Petroleum Science 23 (2026) 3374–3383

Contents lists available at ScienceDirect

Petroleum Science

journal homepage: www.keaipublishing.com/en/journals/petroleum-science

Original Paper

Preparation and performance evaluation of phase change material microcapsules for smart regulation of drilling fluid temperature for marine gas hydrate reservoirs

Xin Zhao [a,b,*], Xiao-Long Zhang [a], Wen-Tuo Li [c], Yu-Jie Kang [a], Qi Geng [a,d], Zheng-Song Qiu [a], Zhi-Yuan Wang [a,b]

[a] School of Petroleum Engineering, China University of Petroleum (East China), Qingdao, 266580, Shandong, China
[b] Shandong Key Laboratory of Offshore Oil & Gas and Hydrates Development, China University of Petroleum (East China), Qingdao, 266580, Shandong, China
[c] CNOOC China Limited, Hainan Branch, Haikou, 570100, Hainan, China
[d] Oilfield Production Department, China Oilfield Services Limited, Tianjin, 300459, China

ARTICLE INFO

Article history:
Received 4 March 2025
Received in revised form
2 March 2026
Accepted 3 March 2026
Available online 6 March 2026

Edited by Jia-Jia Fei

Keywords:
Hydrate decomposition
Hydrate regeneration
Microcapsule
Drilling fluid
Binary composite PCM
Cold storage

ABSTRACT

In the drilling process of hydrates, hydrate decomposition and regeneration can cause wellbore collapse and plugging. Herein, phase change materials (PCMs) were introduced into the drilling fluids to regulate their temperature for controlling hydrate decomposition. The binary composite PCM and polymethyl methacrylate (PMMA) were used to prepare PCM microcapsules (PCMMs) by suspension polymerization. Basic characteristics of PCMM were studied, and its temperature-regulating effect, inhibitory performance on hydrate decomposition and regeneration, strength, and compatibility with drilling fluids were systematically investigated. The phase change temperature of the binary composite PCM could be regulated from 16 to 20 °C through the optimization of the ratio of dodecanol and fatty alcohol. When the ratio of dodecanol was 90%, the phase change temperature of PCMMs was 18 °C with the enthalpy of 93.9 $J \cdot g^{-1}$. In the heating process from 16 to 22 °C, 5% and 8% PCMM could smartly cool down the suspension through phase change energy storage to prolong the temperature rise time by 40% and 74%, respectively. Under the condition that the fluid temperature is from 2 °C around the seafloor to 25 °C at the bottom of the well in a simulation drilling process, in the heating period, 8% PCMM demonstrated superior efficacy compared to lecithin in prolonging the hydrate decomposition time by its cold release effect. In addition, the decrease in drilling fluid temperature was also hindered by the cold storage effect during the cooling stage, and the hydrate regeneration time was prolonged by 52.1%. Therefore, PCMM can reduce the risk of wellbore instability and plugging caused by hydrate decomposition and regeneration. Meanwhile, PCMMs exhibited good shearing strength and sealing property under alkaline conditions of drilling fluids and showed relatively minor impacts on the basic drilling fluid properties with a concentration of no more than 8%. This study offers a new method to maintain the safety of the hydrate drilling wellbore.

© 2026 The Authors. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Gas hydrates are the potential candidate for the future clean energy resources because of their global abundance and high energy density. Worldwide, more than 90% of the hydrates are found in deep-sea sediments (Li et al., 2022; Sun et al., 2023). However, the drilling operation can change the stress conditions of the formation, and the drill bit cutting rocks and the friction between drill tool and borehole wall generate a large amount of heat, consequently, the hydrates bearing in the sediments undergo decomposition (Yang et al., 2015; Li et al., 2021). The presence of water and the substantial volume of gas released from the hydrate decomposition led to the increase in the pore pressure and reduction in the formation strength, causing wellbore instability. Moreover, natural gas produced from the hydrate decomposition shows the potential to reconstitute hydrate within the low-temperature drilling fluid,

* Corresponding author.
E-mail address: zhaoxin@upc.edu.cn (X. Zhao).
Peer review under the responsibility of China University of Petroleum (Beijing).

https://doi.org/10.1016/j.petsci.2026.03.005
1995-8226/© 2026 The Authors. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

causing flow barriers (Yang et al., 2019; Zhao et al., 2024; Phan et al., 2025; Li et al., 2025). Therefore, hydrate decomposition is one of the significant technical problems for drilling in hydrate sediments (Wei et al., 2019; Zhang et al., 2022).

