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# Study and Application of Phase Change Materials for Temperature Reduction in High-Temperature Deep-Well Drilling Fluids

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**Abstract:** Phase change materials (PCMs), an innovative class of functional materials, exhibit the ability to store or release thermal energy through reversible transformations at specific phase transition temperatures, which have been extensively employed in aerospace, military, construction, and refrigeration industries. As oil and gas exploration and development word-widely advance into deeper formations, extremely high-temperature and high-pressure conditions in these environments impose significant challenges on drilling fluids and down-hole instruments, limiting the progress of deep hydrocarbon exploration. To address the technical challenges related to the high-temperature resistant stability of drilling fluids in deep formations, this study investigates the integration of PCMs into drilling fluids. Through theoretical analysis and experimental simulations, the feasibility of utilizing the "phase change heat storage principle" of PCMs to reduce circulating drilling fluid temperatures in boreholes was demonstrated. The results indicate that three selected PCMs exhibit phase transition temperatures in the range of 120–145°C and phase change latent heat of 90.3–280.6 J/g, showcasing excellent phase change heat storage properties. The materials were found to be compatible with drilling fluids. At a PCM concentration of 12%, the rheological and filtration properties of the drilling fluids still met operational requirements. Incorporating PCMs into drilling fluids effectively reduced the circulating temperature in boreholes, with a more pronounced cooling effect observed at higher PCM concentrations. At a concentration of 12%, the circulating temperature of drilling fluids was reduced by up to 20°C. Additionally, the PCMs demonstrated good reusability, consistently undergoing the "heat storage and release" phase change process, thereby satisfying the circulating cooling demands of drilling fluids. The findings provide a robust reference for PCM integration in high-temperature drilling fluids, particularly in ultra-deep wells with extreme thermal conditions.

**Keywords:** High-temperature deep wells; Water-based drilling fluids; Drilling fluid cooling; Phase change heat storage; Energy-efficient cooling techniques

## 1 Introduction

Along with the continuous increase in China's dependency on foreign oil and gas supplies, it is of important practical and strategic significance to explore deeper layers of the Earth's crust, expand deep oil and gas resources and achieving efficient exploration and development of deep oil and gas resources, thereby strengthening the resource foundation for national energy security. It is estimated that China's deep and ultra-deep oil and gas resources amount to approximately 67.1 billion tonnes of oil equivalent, representing 34% of the total oil and gas reserves. These resources, characterized by significant oil reserves and considerable development potential, are considered key to the future of domestic oil and gas exploration and production [1–5].

Field practices have demonstrated that drilling operations in deep oil and gas reservoirs are increasingly encountering high-temperature and ultra-high-temperature conditions. For instance, in the Shunbei and Shunnan regions of the Tarim Basin, bottom-hole temperatures typically range between 180°C and 260°C. Under such extreme conditions, the components of drilling fluids are prone to dispersion, agglomeration, degradation, and cross-linking reactions, resulting in dramatic alterations in the rheological and filtration properties of the drilling fluids. These changes may even render drilling operations unfeasible [6, 7]. Moreover, high-temperature and ultra-high-temperature environments significantly affect drilling tools, logging instruments, and measurement-while-drilling equipment, leading to severe reductions in the service life of these instruments [8, 9] and substantial increases in drilling costs. In addition, with the ongoing implementation of geothermal resource development and deep scientific drilling projects in China, the frequency of encountering high-temperature geological formations is steadily rising. In dry hot rock geothermal wells, bottom-hole temperatures often exceed 200℃, with some reaching temperatures above 300℃ [10]. Consequently, the extremely high-temperature and high-pressure conditions associated with deep oil and gas reservoirs and dry hot rocks pose severe challenges to drilling fluid technologies and downhole equipment. These conditions have become a critical barrier to the efficient drilling and development of deep oil and gas resources, as well as clean geothermal resources.

Currently, drilling fluid cooling methods both domestically and internationally primarily include natural cooling, low-temperature medium mixing cooling, and forced cooling through cooling equipment. Notably, drilling fluid cooling technologies and associated equipment have been developed abroad and widely applied in high-temperature deep wells, geothermal wells, and permafrost zones [11–13]. However, these methods typically reduce the temperature of drilling fluids only at the inlet, thereby indirectly lowering the circulating temperature within the borehole. Significant drawbacks, including substantial equipment investment, high energy consumption, and extensive use of cooling media, limit the effectiveness of these approaches in meeting the cooling requirements for drilling fluids in high-temperature deep wells.

PCMs represent an innovative class of functional materials that store thermal energy through phase transitions, effectively regulating the ambient temperature. These materials have been extensively employed in aerospace, military, construction, and refrigeration industries [14, 15]. For example, PCMs could absorb and release a large amount of latent heat of phase change at a relatively constant temperature, which could be applied as a medium for thermal energy storage and temperature control in the field of human body thermal management in the aerospace industry. To date, research and applications of PCMs in drilling engineering have primarily focused on low-heat cement slurry systems [16, 17], while the integration of PCMs into drilling fluids has not been explored. Compared with conventional drilling fluid cooling methods, PCMs might be directly added into the high-temperature drilling fluid in deep wells, which is directly used to regulate the circulating temperature of the drilling fluid within the borehole. It is expected to significantly improve the cooling efficiency of the high-temperature drilling fluid in deep wells and reduce energy consumption.

To address the challenges posed by the high temperature resistant stability of drilling fluids during deep oil and gas exploration, this study introduces PCMs into drilling fluids for the first time. A novel method was proposed for regulating the circulating temperature of borehole drilling fluids using PCMs. The feasibility and applicability of this approach, based on the “phase change heat storage principle” of PCMs, were demonstrated through theoretical analysis and simulated experiments. This investigation provides critical references for the research on PCMs and technology applications for subsequent drilling fluid cooling.

