Supplementary file

Recent advances in phase change microcapsules for oilfield applications

Fengbao Liu[1,2], Ziheng Zhang[1], Bo Liao[1], Jinsheng Sun[1,3,4], Muhammad Arqam Khan[5], Mei-Chun Li[1,3,4*]

[1] School of Petroleum Engineering, China University of Petroleum (East China), Qingdao 266580, P. R. China

[2] PetroChina Tarim Oilfield Company, Korla 841000, P. R. China

[3] State Key Laboratory of Deep Oil and Gas, China University of Petroleum (East China), Qingdao 266580, P. R. China

[4] Shandong Key Laboratory of Oil and Gas Field Chemistry, China University of Petroleum (East China), Qingdao 266580, P. R. China

[5] Department of Petroleum Engineering, NED University of Engineering & Technology, University Road, Karachi 75270, Pakistan

E-mail address: liufengbao100@126.com (F. Liu); zzh1292239391@163.com (Z. Zhang); liaob@outlook.com (B. Liao); sunjsdri@cnpc.com.cn (J. Sun); arqamkhan@neduet.edu.pk (M. A. Khan); mli@upc.edu.cn (M. -C. Li).

* Corresponding author (ORCID: 0000-0001-9381-0093)

Liu, F., Zhang, Z., Liao, B., et al. Recent advances in phase change microcapsules for oilfield applications. Advances in Geo-Energy Research, 2025, 16(3): 211-228.
The link to this file is: https://doi.org/10.46690/ager.2025.06.03

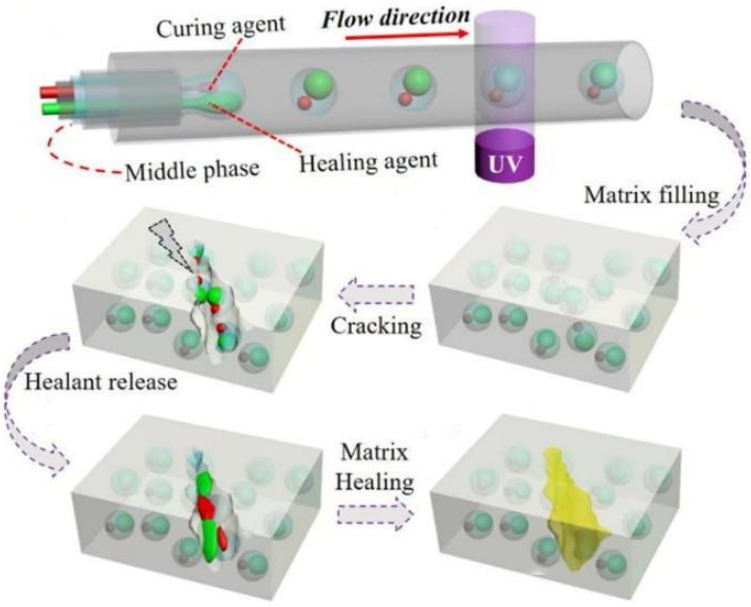

Fig. S1. Schematic diagram of MPCMs preparation by microfluidics (Kim et al., 2022).