During the hydrate drilling process, the drilling fluid directly interacts with the hydrate, and the direct method to restrain the hydrate decomposition is to lower the drilling fluid temperature (Dong et al., 2023; Zhao et al., 2023). The ideal approach involves the implementation of a real-time control of the drilling fluid temperature in the entire drilling process. To achieve this, the key is to explore smart temperature-control additives for hydrate drilling conditions.

Phase change material (PCM) is a type of material that uses latent heat to store, transform, and utilize heat (Xu et al., 2018; Liu et al., 2024), thus, it shows potential application in the domains of air conditioning and refrigeration, refrigerated transportation, smart temperature-adjusting textiles, and building energy conservation (Yan et al., 2005; Shi et al., 2022; Liu et al., 2025). In the presence of PCM, a liquid–solid phase change occurs when the drilling fluid circulates in the wellbore, which is cooled down by the seawater. Once the fluid temperature increases to the phase change temperature of PCM in the wellbore, the PCM gets converted from the solid state to the liquid state to release cold energy (heat storage), and the drilling fluid cools down to slow down the temperature rise, thus inhibiting the hydrate decomposition. The temperature of the drilling fluid drops when it is circulated to the cold seawater well part, and the low-temperature condition raises the possibility of hydrate formation and regeneration in the borehole. As soon as the temperature drops to the PCM's phase change temperature, it changes from liquid to solid state releasing heat (cold storage). It can then heat the cold drilling fluid in the wellbore, raise its temperature, and prevent the hydrate formation and regeneration. This provides a new potential solution to address the drawbacks of traditional thermodynamic hydrate inhibitors (THIs) and kinetic hydrate inhibitors (KHIs).

As is well known, current deepwater drilling fluids rely on the addition of THIs to suppress hydrate formation, typically sodium chloride, methanol, and ethylene glycol. The concentration of thermodynamic inhibitors is very high, usually ranging from 10% to 50%, which comes with disadvantages such as high costs, environmental unfriendliness, and negative impacts on drilling fluid performance. Particularly when drilling in natural gas hydrate formations, high concentrations of THIs can [illegible]

6 7 L C
6 7 %
: 4((
C 6 6 6
7

: . : =

2 C 8L 19
8%2%8 (B
3 4 7 7 (8((-9
6 % -
3 4 7 7 -: 8-53L9
A 6 % 4 &
4 7 7 8 49 6 C
3 4 7 7

: : =

: : . : >$ $))
3 H
% 4 %
6 ; > 4
6 C
4(6
7 3
6 H
/H 7 8;9 8)9 6
4(8 7
; <<+97
6
4(7 6 H
: 7 0 6 C
6 6 C 6
++ 4 ; 7 L C C 6
'*
C 7 0 C 6
6 4(7

0 ^ ' 0 8;9
' 0 ? @

X @
' ^ 0 8)9
0
^ 5<

6 0
4(8 49 '
4(8!F 9 0 5
+ 8 49 ' 5
+ 8!F 9 ? 8>7; ' !F8 "99 @
5 + 8@ ‡ @^ ;97

: : : $))

8;9 %

4(6
6
6 B)+ 4 6 6
7 6 H B B
> 4

6 7 -
6
7 2 6
4(:
C 4(
6 6 6
6 : 7

8)9 2

2 82%49 6 :
4(
) ; ' 7 6
6 .+ ; 6 ; *
.* 4) 4 ; 7

8.9 4

4(6
)+ > 4
6)* 7 A 6
6 6
6 6
: 7

: :2:) ==
% : 6
4((: ((- 6 4(
6 0 7) 7 6 E
8;9 + 6 ((-
6 6 B 7
-53L B
6 C 6 J
7 8)9 - A
: 6 6 6 H A
6 7 6 6 6
)* * * ; 7 8.9 L C
6 B B 6 6
6 6 6
B7 - 6
6 6 6 A
4((7