## 2 Evaluation of the Physicochemical Properties of PCMs

PCMs exhibit the ability to undergo reversible transformations between different phases at specific phase transition temperatures, absorbing or releasing substantial amounts of latent heat during the process. The phase change process is characterised by three notable features: (a) high latent heat capacity, which exceeds the heat storage capacity of sensible heat storage materials (e.g., cement or rocks) by more than 40 times per unit volume; (b) nearly constant medium temperature during the phase change process; and (c) environmentally friendly, reusable properties [18].

Based on these advantageous characteristics, PCMs were introduced into drilling fluids in this study to explore their characteristics of absorbing phase change latent heat and maintaining temperature stability (phase change heat storage) during the phase change process, thereby reducing circulating temperatures of drilling fluids in boreholes. During drilling operations, a specific quantity of PCM was incorporated into the drilling fluid. As the fluid circulated into the borehole and its circulating temperature reached the phase transition temperature, the PCM underwent a phase change, absorbing a substantial amount of latent heat and storing the thermal energy within the material. This process effectively reduced the circulating temperature of the drilling fluid. When the drilling fluid returned to the surface, the temperature decreased, prompting the PCM to undergo a reversible phase change and release the stored heat. This cyclical process ensures that the temperature regulation requirements of circulating drilling fluids are met.

When utilising PCMs as cooling agents in drilling fluids, several key selection criteria must be satisfied as follows:

a) The PCM must be highly compatible with drilling fluids, ensuring that it does not negatively affect the rheological or filtration properties of the drilling fluid before or after the phase change.

b) The PCM must exhibit strong heat absorption capabilities, characterized by a high latent heat of phase change. Additionally, the PCM must possess an appropriate phase transition temperature to meet the cooling requirements of drilling fluids in high-temperature deep wells. For example, when the circulating temperature of the drilling fluid within the borehole is up to 180–260℃, several experiments demonstrate that the phase transition temperature of PCMs should be 100–150℃.

c) The PCM must demonstrate excellent chemical and thermal stability, ensuring that no decomposition, ageing, or phase separation occurs during repeated phase change cycles involving heat absorption and release in downhole environments.

d) The particle size of the PCM should fall within the micro- or nanoscale range, and the material must exhibit good reversibility in the phase change process. The PCM must remain reusable and capable of circulating with the drilling fluid without being removed by the drilling solid control system.

In addition to these technical requirements, the PCM must also be readily available, cost-effective, and safe to use, meeting standards for non-toxicity and non-flammability. Based on these selection criteria, three PCMs were identified and evaluated in this study. Their thermophysical properties were tested, and their phase change thermal storage and temperature regulation behaviours were experimentally assessed. These findings provide a foundation for subsequent experimental investigations into the use of PCMs for cooling drilling fluids in simulated conditions.

### 2.1 Thermal Property Evaluation of PCMs

The thermal properties of the PCMs, including phase transition temperature and latent heat of phase change, were determined using differential scanning calorimetry (DSC). The testing procedure was as follows:

a) The temperature was increased from 30℃ to 200℃ at a rate of 10℃/min.

b) The sample was held at 200℃ for 10 minutes.

c) The temperature was then decreased from 200℃ to 30℃ at a rate of 10℃/min.

d) The sample was held at 30℃ for 10 minutes.

e) The temperature was increased again from 30℃ to 200℃ at a rate of 10°C/min, and the DSC curve was obtained.

Taking the DSC curve of PCM 2 (Figure 1) as an example, the analysis was conducted in accordance with the standards established by the International Confederation for Thermal Analysis and Calorimetry (ICTA). In the DSC curve, exothermic peaks point upward, and endothermic peaks point downward. The melting point was identified as the intersection of the baseline's forward extension with the tangent at the maximum slope of the peak's leading edge. The characteristic peak corresponding to recrystallisation during melting was selected for analysis to determine parameters such as phase transition temperature and latent heat of phase change [19–21].