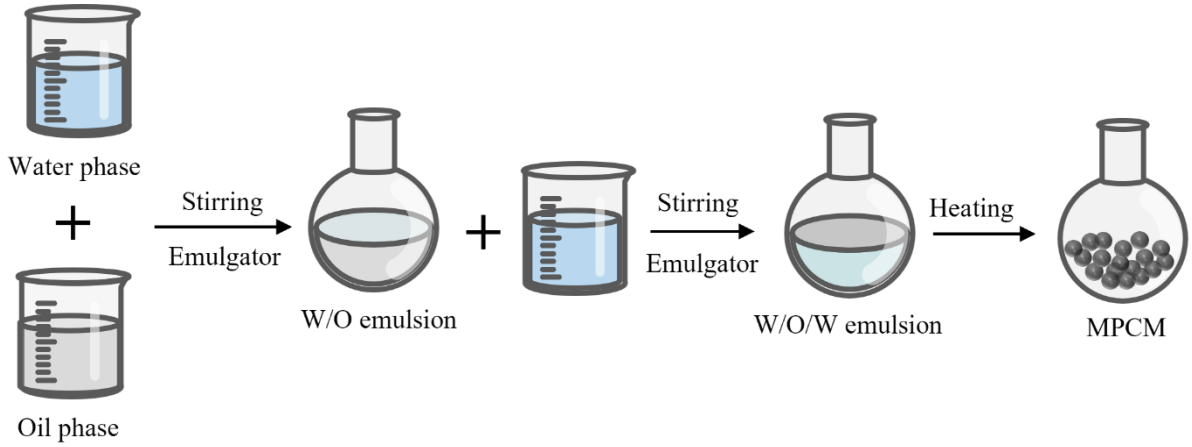

Fig. S2. Schematic diagram of MPCMs preparation by solvent evaporation.

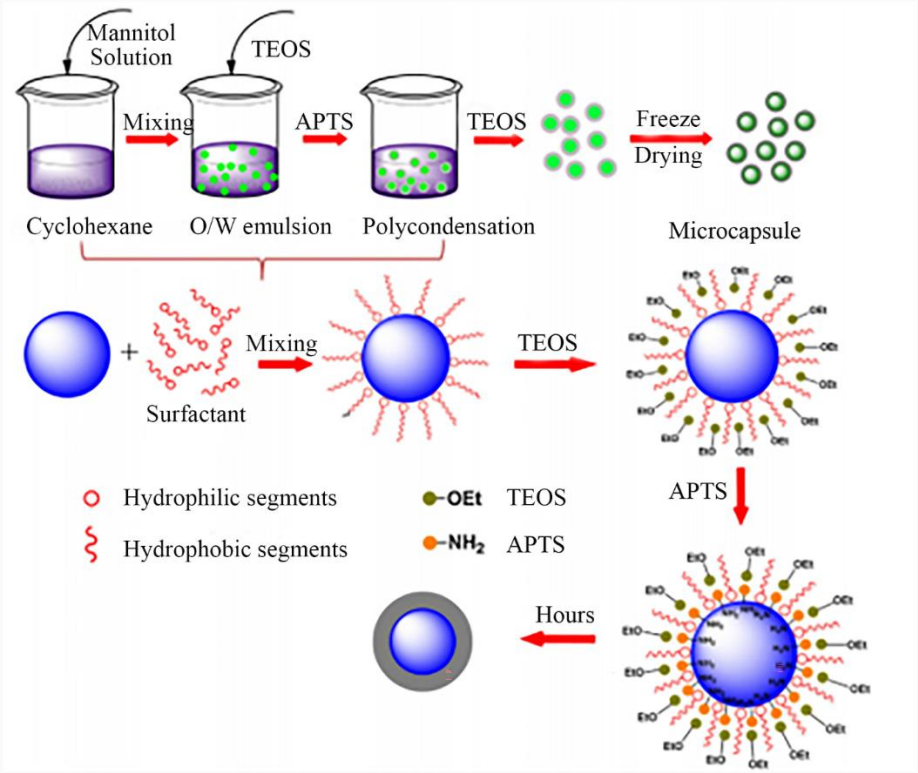

Fig. S3. Schematic diagram of MPCMs preparation by Interfacial polymerization (Wu et al., 2014).

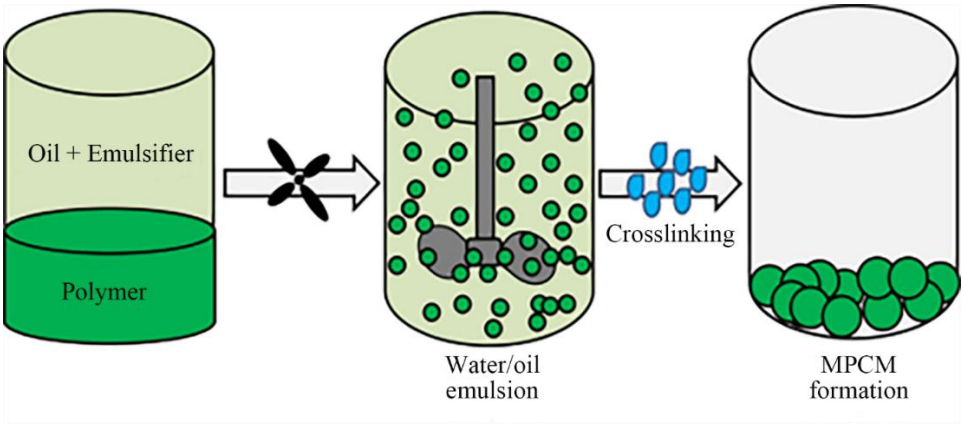

Fig. S4. Schematic diagram of MPCMs preparation by emulsion polymerization (Huang et al., 2019).