: :3: A ==
- L C >?* 0 80 5&9
6 5& 7 - %@>;**
8%/(9 6 :
3 :)* * *
: : 6
: 7

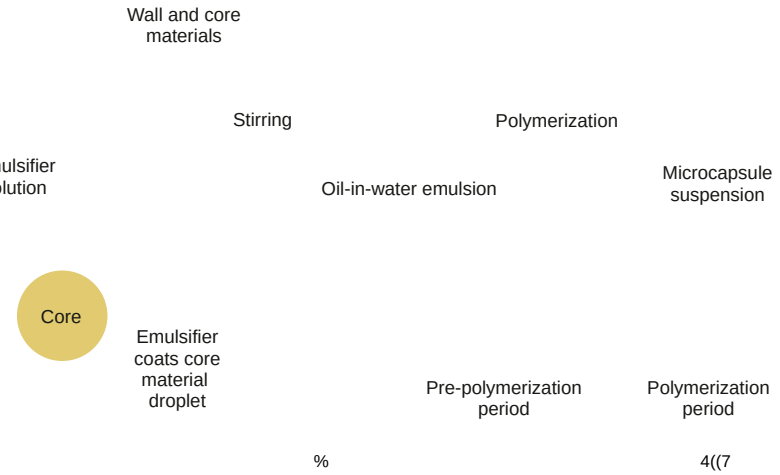
: : : ==

8;9

0 : 4((
2%46
; *
.* 47

8)9

-H 4 8*7=9 6 4((
8*= += >= 9 6 7
; +)+ 4 6



% 4((7

H 6 6 8(9 0 8"9 B
7 L C 8 ¦9 ?
6 0 7
7 0 $
7
8.9 1
8'9 %

3 C 6 L 1 6 1
8 7)* ; <9 ? ; * ; ; ;) .*
6 8 7)*)+ 9 8)* * *
4(6 : 7 '* ** ,* ** >*** ; * * * * ¦974((6 6
4 6 A
8*7=9 4 8*7=9 6 8*7+=9 4 6 6 7 - /H78'9
8*7=9 6 4((8>=96 : 7 6 6
C 6 E %2% 8 E :
*7**)+=9 6 J :
6) 4 6 7
;) (J
B 6 7 ^ ___(;**= 8'9
:
6 6 6 4((8=9 (
6 7 6 A 4((8 9
) 4 6 B 8=97 4((6
7 6 6)+ 4
B H 6
7 - . 6 7
6) 47

8+9%
6 7 - ; * 3
6 B 6 B
C 7 3 A 6 6 :
B & H 8/H78.99 7- 4((6 L 1
8 7)* ; <96 6 1 ? ; * ; ; ;)
C 6 7 L C 6
4((6 8)* * ¦9 ; . ? ; + 70
6 : 7 6 6 A 6 7
6 6
^ ?0 .0† 8.9
B $ B .B ‡ $†‡ $.B $†