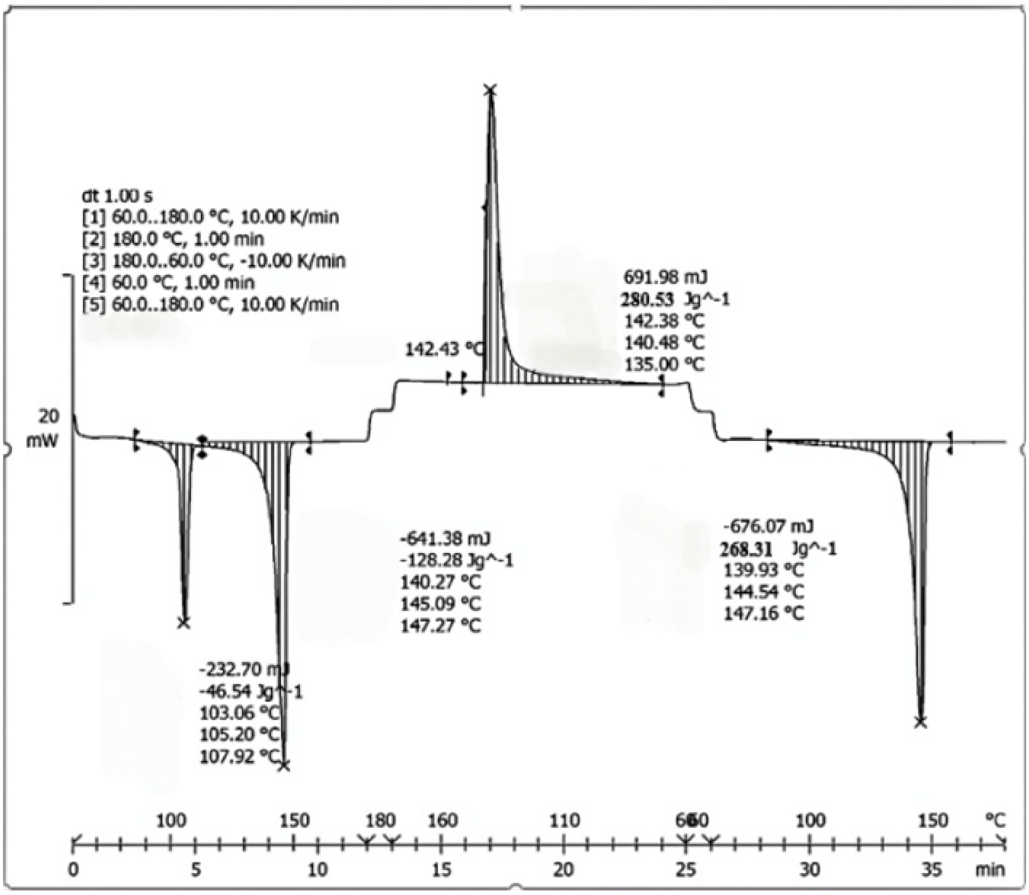



**Figure 1.** DSC curve of PCM 2

**Table 1.** Test results of the thermophysical properties of the PCMs

| Material No. | D90 Particle Size (μm) | Phase Transition Temperature (℃) | Latent Heat of Phase Change (J/g) |
|---|---|---|---|
| PCM 1 | 32.1 | 145 | 90.3 |
| PCM 2 | 28.4 | 120 | 280.6 |
| PCM 3 | 12.7 | 132 | 126.2 |

Table 1 shows the test results of the thermophysical properties of the PCMs. From the analysis, PCM 1 was identified as a composite PCM with a phase transition temperature of 145℃ and a relatively low latent heat of phase change at 90.3 J/g. PCM 2, a solid-solid PCM, demonstrated a phase transition temperature of 120℃ and the highest latent heat of 280.6 J/g among the tested samples. PCM 3, a microencapsulated PCM, exhibited a phase transition temperature of 132℃ and a latent heat of 126.2 J/g. Furthermore, the D90 particle sizes of PCM 1 through PCM 3 were all less than 75 μm, enabling the materials to pass through 200-mesh screens and other solid control equipment without obstruction. This ensures their suitability for recirculating use within drilling fluid systems.

### 2.2 Evaluation of the Heat Storage Characteristics of PCMs

A pure heating medium was heated to 200℃, with temperature measurements recorded every 30 seconds to generate a baseline heating curve. Subsequently, 12% PCM by weight was added to the heating medium, mixed thoroughly, and subjected to the same heating procedure. The temperature was recorded at 30-second intervals, and the heat storage and temperature regulation curve for the PCM-enhanced medium was obtained.