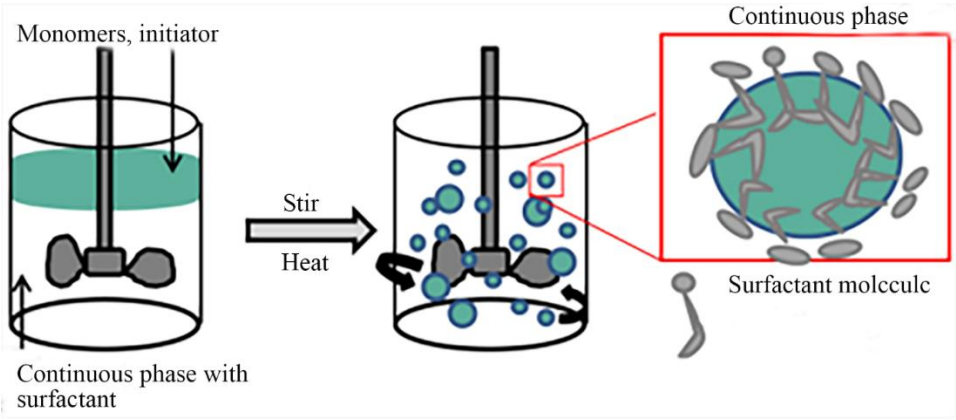

Fig. S5. Schematic diagram of MPCMs preparation by emulsion polymerization suspension polymerization (Huang et al., 2019).

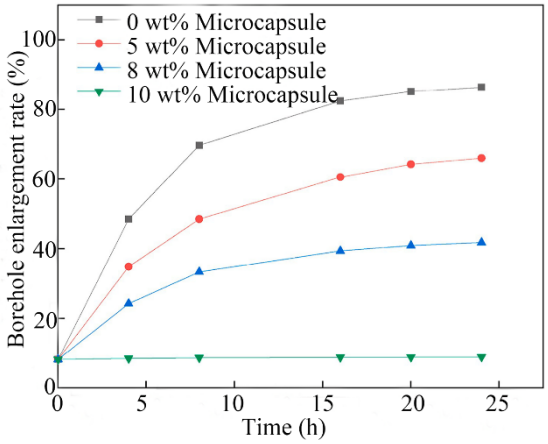

Fig. S6. Borehole enlargement rate at different microcapsule concentrations (Zhao et al., 2023).

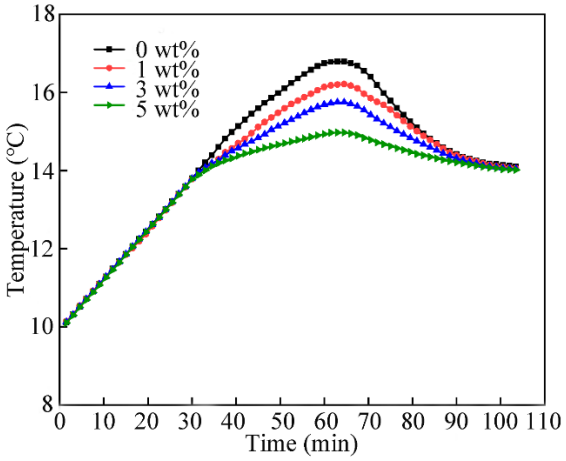

Fig. S7. Temperature–time curves of different microcapsule solutions (Zhang et al., 2021).

