–712.
- [4] P. G. Brewer, G. Friederich, E. T. Peltzer, and F. M. Orr. Direct Experiments on the Ocean Disposal of Fossil Fuel CO2.Science, Vol. 284, No. 5416, p. 943–945, May 1999
- [5] A. Li, L. Jiang, and S. Tang. An experimental study on carbon dioxide hydrate formation using a gasinducing agitated reactor. Energy, Vol. 134, p. 629–637, Sep. 2017
- [6] H. J. Hong, C. H. Ko, M. H. Song, S. Lee, and K. Seong, "Effect of ultrasonic waves on dissociation kinetics of tetrafluoroethane (CH2FCF3) hydrate.J. Ind. Eng. Chem. Vol. 41, p. 183–189, Sep. 2016
- [7] D. Myre and A. Macchi. Heat transfer and bubble dynamics in a three-phase inverse fluidized bed. Chem. Eng. Process. Process Intensif. Vol. 49, No. 5, p. 523–529, May 2010
- [8] A. K. Sum, C. A. Koh, and E. D. Sloan. Clathrate Hydrates: From Laboratory Science to Engineering Practice. Ind. Eng. Chem. Res. Vol. 48, No. 16, p. 7457–7465, Aug. 2009

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- [9] A. Kumar, G. Bhattacharjee, V. Barmecha, S. Diwan, and O. S. Kushwaha, "Influence of kinetic and thermodynamic promoters on post-combustion carbon dioxide capture through gas hydrate crystallization. J. Environ. Chem. Eng., Vol. 4, No. 2, p. 1955–1961, Jun. 2016
- [10] G. Bhattacharjee, A. Kumar, T. Sakpal, and R. Kumar, "Carbon Dioxide Sequestration: Influence of Porous Media on Hydrate Formation Kinetics. ACS Sustain. Chem. Eng., Vol. 3, No. 6, p. 1205–1214, Jun. 2015
- [11] Q. Hu and X. Xiao, "Formation methods and applications of carbon dioxide hydrate: An overview. Carbon Capture Sci. Technol., Vol. 7, p. 100113, Jun. 2023
- [12] N. Xu, Y. Liu, Z. Cheng, S. Wang, L. Jiang, and Y. Song, "Morphology-Based Kinetic Study of the Formation of Carbon Dioxide Hydrates with Promoters. Energy Fuels, Vol. 34, No. 6, p. 7307–7315, Jun. 2020
- [13] W. Lin, A. Delahaye, and L. Fournaison, "Phase equilibrium and dissociation enthalpy for semi-clathrate hydrate of CO2+TBAB," Fluid Phase Equilibria, Vol. 264, No. 1, p. 220–227, Mar. 2008,
- [14] P. Warrier, M. Naveed Khan, M. A. Carreon, C. J. Peters, and C. A. Koh, "Integrated gas hydratemembrane system for natural gas purification. J. Renew. Sustain. Energy, Vol. 10, No. 3, p. 034701, May 2018
- [15] E. D. S. Jr and C. A. Koh, Clathrate Hydrates of Natural Gases. CRC Press, 2007.
- [16] "Crystallographic Studies of Clathrate Hydrates. Part I: Molecular Crystals and Liquid Crystals: Vol 141 (2023), No. 1-2.
- [17] P. Linga, N. Daraboina, J. A. Ripmeester, and P. Englezos, "Enhanced rate of gas hydrate formation in a fixed bed column filled with sand compared to a stirred vessel. Chem. Eng. Sci., Vol. 68, No. 1, p. 617– 623, Jan. 2012
- [18] L. C. Jacobson, W. Hujo, and V. Molinero, "Amorphous Precursors in the Nucleation of Clathrate Hydrates. J. Am. Chem. Soc., Vol. 132, No. 33, p. 11806–11811, Aug. 2010
- [19] L. C. Jacobson, W. Hujo, and V. Molinero, "Nucleation Pathways of Clathrate Hydrates: Effect of Guest Size and Solubility. J. Phys. Chem. B, Vol. 114, No. 43, p. 13796–13807, Nov. 2010
- [20] M. H. A. Hassan et al., "Hydrothermally engineered enhanced hydrate formation for potential CO2 capture applications. J. Environ. Chem. Eng., Vol. 9, No. 6, p. 106515, Dec. 2021
- [21] P. Linga, R. Kumar, J. D. Lee, J. Ripmeester, and P. Englezos, "A new apparatus to enhance the rate of gas hydrate formation: Application to capture of carbon dioxide. Int. J. Greenh. Gas Control, Vol. 4, No. 4, p. 630–637, Jul. 2010
- [22] C.-G. Xu, X.-S. Li, Q.-N. Lv, Z.-Y. Chen, and J. Cai. Hydrate-based CO2 (carbon dioxide) capture from IGCC (integrated gasification combined cycle) synthesis gas using bubble method with a set of visual equipment. Energy, Vol. 44, No. 1, p. 358–366, Aug. 2012
- [23] Y. H. Mori, "Clathrate hydrate formation at the interface between liquid CO2 and water phases—a review of rival models characterizing 'hydrate films. Energy Convers. Manag., Vol. 39, No. 15, p. 1537–1557, Oct. 1998
- [24] C.-G. Xu, J. Cai, X.-S. Li, Q.-N. Lv, Z.-Y. Chen, and H.-W. Deng, "Integrated Process Study on Hydrate-Based Carbon Dioxide Separation from Integrated Gasification Combined Cycle (IGCC) Synthesis Gas in Scaled-Up Equipment. Energy Fuels, Vol. 26, No. 10, p. 6442–6448, Oct. 2012,
- [25] S.-S. Park and N.-J. Kim, "Study on methane hydrate formation using ultrasonic waves. J. Ind. Eng. Chem., Vol. 19, No. 5, p. 1668–1672, Sep. 2013
- [26] S. Devarakonda, J. M. B. Evans, and A. S. Myerson, "Impact of Ultrasonic Energy on the Flow Crystallization of Dextrose Monohydrate," Cryst. Growth Des., Vol. 4, No. 4, p. 687–690, Jul. 2004,
- [27] Shicai Sun, Yang Zhendong, and Gu Linlin, "Effects of ultrasonic on CO2 hydrate formation," Sci. Eng., Vol. 22, No. 2, p. 628–634, 2022.