B 7 0
6 /H78'9 6
7

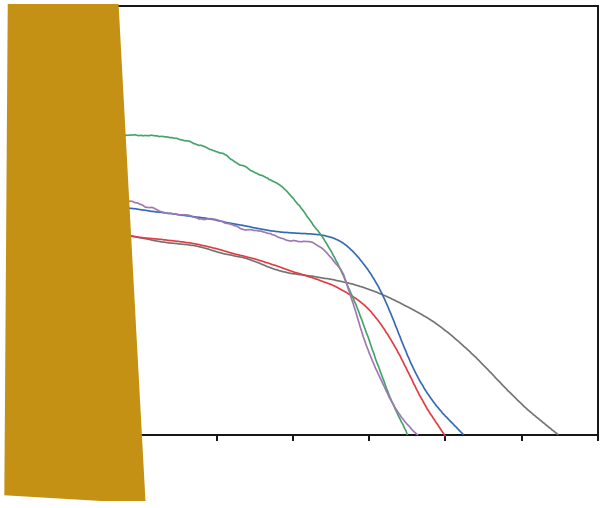
8,9 /

C C 6 4((
A
7 A 6)+
) 4 6 += >= 4((
7

2:.. : @))) $
) =

2:.. :.. :)8
C 4(6
7
4(6
6 0 7 . ' 7 A
6 4(
A 7 4
H 4(; > 4 6
?>= <*=
6 ; ?7, 4 6
H 7 1 6
G 4(6 <*=
6 7

2:.. : : (
0 7 + 2%4 4(6
6 <*=7 <*=
; ?7> 4 6
6
% .7; 7 7 B ; <7, 4
; >)7) ! ; 7 (2%4 6
B
4(6
<*= 6
6 7



% 4(6 7

4(6
7

2%4 4(6 <*=7

2:.. :2: $
4(6
)* 6
0 7 , 7 C
4(6
)* 7
4(
6 6
7

2: : A ==

2: : . : =)) A $
0 7 ? > 6 %/(:
4((7 0 7 ?8 9
6
6 7 0 7 ?8 9 6 6
6
6
7 -

of the core material presented in Section 3.1.2. The peak temperature of phase change is 19.9 °C, that is, the core material begins to melt when the drilling fluid temperature exceeds 18 °C, and gradually releases cold energy to play a role in cooling, so as to avoid or delay the fluid temperature rise to the hydrate decomposition temperature. The enthalpy value of phase change is high, that is 93.9 $J \cdot g^{-1}$, which can ensure good phase change temperature control efficiency.

3.3.2. Phase change temperature control performance

Fig. 11 shows the temperature-time curve during the heating process with 0.1% XC solution and added 5% and 8% phase change microcapsules, respectively. The starting test solution temperature was fixed at 16 °C, and the test solution temperature required 53 min to increase from 16 to 22 °C without adding microcapsules. After the addition of PCMM, the suspension shows an obvious temperature step at 18–20 °C because of the release of cold energy during its phase change. Moreover, the time for the suspension to heat up to 22 °C extends to 74 and 92 min by using 5% and 8% PCMM, respectively, that is, the heating time is respectively prolonged by 40% and 74%. The results show that the PCMM can significantly delay the temperature rise of the suspension through phase change.

3.3.3. Hydrate decomposition and regeneration inhibition performance

During hydrate drilling, the fluid temperature rise causes hydrate decomposition, and the time for the produced gas and water to regenerate hydrate is shorter than that for the first generation of hydrate, which is called "Memory Effect" (Parent and Bishnoi, 1996; Takeya et al., 2000). Therefore, the gas generated by hydrate decomposition is more likely to again produce hydrate in the wellbore, resulting in wellbore plugging. Fig. 12 shows a graph comparing pressure, temperature, during hydrate decomposition and regeneration in a 0.1% XC solution, 0.1% XC solution with 0.5% lecithin, and a 0.1% XC solution with 8% PCMM.

As illustrated in Fig. 12(a–c), during the heating phase, compared to the 0.1% XC solution, the addition of 0.5% lecithin to the 0.1% XC solution extended the hydrate decomposition time from 2.5 to 2.8 h. Under identical conditions, PCMM further prolonged the decomposition time from 2.5 to 3.0 h. Mechanistically, lecithin inhibited hydrate dissociation by adsorbing onto the hydrate surface via its choline groups and methyl-functionalized

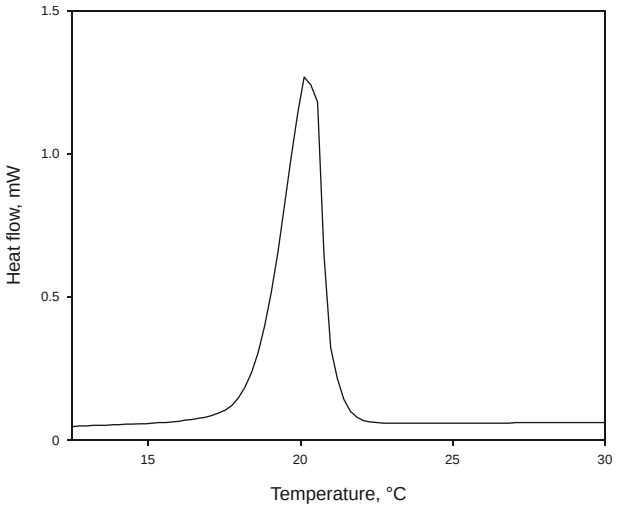


Fig. 10. DSC curve of PCMM.