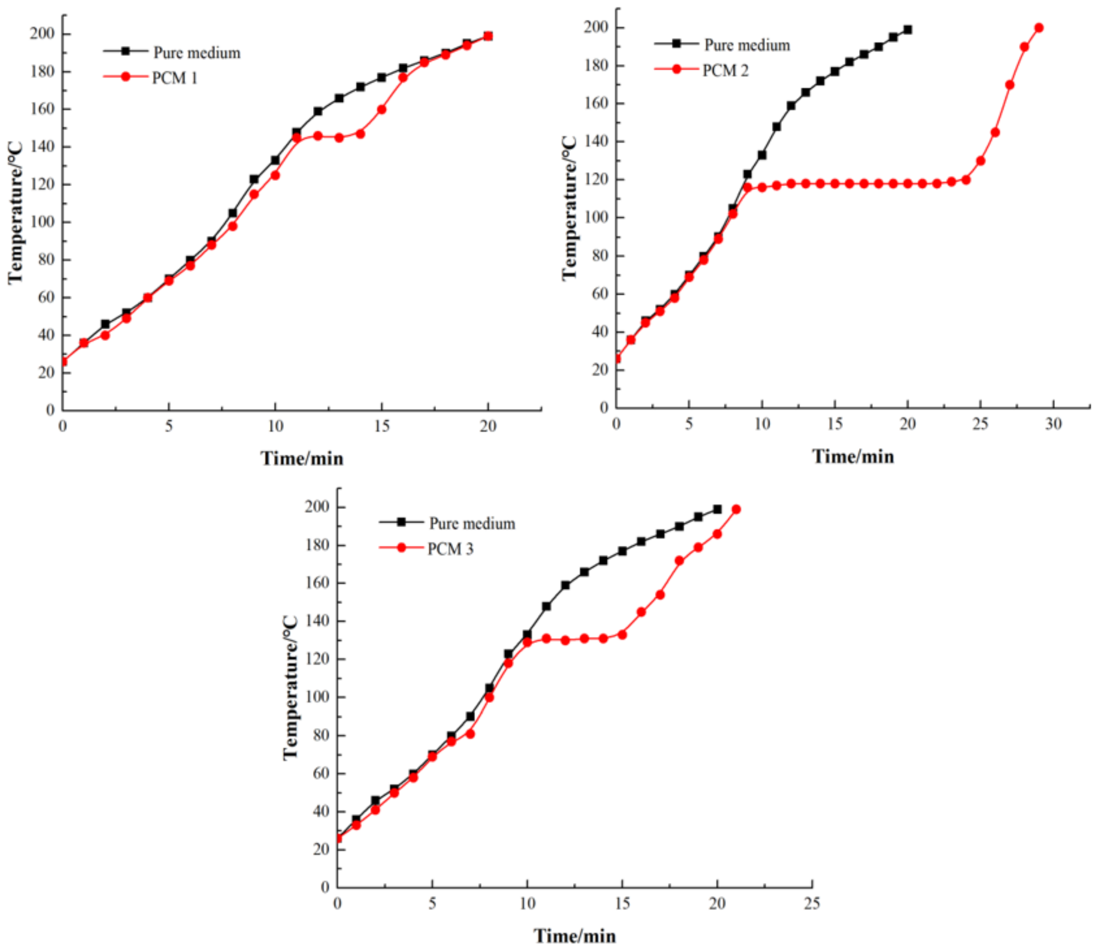



**Figure 2.** Heat storage and temperature regulation curves of PCMs 1-3

Figure 2 illustrates the heat storage and temperature regulation curves for PCMs 1, 2, and 3. Analysis of the results indicates that, during heating, the pure heating medium rapidly reached 200℃. When PCM 1 was added, the heating medium initially experienced a rapid temperature increase. However, upon reaching the phase transition temperature of approximately 140°C, the PCM underwent a phase change, absorbing a substantial amount of latent heat and forming a distinct isothermal plateau at the phase transition temperature. Similar behaviours were observed for PCM 2 and PCM 3. The experimental results demonstrate that the temperature of the isothermal plateau is determined by the phase transition temperature of the PCM, while the duration of the plateau is directly related to the latent heat of the PCM. Among the tested materials, PCM 2 exhibited the highest latent heat of phase change, resulting in the longest isothermal plateau duration.

## 3 Evaluation of Compatibility Between PCMs and Drilling Fluids

To utilise PCMs as cooling agents in drilling fluids, the materials must exhibit excellent compatibility with commonly used drilling fluid systems. Therefore, a standard high-temperature resistant water-based drilling fluid formulation was selected to assess the basic properties of the drilling fluid, including rheology and filtration performance, before and after the addition of PCMs. The compatibility of the PCMs with the drilling fluid system was evaluated based on these experimental results. The experimental drilling fluid formulations are as follows:

- HT-MUD-1 (high temperature resistant water-based drilling fluid): 2% bentonite + 0.8% HT-POLY + 1.5% HT-FR + 2% HT-LSA + 3.5% HT-SEAL + 0.5% HT-CSP + 1% HT-LUBE (weighted with barite to 1.5 g/cm$^3$).
- HT-MUD-2: 2% bentonite + 0.8% HT-POLY + 1.5% HT-FR + 2% HT-LSA + 3.5% HT-SEAL + 0.5% HT-CSP + 1% HT-LUBE + 12% PCM 1 (weighted with barite to 1.5 g/cm$^3$).
- HT-MUD-3: 2% bentonite + 0.8% HT-POLY + 1.5% HT-FR + 2% HT-LSA + 3.5% HT-SEAL + 0.5% HT-CSP + 1% HT-LUBE + 12% PCM 2 (weighted with barite to 1.5 g/cm$^3$).
- HT-MUD-4: 2% bentonite + 0.8% HT-POLY + 1.5% HT-FR + 2% HT-LSA + 3.5% HT-SEAL + 0.5% HT-CSP + 1% HT-LUBE + 12% PCM 3 (weighted with barite to 1.5 g/cm$^3$).

PCMs were directly added into drilling fluids and mixed for 10 minutes while continuously stirring. Table 2 summarises the evaluation results of the rheological and filtration properties of drilling fluids before and after the addition of PCMs. Analysis reveals that, compared to the HT-MUD-1 formulation, the addition of 12% PCM (based on previous research) resulted in a slight increase in plastic viscosity and yield point, while the filtration performance remained relatively unchanged. These findings indicate that PCMs, when used as cooling agents in drilling fluids, exhibit excellent compatibility with the drilling fluid system. Even at a concentration of 12%, the rheological and filtration properties of the drilling fluids remained within acceptable ranges for drilling operations. Among the tested PCMs, PCM 3 had the least impact on the rheological and filtration properties of the drilling fluid. The microencapsulation of PCM 3 provides a protective barrier that prevents direct interaction with the drilling fluid components, thereby maintaining the fluid's rheological stability and filtration performance.

**Table 2.** Evaluation of rheological and filtration properties of drilling fluids

| Formulation | Testing Condition | AV (mPa.s) | PV (mPa.s) | YP (Pa) | Gel (Pa) | $FL_{API}$ (mL) | $FL_{HTHP}$ (mL) | pH |
|---|---|---|---|---|---|---|---|---|
| HT-MUD-1 | Before hot rolling | 41.0 | 31.0 | 10.0 | 5.0/8.0 | 3.0 | - | 9.0 |
| | After hot rolling | 43.0 | 30.0 | 13.0 | 4.5/9.0 | 3.2 | 12.4 | 9.0 |
| HT-MUD-2 | Before hot rolling | 51.0 | 39.0 | 12.0 | 5.5/9.0 | 2.8 | - | 9.0 |
| | After hot rolling | 53.0 | 38.5 | 14.5 | 5.5/10.0 | 3.0 | 11.8 | 8.5 |
| HT-MUD-3 | Before hot rolling | 47.5 | 36.0 | 11.5 | 5.0/9.0 | 3.2 | - | 9.0 |
| | After hot rolling | 50.5 | 37.0 | 13.5 | 5.0/10.5 | 2.6 | 11.6 | 8.5 |
| HT-MUD-4 | Before hot rolling | 42.5 | 32.0 | 10.5 | 5.0/8.5 | 3.2 | - | 9.0 |
| | After hot rolling | 43.5 | 31.0 | 12.5 | 5.0/9.5 | 3.0 | 12.0 | 9.0 |

Note: Hot rolling conditions were 180°C for 16 hours. High-temperature, high-pressure (HTHP) filtration loss tests were conducted at 150°C and 3.5 MPa.