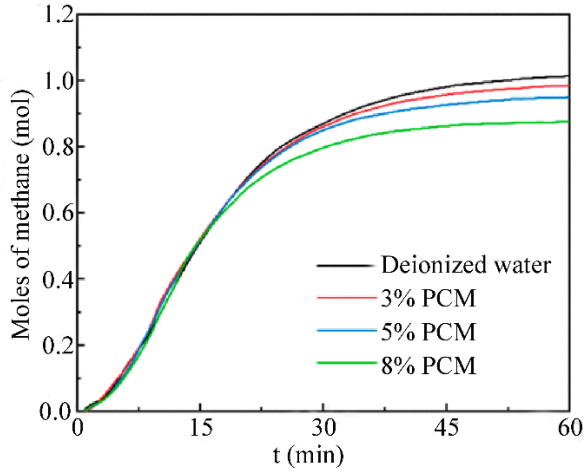

Fig. S8. Curves of methane release under different PCM concentrations (Guo et al., 2024).

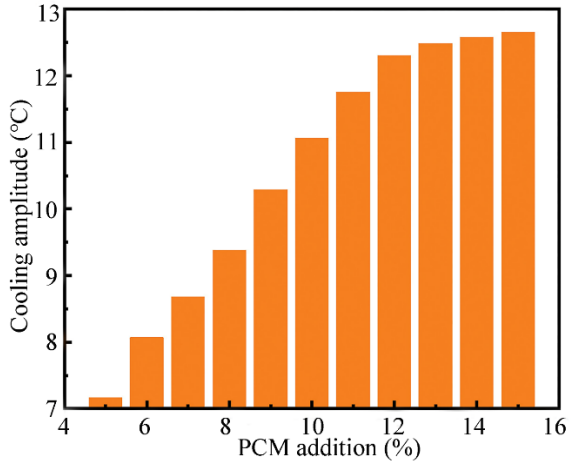

Fig. S9. Cooling effect diagram of MPCMs at different dosages (Zhang et al., 2023).

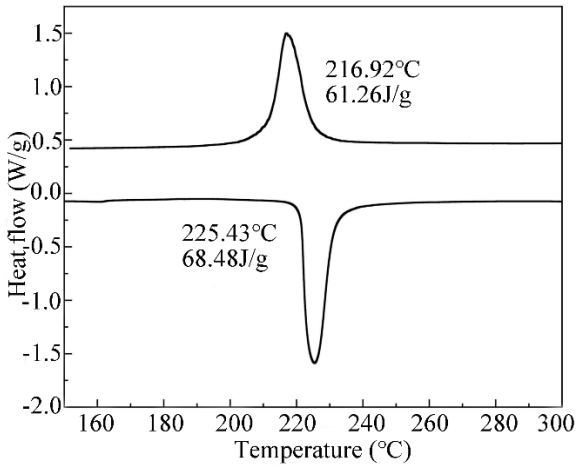

Fig. S10. DSC curves of the microcapsules (Guo et al., 2024).

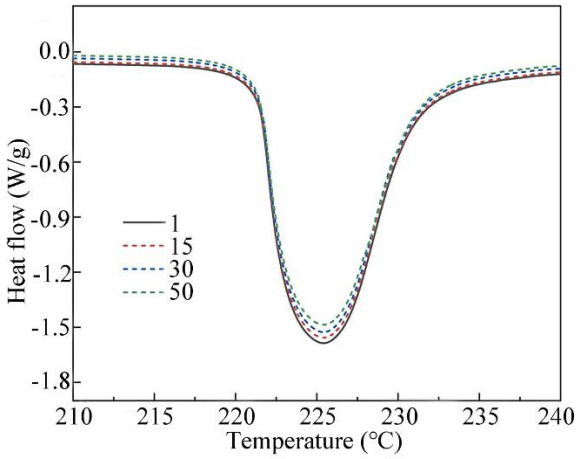

Fig. S11. Temperature-time curves of microcapsule system with different contents (Guo et al., 2024).