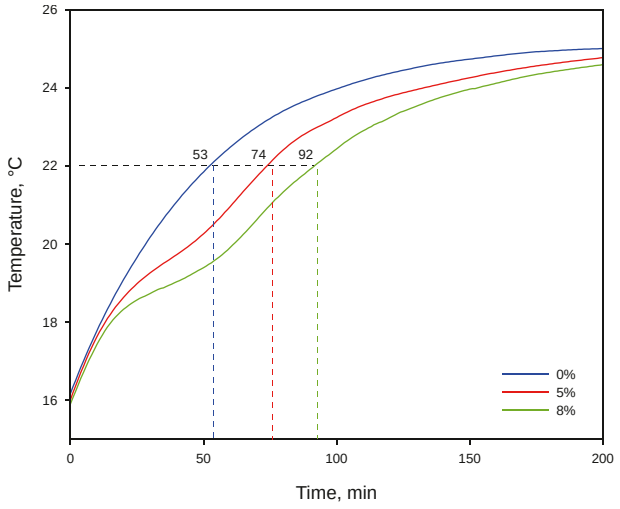


Fig. 11. Temperature-time curves of PCMM suspension.

fatty acid chains. This adsorption delays heat transfer, mitigates structural disruption of the hydrate clathrate framework, and prevents methane escape (Chen et al., 2025). Compared to lecithin, PCMM suppressed hydrate decomposition by delaying the temperature rise in the autoclave through its phase-change cooling effect. Fig. 13 exhibits a temperature comparison curve of the hydrate decomposition and regeneration processes in the three groups of samples, and Fig. 14 presents a comparative analysis of methane release or consumption using the Peng-Robinson equation. Fig. 13 indicates that lecithin did not alter the temperature in the autoclave, resulting in a temperature profile that nearly overlaps with that of the 0.1% XC solution. In comparison, the phase-change cooling effect of the PCMM extended the time required for the system to heat up from the initial temperature to 25 °C by 0.5 h (from 2.3 to 2.8 h). Fig. 14 demonstrates that lecithin reduced the maximum instantaneous methane release from hydrate decomposition by 0.15 mol at the same time point, while the PCMM achieved a significantly higher reduction of 0.39 mol due to its phase-change cooling effect.

Notably, during the cooling phase, compared to the 0.1% XC solution, lecithin shortened the hydrate formation time from 4.8 to 4.4 h, failing to exhibit inhibition effects and even promoting hydrate reformation, thereby increasing the risk of blockages. In contrast, PCMM extended the time required for the system to cool from 25 °C to the same temperature by 0.7 h (from 4.9 to 5.6 h) through its phase-change cold storage capacity. Additionally, PCMM prolonged the hydrate formation time from 4.8 to 7.3 h and reduced the maximum instantaneous methane consumption for hydrate formation by 0.4 mol at the same time. Thus, PCMM demonstrates superior efficacy in inhibiting hydrate generation compared to lecithin.

The effect of PCMM on inhibiting hydrate regeneration in the cooling stage is more obvious than the effect on inhibiting hydrate decomposition in the heating stage. Notably, when the microcapsules release heat during phase change, they may cause the residual methane dissolved in water produced during hydrate decomposition to be released. These bubbles remaining in the water produced by hydrate decomposition are an important reason for shortening the induction period of hydrate regeneration (Uchida et al., 2016; Zhang et al., 2018). Therefore, the "Memory Effect" of secondary formation of hydrate gets weakened, and the induction period of secondary formation of hydrate is prolonged. Moreover, Fig. 12(a–c) clearly reveal that the pressure drop is