## 4 Experimental Investigation on Drilling Fluid Cooling Performance Using PCMs

The aforementioned research has demonstrated that PCMs undergo reversible phase transitions in response to variations in circulating drilling fluid temperatures. These transitions enable the absorption or release of significant amounts of heat, forming a broad isothermal plateau at the phase transition temperature. Therefore, the simulation experiment of drilling fluid circulation cooling was conducted to evaluate the cooling performance of drilling fluids enhanced with PCMs, which validated the feasibility of using the "phase change heat storage principle" of PCMs for reducing circulating temperatures of the drilling fluid.

### 4.1 Simulated Experimental Method for Drilling Fluid Circulation Cooling

The experimental setup for simulating drilling fluid circulation cooling is illustrated in Figure 3. During the experiment, the drilling fluid was pumped into a simulated wellbore using a vacuum pump with 60 L/s and returned through the annulus in a continuous circulation flow. The wellbore was enclosed by a heating jacket, which was controlled by three temperature sensors (designated as Sensors 1, 2, and 3) arranged in series to achieve the desired wellbore temperature profile. A pressure control valve installed at the annulus outlet allowed for the adjustment of circulating pressure by regulating the outlet pressure. In the simulated cooling experiment, a high-temperature resistant drilling fluid without PCMs was first circulated through the wellbore. The heating jacket, controlled by the three temperature sensors, was adjusted to maintain a bottom-hole fluid temperature of 180℃. The heating power was then stabilised at a constant temperature position by manually adjusting the heating jacket, and the servo control of the temperature sensors was deactivated. Subsequently, a high-temperature resistant drilling fluid containing PCMs was circulated through the system, and the temperature readings from the bottom-hole sensor were continuously recorded, for example, the first cycle, the second cycle. The cooling performance curve of the PCM-enhanced drilling fluid was obtained based on these experimental results.

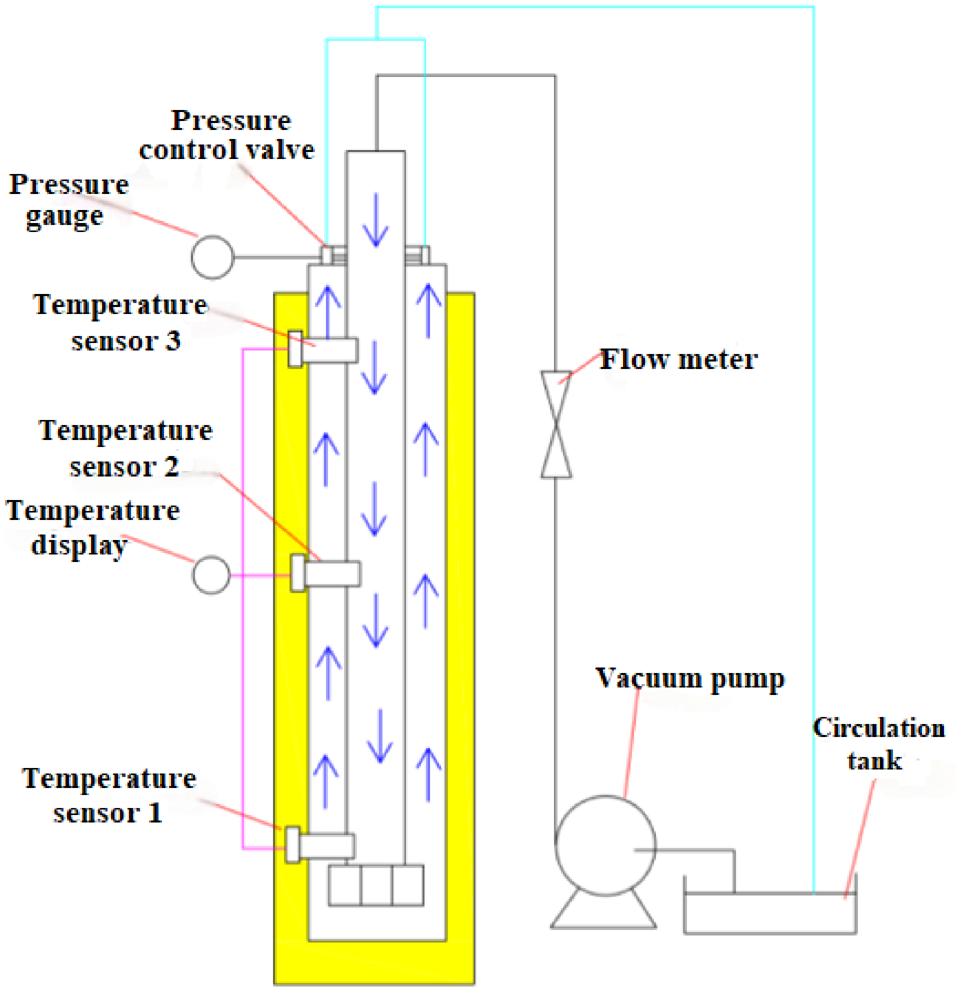
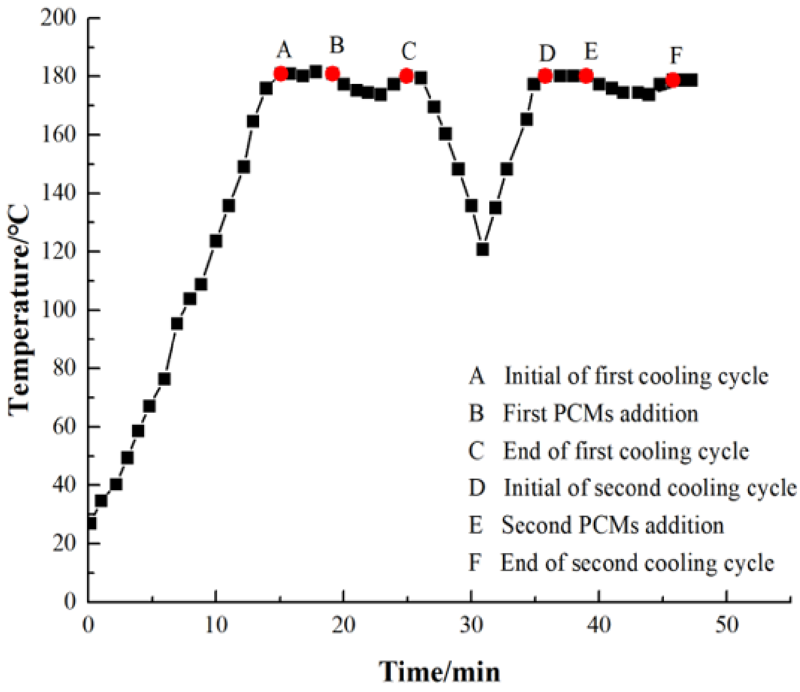