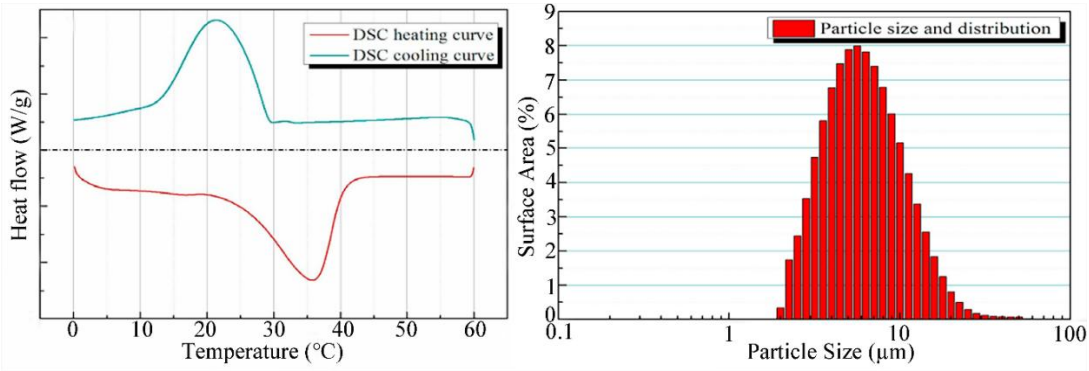

Fig. S12. DSC and particle size distribution curves of MPCMs (Huo et al., 2019).

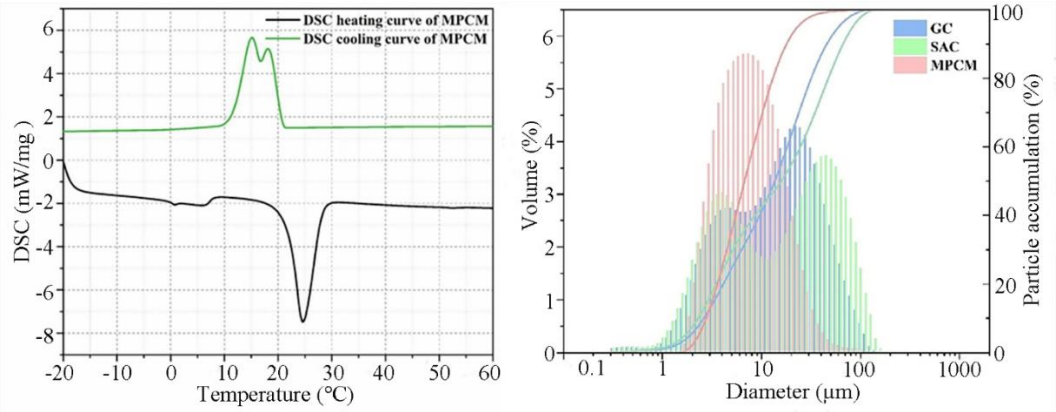

Fig. S13. DSC curves and particle size distribution curves of MPCMs (Cai et al., 2023)

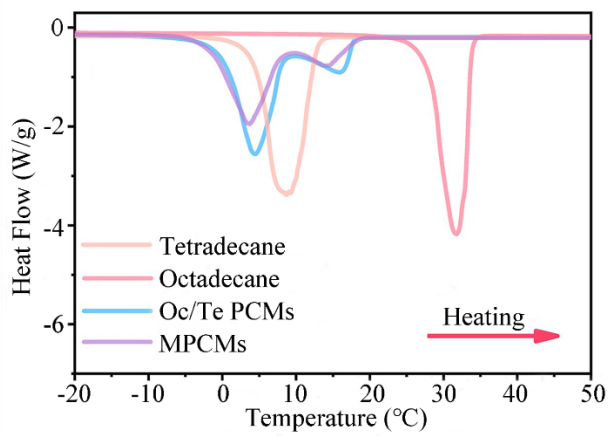

Fig. S14. DSC curves of the different samples (Yang et al., 2024).

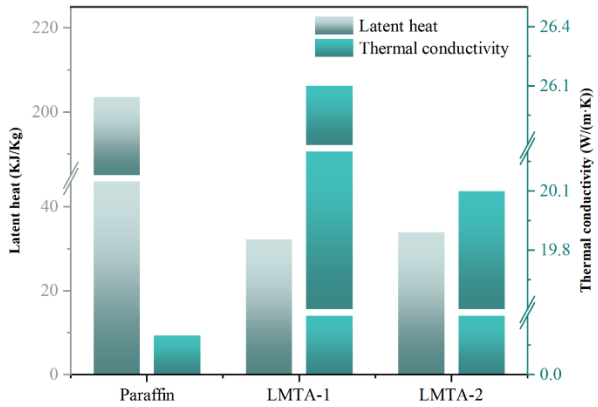

Fig. S15. Thermal properties bar chart of different PCMs (He et al., 2022).