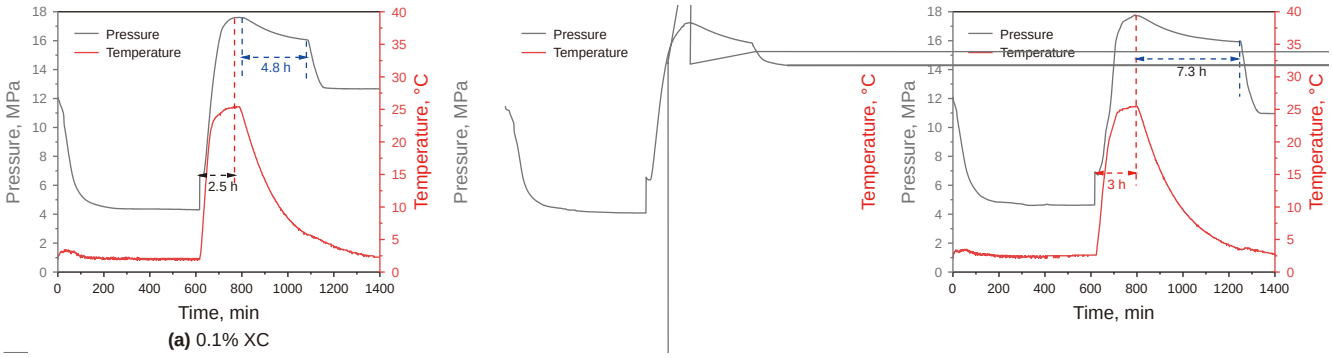


Fig. 12. Comparison curves of temperature, pressure in the course of hydrate decomposition and regeneration when injecting different test solutions.

Fig. 13. Comparison curves of temperature in the course of hydrate decomposition and regeneration when injecting different test solutions.

Fig. 14. Comparison curves of methane release or consumption in the course of hydrate decomposition and regeneration when injecting different test solutions.

divided into two stages after the temperature drop starts at 800 min. The pressure drop in the first stage may be caused by the re-dissolution of methane released by hydrate decomposition in water (mainly water produced by hydrate decomposition). Compared with Fig. 14, it is observed that no hydrate is produced during the first stage, while decrease in the autoclave pressure during the second phase is caused by the formation of copious hydrate.

The above-mentioned experimental results indicate that the PCMM prepared in this study exhibits good performance of inhibiting hydrate decomposition and regeneration, which is conducive to reducing the risk of wellbore instability caused by hydrate decomposition and wellbore plugging caused by hydrate regeneration in marine natural gas hydrate drilling.

3.3.4. *Strength of microcapsule wall material*

(1) Shear resistance

Fig. 15 shows the PCMM breakage rate at various centrifugal shear rates in different pH environments. The results show that the wall materials of some PCMMs were broken by high-speed stirring and shearing, and the breakage rate of PCMM increased with increasing shear rate. At 10,000 r·min^{-1}, the breakage rate was 8%, and the PCMM exhibited good shear strength. Notably, as the pH increased, the mass loss curves of PCMMs showed negligible deviation from those at a pH value of 7, demonstrating that PCMMs maintain excellent shear resistance under alkaline conditions of drilling fluids, even at a pH value of 12.

Fig. 15. Damage rate of PCMM at different shear rate.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the Oil & Gas Major Project of China (2025ZD1403200), the National Natural Science Foundation of China (52474024), and the Fundamental Research Funds for the Central Universities (25CX02026A).

References

Aiswarya, V., Das, S., Watmode, P.D., Gajghate, S.S., 2024. Development of hybrid MgO/GO modified microencapsulated phase change material for thermal energy management: An experimental approach. J. Clean. Prod. 434, 140399. https://doi.org/10.1016/j.jclepro.2023.140399.

Chen, D., Miao, T., Chang, C., Guo, X., An, M., Guan, M., Ji, Z., 2025. Molecular insights into inhibition and manipulation of methane hydrate dissociation by lecithin and poly (N-vinylpyrrolidone). Fuel 381, 133580. https://doi.org/10.1016/j.fuel.2024.133580.

Das, S., Mahto, V., Udayabhanu, G., Lall, M.V., Singh, K., Deepak, M., 2023. Evaluation of L-ascorbic acid as a green low dosage hydrate inhibitor in water-based drilling fluid for the drilling of gas hydrate reservoirs. J. Pet. Sci. Eng. 220, 111156. https://doi.org/10.1016/j.petrol.2022.111156.

Dong, L., Wu, N., Leonenko, Y., Wan, Y., Liao, H., Hu, G., Li, Y., 2023. A coupled thermal-hydraulic-mechanical model for drilling fluid invasion into hydrate-bearing sediments. Energy 278, 127785. https://doi.org/10.1016/j.energy.2023.127785.

Li, C., Pei, J.L., Wu, N.H., et al., 2022. Rotational failure analysis of spherical-cylindrical shell pressure controllers related to gas hydrate drilling investigations. Pet. Sci. 19, 789–799. https://doi.org/10.1016/j.petsci.2022.02.005.