**Figure 3.** Schematic diagram of the drilling fluid circulation cooling simulation test equipment

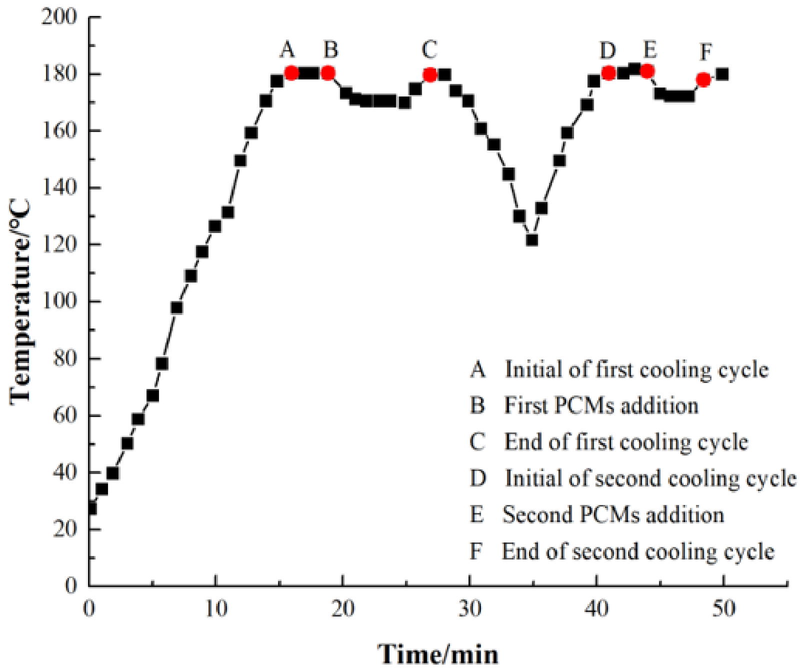
### 4.2 Experimental Results of the Drilling Fluid's Cooling Performance

The cooling performance of PCM-enhanced drilling fluids was analysed using PCM 2 as an example because of its larger latent heat of phase change to maintain better cooling effect. Figure 4 illustrates the experimental results. It was observed that when the bottom-hole drilling fluid temperature reached 180℃, circulating a high-temperature resistant drilling fluid containing PCM 2. At the elevated temperatures of the bottom-hole environment, PCM 2 underwent a phase transition near its phase transition temperature, absorbing a substantial amount of heat in a "phase change heat storage" process. This resulted in a reduction in the circulating temperature of the bottom-hole drilling fluid. The reduction in bottom-hole circulating temperature was found to be more pronounced with increasing concentrations of PCM 2. When PCM 2 was added at a concentration of 3%, the bottom-hole temperature decreased by approximately 5℃. As the concentration of PCM 2 was increased to 6%, 9%, 12%, and 15%, the bottom-hole temperature was reduced by approximately 9℃, 16℃, 20℃, and 24℃, respectively.

To simulate the cooling performance of PCMs under continuous circulation conditions, a second cooling experiment was conducted. After completing the first cooling experiment, the high-temperature resistant drilling fluid containing PCM 2 (phase transition temperature of 120℃) was cooled to approximately 60℃ and recirculated into the simulated wellbore. Analysis of Figure 4 further indicates that, due to the reversible nature of the phase transition process, characterised by "heat storage and release," the PCM-enhanced drilling fluid continued to exhibit effective cooling performance upon re-circulation. The temperature reduction achieved in the second cooling cycle differed by less than 2℃ from that observed in the first cycle. These results demonstrate that the PCM exhibits excellent reusability and confirm the feasibility of reducing circulating temperatures of the drilling fluid through the "phase change heat storage principle" of PCMs.