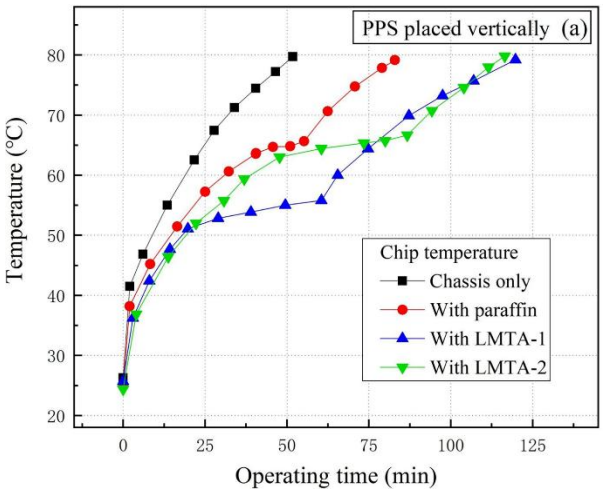

Fig. S16. Transient temperature changes of different PCMs under vertical layout (He et al., 2022).

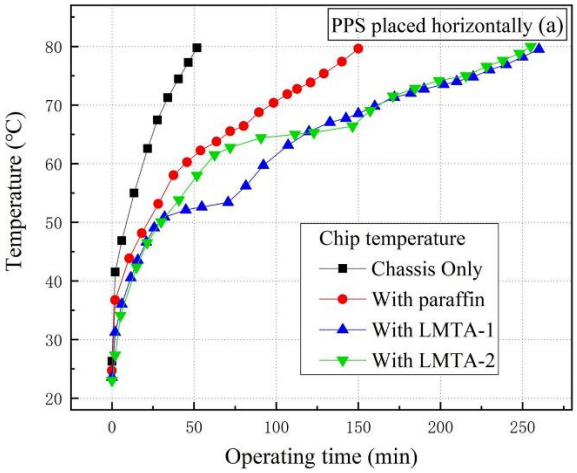

Fig. S17. Transient temperature changes of different PCMs under horizontal layout (He et al., 2022).

Table S1. Summaries on the application of MPCMs in oilfield.

Application	MPCMs		Thermophysical properties			Cooling result	Ref.
	Core	Shell	PS (μm)	PCT (℃)	LH (kJ/kg)		
Drilling fluids	Tetradecane	MUF	0.7-10	6.7	116	5.4	(Zhao et al., 2023)
	$NaNO_3/KNO_3$	Nano-Silica	4-16	225.43	68.48	2.1	(Guo et al., 2024)
	Modified n-Alkane	Nano-Silica	5–28	14.06	136.8	1.8	(Zhang et al., 2021)
	EG/MNA	N/A	7.3-53.2	16.43	163.3	2.12	(Zhang et al., 2022)
	N-tetradecane/N-hexadecane	Sodium alginate	122.41	13.72℃	158.04	N/A	(Guo et al., 2024)
	Cholesteryl Stearate	N/A	N/A	83	109	N/A	(Monteiro et al., 2012)
	Zinc Stearate	N/A	N/A	128	150	N/A	(Monteiro et al., 2012)
	Wax	N/A	N/A	90	300	5.5	(Monteiro et al., 2012)
	Paraffin	N/A	N/A	125	264.15~265.53	12.3	(Zhang et al., 2023)
	Paraffin/EG	N/A	< 32.1	145	90.3	10	(Junyi et al., 2021)
	Isopentaerythritol, neopentanediol	N/A	< 28.4	120	280.6	12.5	(Junyi et al., 2021)
	Erythritol	Polymer	< 12.7	132	126.2	24	(Junyi et al., 2021)
	Erythritol	PES	20-80	100-135	193.2-286.3	4.7-19.3	(Su et al., 2023)
Oilwell cement slurry	Paraffin-6	Polymer	17-20	6	157-167	N/A	(Pang et al., 2015)
	Paraffin-56	Polymer	15-25	56	160-180	15	(Pang et al., 2015)
	CA-MA	Conment	< 150	21.13	41.78	N/A	(Sarı et al., 2018)
	Paraffin	polyurea	150-350	27.77	124.8	4.1	(Cui et al., 2015)
	PEG	N/A	N/A	53.39	191.52	N/A	(Du et al., 2020)