- [28] N. S. Molokitina, A. N. Nesterov, L. S. Podenko, and A. M. Reshetnikov, "Carbon dioxide hydrate formation with SDS: Further insights into mechanism of gas hydrate growth in the presence of surfactant," Fuel, Vol. 235, p. 1400–1411, Jan. 2019

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- [29] X.-Y. Deng, Y. Yang, D.-L. Zhong, X.-Y. Li, B.-B. Ge, and J. Yan, "New Insights into the Kinetics and Morphology of CO2 Hydrate Formation in the Presence of Sodium Dodecyl Sulfate," Energy Fuels, Vol. 35, No. 17, p. 13877–13888, Sep. 2021
- [30] P. Babu, R. Kumar, and P. Linga, "A New Porous Material to Enhance the Kinetics of Clathrate Process: Application to Precombustion Carbon Dioxide Capture," Environ. Sci. Technol., Vol. 47, No. 22, p. 13191–13198, Nov. 2013
- [31] Y. Cai et al., "CO2 Hydrate Formation Promoted by a Natural Amino Acid I-Methionine for Possible Application to CO2 Capture and Storage," Energy Technol., Vol. 5, No. 8, p. 1195–1199, 2017
- [32] H. Khandelwal et al., "Effect of l-Tryptophan in Promoting the Kinetics of Carbon Dioxide Hydrate Formation," Energy Fuels, Dec. 2020
- [33] H. Dashti, L. Zhehao Yew, and X. Lou, "Recent advances in gas hydrate-based CO2 capture," J. Nat. Gas Sci. Eng., Vol. 23, p. 195–207, Mar. 2015
- [34] M. Yang, Y. Song, X. Ruan, Y. Liu, J. Zhao, and Q. Li, "Characteristics of CO2 Hydrate Formation and Dissociation in Glass Beads and Silica Gel," Energies, Vol. 5, No. 4, Art. No. 4, Apr. 2012
- [35] J. S. Pandey, Y. J. Daas, and N. von Solms, "Screening of Amino Acids and Surfactant as Hydrate Promoter for CO2 Capture from Flue Gas," Processes, Vol. 8, No. 1, Art. No. 1, Jan. 2020
- [36] S. Kim, S. H. Lee, and Y. T. Kang, "Characteristics of CO2 hydrate formation/dissociation in H2O + THF aqueous solution and estimation of CO2 emission reduction by district cooling application," Energy, Vol. 120, p. 362–373, Feb. 2017
- [37] C. F. D. S. Lirio, F. L. P. Pessoa, and A. M. C. Uller, "Storage capacity of carbon dioxide hydrates in the presence of sodium dodecyl sulfate (SDS) and tetrahydrofuran (THF)," Chem. Eng. Sci., Vol. 96, p. 118– 123, Jun. 2013
- [38] N. H. Duc, F. Chauvy, and J.-M. Herri, "CO2 capture by hydrate crystallization A potential solution for gas emission of steelmaking industry," Energy Convers. Manag., Vol. 48, No. 4, p. 1313–1322, Apr. 2007
- [39] P. Babu, W. I. Chin, R. Kumar, and P. Linga, "Systematic Evaluation of Tetra- n -butyl Ammonium Bromide (TBAB) for Carbon Dioxide Capture Employing the Clathrate Process," Ind. Eng. Chem. Res.Vol. 53, No. 12, p. 4878–4887, Mar. 2014
- [40] J. Zhang and J. W. Lee, "Enhanced Kinetics of CO2 Hydrate Formation under Static Conditions," Ind. Eng. Chem. Res. Vol. 48, No. 13, p. 5934–5942, Jul. 2009
- [41] L. C. Ho, P. Babu, R. Kumar, and P. Linga, "HBGS (hydrate based gas separation) process for carbon dioxide capture employing an unstirred reactor with cyclopentane," Energy, Vol. 63, p. 252–259, Dec. 2013
- [42] S. Park, S. Lee, Y. Lee, Y. Lee, and Y. Seo, "Hydrate-based pre-combustion capture of carbon dioxide in the presence of a thermodynamic promoter and porous silica gels," Int. J. Greenh. Gas Control, Vol. 14, p. 193–199, May 2013
- [43] E. D. S. Jr and C. A. Koh, Clathrate Hydrates of Natural Gases. CRC Press, 2007.
- [44] D. L. Fowler, W. V. Loebenstein, D. B. Pall, and C. A. Kraus, "Some Unusual Hydrates of Quaternary Ammonium Salts," J. Am. Chem. Soc., Vol. 62, No. 5, p. 1140–1142, May 1940
- [45] F.-P. Liu, A.-R. Li, S.-L. Qing, Z.-D. Luo, and Y.-L. Ma, "Formation kinetics, mechanism of CO2 hydrate and its applications," Renew. Sustain. Energy Rev. Vol. 159, p. 112221, May 2022
- [46] P. Meysel, L. Oellrich, P. Raj Bishnoi, and M. A. Clarke, "Experimental investigation of incipient equilibrium conditions for the formation of semi-clathrate hydrates from quaternary mixtures of (CO2+N2+TBAB+H2O)," J. Chem. Thermodyn. Vol. 43 (2011). No. 10, p. 1475–1479.