(a)

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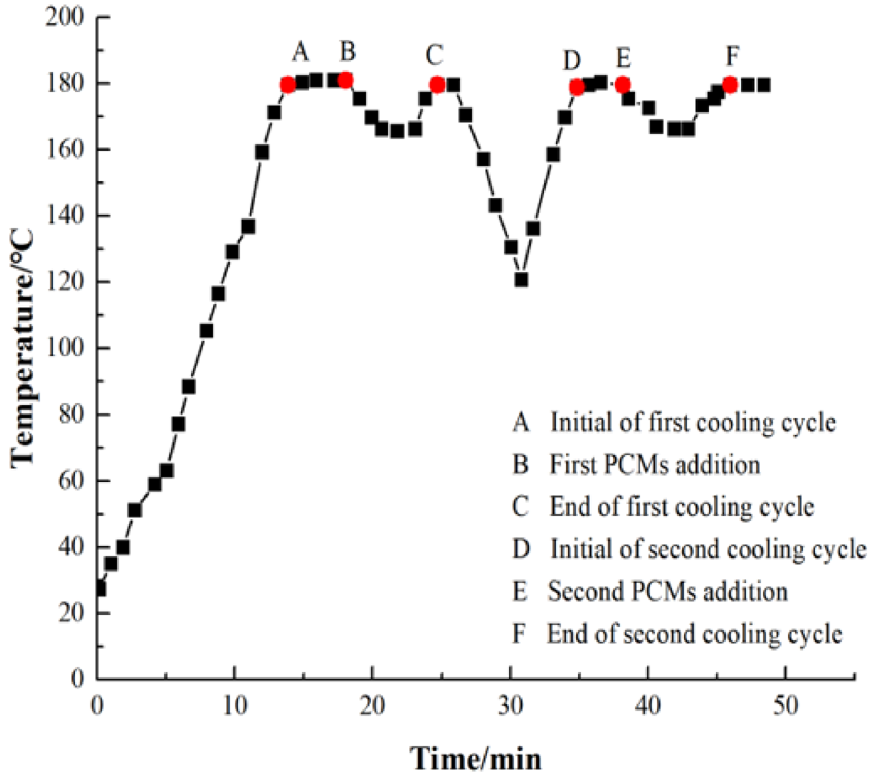
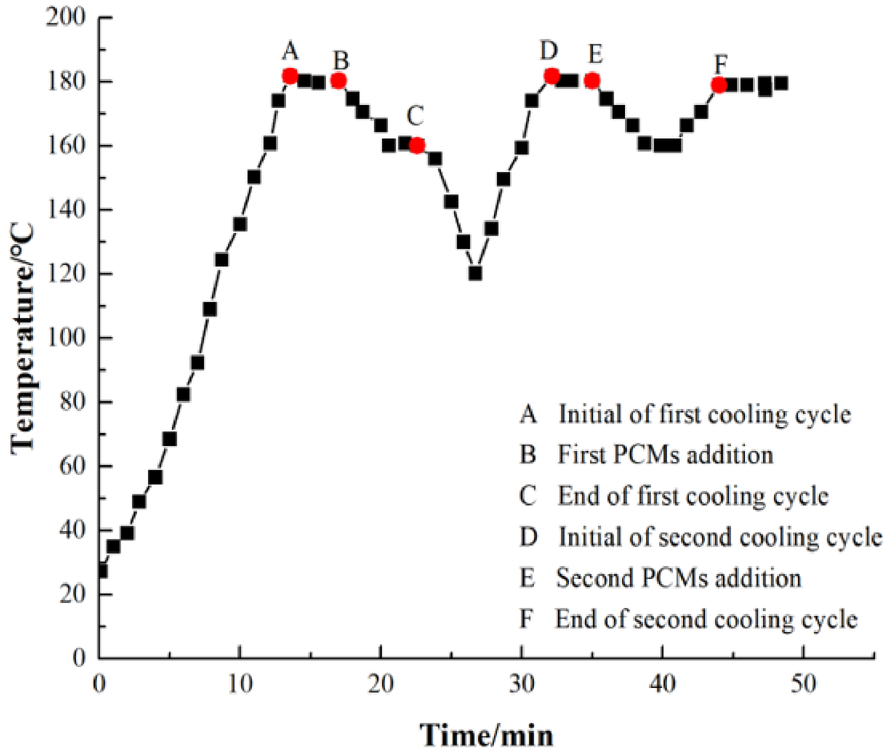
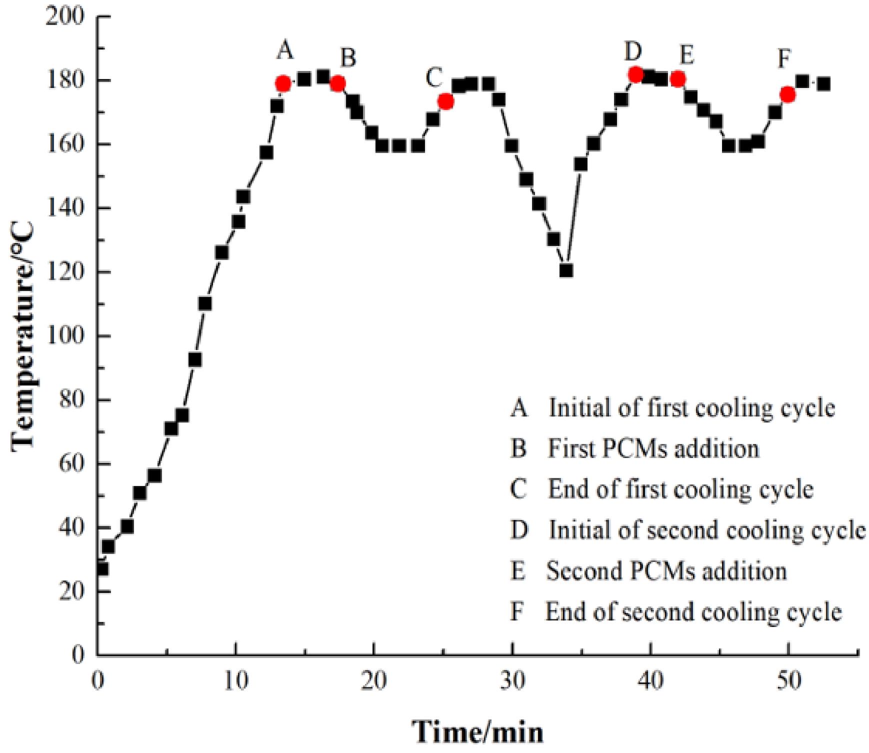