	PEG/conment	N/A	N/A	53.76	37.47	6.2	(Du et al., 2020)
	n-octadecane/EG	N/A	N/A	26.37	184.8	8.7	(Zhang et al., 2013)
	Paraffin/diatomite	N/A	N/A	41.11	70.51	N/A	(Xu et al., 2013)
	n-octadecane	N/A	N/A	23.8	119.83	N/A	(Liu et al., 2017)
	Dodecanol/cement	N/A	N/A	21.06	18.39	N/A	(Memon et al., 2013)
	Dodecanol	N/A	N/A	25	205.4	N/A	(Memon et al., 2013)
	Wax	urea formaldehyde resin	5.744	35.85	85.69	35.9	(Huo et al., 2019)
	Paraffin	PMMA	200-250	17.1	67.02	N/A	(Liu et al., 2017)
	PCM-30	Metakaolin/resin	200	N/A	N/A	23.7	(Bu et al., 2021)
	Paraffin	SiO_2	22.48	30.52	72.4	9.9	(Feng et al., 2022)
	DA/CA	SiO_2	7.56	24.31	150.64		(Cai et al., 2023)
	N-tetradecane/ n-octadecane	$BaCO_3$	N/A	3.5/13.9	N/A	N/A	(Yang et al., 2024)
Drilling equipment	Paraffin	N/A	N/A	51.2	203.5	N/A	(He et al., 2022)
	LMTA-1	N/A	N/A	50.6	32.19	N/A	(He et al., 2022)
	LMTA-2	N/A	N/A	60.5	33.83	N/A	(He et al., 2022)
	N/A	N/A	N/A	72.8	251.4	N/A	(Sarı et al., 2018)
Submarine oil and gas pipelines	MPCM	PU	N/A	18	35.95	N/A	(Wang et al., 2023)

Note: PS- Particle size; PCT-Phase-transition temperature; LH- Latent heat

References

Bu, Y., Ma, R., Liu, H., et al. Low hydration exothermic well cement system: The application of energy storage microspheres prepared by high-strength hollow microspheres carrying phase change materials. Cement and Concrete Composites, 2021, 117: 103907.

Cai, J., Zhou, J., Liu, C., et al. Microencapsulated phase change material-cement composites for cementing the natural gas hydrate layer. Construction and Building Materials, 2023, 399: 132591.

Cui, H., Liao, W., Mi, X., et al. Study on functional and mechanical properties of cement mortar with graphite-modified microencapsulated phase-change materials. Energy and Buildings, 2015, 105: 273-284.

Du, Y., Liu, P., Quan, X., et al. Characterization and cooling effect of a novel cement-based composite phase change material. Solar Energy, 2020, 208: 573-582.

Feng, Q., Zhang, Y., Peng, Z., et al. Preparation and investigation of microencapsulated thermal control material used for the cementing of gas hydrate formations. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2022, 648: 129182.

Guo, J., Wang, J., Liao, B., et al. Hydrate Decomposition Inhibitors by Phase Change Cooling Storage Based on an Electrostatic Spraying Method. Energy & Fuels, 2024, 38(14): 12978-12988.

Guo, P., Qiu, Z., Zhang, Y., et al. Preparation and characterization of phase change microcapsules for improving the applicable temperature and stability of high temperature resistant drilling fluids. Chemical Engineering Research and Design, 2024, 201: 389-398.

He, J., Wang, Q., Wu, J., et al. Hybrid thermal management strategy with PCM and insulation materials for pulsed-power source controller in extreme oil-well thermal environment. Applied Thermal Engineering, 2022, 214: 118864.