Li, E., Wang, Z.Y., Zhang, Y., Guo, Y.K., Li, P.F., Zhang, J.B., Kong, Q.W., 2025. Microscopic forces between methane hydrate particle and droplet-wetted sand grain surface in a high-pressure system: experiments and mechanisms. Pet. Sci. https://doi.org/10.1016/j.petsci.2025.11.042.

Li, Y., Liu, L., Jin, Y., Wu, N., 2021. Characterization and development of natural gas hydrate in marine clayey-silt reservoirs: A review and discussion. Adv. Geotherm. Energy Res. 5, 75–86. https://doi.org/10.46690/ager.2021.01.08.

Liu, Y., Zhu, X., Zhang, M., Zhang, Z., Liu, B., Shi, J., 2025. Cenosphere composite phase change materials in ultra-lightweight foam geopolymer: A pathway to enhance thermophysical and mechanical properties. Constr. Build. Mater. 489, 142053. https://doi.org/10.1016/j.conbuildmat.2025.142053.

Liu, X.Q., Han, Z.X., Luo, Z.L., Lu, H.L., Sun, Y., You, Q., Guo, T.K., Qu, Z.Q., 2024. Sand control mechanism of radial well filled with phase change material in hydrate reservoirs. Pet. Sci. 21, 2571–2582. https://doi.org/10.1016/j.petsci.2024.04.008.

Maiti, M., Bhaumik, A.K., Mandal, A., 2021. Performance of water-based drilling fluids for deepwater and hydrate reservoirs: designing and modelling studies. Pet. Sci. 18, 1709–1728. https://doi.org/10.1016/j.petsci.2021.09.001.

Meng, D., Zhao, K., Wang, A., Wang, B., 2020. Preparation and properties of paraffin/PMMA shape-stabilized phase change material for building thermal energy storage. J. Wuhan Univ. Technol.-Materials Sci. Ed. 35, 231–239. https://doi.org/10.1007/s11595-020-2248-y.

Nazir, H., Batool, M., Ali, M., Kannan, A.M., 2018. Fatty acids based eutectic phase change system for thermal energy storage applications. Appl. Therm. Eng. 142, 466–475. https://doi.org/10.1016/j.applthermaleng.2018.07.025.

Parent, J.S., Bishnoi, P.R., 1996. Investigations into the nucleation behaviour of methane gas hydrates. Chem. Eng. Commun. 144, 51–64. https://doi.org/10.1080/00986449608936444.

Phan, A., Farhadian, A., Iravani, D., et al., 2025. Renewable oilfield reagents with multiple flow-assurance actions: Oleic acid – derived compounds inhibit gas hydrate agglomeration and corrosion. Energy 315, 134368. https://doi.org/10.1016/j.energy.2025.134368.

Shi, J., Tan, J., Liu, B., Liu, Y., Xu, H., Wang, Z., Xiong, T., Shi, J., 2020. Thermal and mechanical properties of thermal energy storage lightweight aggregate mortar incorporated with phase change material. J. Energy Storage 32, 101719. https://doi.org/10.1016/j.est.2020.101719.

Shi, J., Liu, Y., Wang, E., Wang, L., Li, C., Xu, H., Zheng, X., Yuan, Q., 2022. Physico-mechanical, thermal properties and durability of foamed geopolymer concrete containing cenospheres. Constr. Build. Mater. 325, 126841. https://doi.org/10.1016/j.conbuildmat.2022.126841.

Sun, W., Wei, N., Zhao, J., et al., 2022. Imitating possible consequences of drilling through marine hydrate reservoir. Energy 239, 121802. https://doi.org/10.1016/j.energy.2021.121802.

Sun, Y.F., Cao, B.J., Chen, H.N., et al., 2023. Influences of pore fluid on gas production from hydrate-bearing reservoir by depressurization. Pet. Sci. 20, 1238–1246. https://doi.org/10.1016/j.petsci.2022.09.015.

Takeya, S., Hori, A., Hondoh, T., Uchida, T., 2000. Freezing-memory effect of water on nucleation of CO_2 hydrate crystals. J. Phys. Chem. B. 104, 4164–4168. https://doi.org/10.1021/jp993759.

Uchida, T., Yamazaki, K., Gohara, K., 2016. Generation of micro- and nano-bubbles in water by dissociation of gas hydrates. Kor. J. Chem. Eng. 33, 1749–1755. https://doi.org/10.1007/s11814-016-0032-7.

Wang, S., Zhao, X., Wang, Z., Zhang, Y., Wang, H., Zou, D., 2023. Micro-encapsulation of a low-melting-point alloy phase change material and its application in electronic thermal management. J. Clean. Prod. 417, 138058. https://doi.org/10.1016/j.jclepro.2023.138058.

Wei, J., Cheng, Y., Yan, C., Li, Q., Zou, D., Zhang, H., 2019. Drilling parameter optimizing strategies to prevent hydrate decomposition risks. Appl. Therm. Eng. 146, 405–412. https://doi.org/10.1016/j.applthermaleng.2018.09.135.

Xu, Q., Liu, H., Wang, X., Wu, D., 2018. Smart design and construction of nanoflake-like MnO_2/SiO_2 hierarchical microcapsules containing phase change material for in-situ thermal management of supercapacitors. Energy Convers. Manag. 164, 311–328. https://doi.org/10.1016/j.enconman.2018.03.006.

Yan, Q., Wang, W., Yu, D., 2005. An study on phase change materials applied in the building envelope. Mater. Rev. 19, 102–105 (in Chinese).

Yang, L., Zhao, J., Liu, W., Li, Y., Yang, M., Song, Y., 2015. Microstructure observations of natural gas hydrate occurrence in porous media using microfocus X-ray computed tomography. Energy Fuels 29, 4835–4841. https://doi.org/10.1021/acs.energyfuels.5b00881.

Yang, M., Zhao, J., Zheng, J.N., Song, Y., 2019. Hydrate reformation characteristics in natural gas hydrate dissociation process: A review. Appl. Energy. 256, 113878. https://doi.org/10.1016/j.apenergy.2019.113878.

Yin, B., Chen, C., Feng, K., Liu, S., Ren, M., Wang, Z., Sun, B., 2025. Multiphase transient flow in wellbore during shallow hydrate reservoir drilling in deep water. ACS Omega 10, 13701–13714. https://doi.org/10.1021/acsomega.5c01229.

Zhang, L., Zhang, Y., Chen, C., Li, X.S., Chen, Z.Y., 2022. Numerical simulation of hydrate decomposition during the drilling process of the hydrate reservoir in the Northern South China Sea. Energies 15, 3273. https://doi.org/10.3390/en15093273.

Zhang, P., Wu, Q., Mu, C., Chen, X., 2018. Nucleation mechanisms of CO_2 hydrate reflected by gas solubility. Sci. Rep. 8, 10441. https://doi.org/10.1038/s41598-018-28555-y.

Zhang, Y., Su, Y., Ge, X., 1995. Prediction of the melting temperature and the fusion heat of (quasi-) eutectic PCM. J. Univ. Sci. Technol. China. 25, 474–478. https://api.semanticscholar.org/CorpusID:203522106 (in Chinese).

Zhao, J., Yang, Y., Li, Y., Zhao, L., Wang, H., Song, G., Tang, G., 2017. Micro-encapsulated phase change materials with TiO_2-doped PMMA shell for thermal energy storage and UV-shielding. Sol. Energy Mater. Sol. Cells 168, 62–68. https://doi.org/10.1016/j.solmat.2017.04.014.

Zhao, X., Qiu, Z., Zhao, C., Xu, J., Zhang, Y., 2019. Inhibitory effect of water-based drilling fluid on methane hydrate dissociation. Chem. Eng. Sci. 199, 113–122. https://doi.org/10.1016/j.ces.2018.12.057.

Zhao, X., Zhang, X., Li, S., Fang, Q., Qiu, Z., Wang, Z., 2024. Dual function of lecithin as an environmentally-friendly inhibitor of hydrate agglomeration and adhesion to the pipe in gas hydrate production. Fuel 376, 132718. https://doi.org/10.1016/j.fuel.2024.132718.

Zhao, X., Geng, Q., Zhang, Z., et al., 2023. Phase change material microcapsules for smart temperature regulation of drilling fluids for gas hydrate reservoirs. Energy 263, 125715. https://doi.org/10.1016/j.energy.2022.125715.