Huang, X., Zhu, C., Lin, Y., et al. Thermal properties and applications of microencapsulated PCM for thermal energy storage: A review. Applied Thermal Engineering, 2019, 147: 841-855.

Huo, J.-h., Peng, Z.-g., Xu, K., et al. Novel micro-encapsulated phase change materials with low melting point slurry: Characterization and cementing application. Energy, 2019, 186: 115920.

Junyi, L., Erding, C., Guangquan, L., et al. Experimental Study of Drilling Fluid Cooling in Deep Wells Based on Phase Change Heat Storage. Petroleum Drilling Techniques, 2021, 49(1): 53-58.

Kim, E., Lee, H. Mechanical characterization of soft microparticles prepared by droplet microfluidics. Journal of Polymer Science, 2022, 60(11): 1670-1699.

Liu, F., Wang, J., Qian, X. Integrating phase change materials into concrete through microencapsulation using cenospheres. Cement and Concrete Composites, 2017, 80: 317-325.

Liu, H., Bu, Y., Guo, Q., et al. Converting hydration heat to achieve cement mixture

with early strength and low hydrating-thermal dissipation. Construction and Building Materials, 2017, 151: 113-118.
Memon, S. A., Lo, T. Y., Cui, H., et al. Preparation, characterization and thermal properties of dodecanol/cement as novel form-stable composite phase change material. Energy and Buildings, 2013, 66: 697-705.
Monteiro, O., Quintero, L., Bates, M., et al. Temperature Control of Drilling Fluid with Phase-Change Materials. 2012 AIChE Spring National Meeting, 3 April, 2012.
Pang, X., Jimenez, W. C., Goel, V. Use of Microencapsulated Phase-Change Materials To Regulate the Temperature of Oilwell Cement. SPE Drilling & Completion, 2015, 31(01): 063-070.
Sarı, A., Bicer, A., Karaipekli, A., et al. Preparation, characterization and thermal regulation performance of cement based-composite phase change material. Solar Energy Materials and Solar Cells, 2018, 174: 523-529.
Su, J. L., Tan, Y., Dong, X. R., et al. The invention relates to a phase change heat storage microcapsule material suitable for cooling drilling fluid and a preparation method thereof. China. 2023.
Wang, H., Dang, J., Zheng, M., et al. High thermal storage polyurethane composite embedded with microencapsulated phase change materials and analysis of its unsteady heat transfer. Advanced Composites and Hybrid Materials, 2023, 6(5): 165.
Wu, C.-B., Wu, G., Yang, X., et al. Preparation of Mannitol@Silica core–shell capsules via an interfacial polymerization process from water-in-oil emulsion. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2014, 457: 487-494.
Xu, B., Li, Z. Paraffin/diatomite composite phase change material incorporated cement-based composite for thermal energy storage. Applied Energy, 2013, 105: 229-237.
Yang, G., Lei, G., Liu, T., et al. Development and application of low-melting-point microencapsulated phase change materials for enhanced thermal stability in cementing natural gas hydrate layers. Geoenergy Science and Engineering, 2024, 238: 212846.
Zhang, J., Xie, J., Li, X., et al. Simulation study of drilling fluid cooling in long horizontal wells based on phase change heat absorption. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2023, 45(4): 12134-12151.
Zhang, Y., Qiu, Z., Mu, J., et al. Intelligent Temperature-Control of Drilling Fluid in Natural Gas Hydrate Formation by Nano-Silica/Modified n-Alkane Microcapsules. Nanomaterials, 2021, 11(9): 2370.
Zhang, Y., Qiu, Z., Zhong, H., et al. Preparation and characterization of expanded graphite/modified n-alkanes composite phase change material for drilling in hydrate reservoir. Chemical Engineering Journal, 2022, 429: 132422.
Zhang, Z., Shi, G., Wang, S., et al. Thermal energy storage cement mortar containing

n-octadecane/expanded graphite composite phase change material. Renewable Energy, 2013, 50: 670-675.
Zhao, X., Geng, Q., Zhang, Z., et al. Phase change material microcapsules for smart temperature regulation of drilling fluids for gas hydrate reservoirs. Energy, 2023, 263: 125715.