Temperature/°C
Time/min
A Initial of first cooling cycle
B First PCMs addition
C End of first cooling cycle
D Initial of second cooling cycle
E Second PCMs addition
F End of second cooling cycle

(c)


Temperature/°C
Time/min
A Initial of first cooling cycle
B First PCMs addition
C End of first cooling cycle
D Initial of second cooling cycle
E Second PCMs addition
F End of second cooling cycle

(d)




(e)

**Figure 4.** Cooling performance curves of the drilling fluid with PCM 2 at various concentrations (a) 3%, (b) 6%, (c) 9%, (d) 12%, and (e) 15%

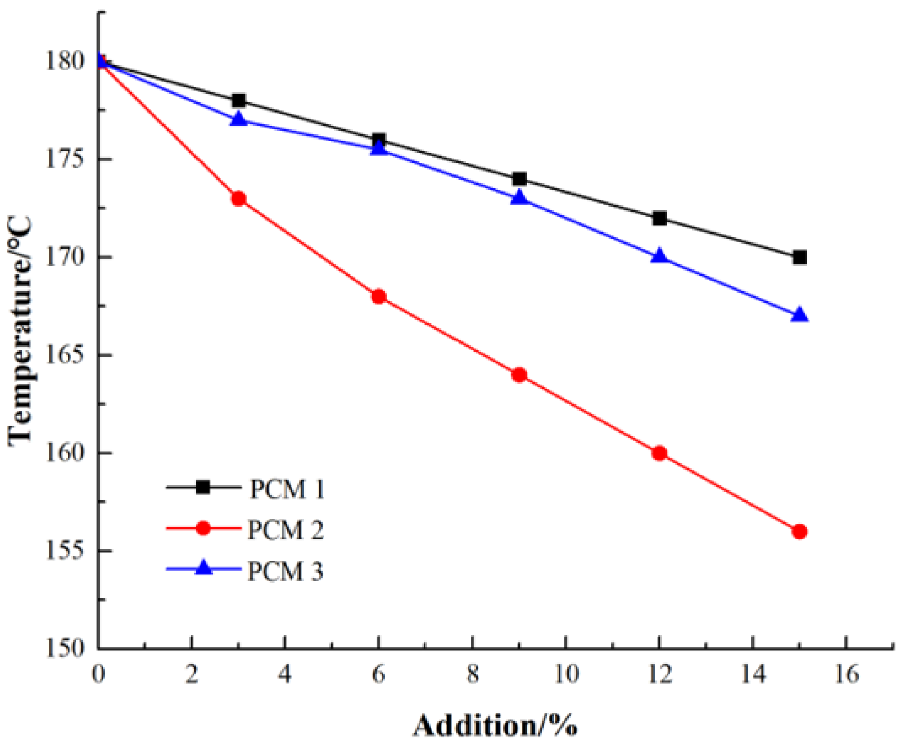



**Figure 5.** Experimental results of cooling performance for PCMs 1-3 in the drilling fluid

Figure 5 presents the experimental results of the cooling performance of PCMs 1, 2, and 3 in the drilling fluid. Analysis indicates that all three PCMs demonstrated satisfactory cooling performance. Using a reduction in drilling fluid temperature of 10℃ as the evaluation criterion, the minimum required concentrations of PCM 1, PCM 2, and PCM 3 were determined to be 15%, 6%, and 12%, respectively. PCM 2 exhibited the best cooling performance, attributed to its highest latent heat of phase change among the tested materials. These results highlight the significant influence of latent heat on the cooling performance of PCMs in drilling fluids. Higher latent heat was associated with more effective temperature reduction during circulation.

## 5 Conclusions and Insights

Phase change materials (PCMs) are widely used to regulate ambient temperature in the aerospace, military, construction, and refrigeration industries through absorbing or releasing thermal energy through reversible transformations, which could be a potential method for regulating the circulating temperature of drilling fluids in ultra-deep wells with extreme thermal conditions.

In this study, the feasibility of reducing circulating temperatures of the drilling fluid based on the "phase change heat storage principle" of PCMs was demonstrated through theoretical analysis and simulated experiments, which could be an economical way to replace expensive cooling equipment for drilling fluid cooling in the future. Three PCMs were selected with phase transition temperatures ranging from 120℃ to 145℃ and latent heat values between 86.2 J/g and 280.4 J/g. These materials exhibited excellent phase change heat storage characteristics and good compatibility with drilling fluids.

Taking PCM 2 as an example, the incorporation of PCMs into the drilling fluid was shown to effectively reduce circulating temperatures. At a PCM concentration of 12%, the circulating temperature of the drilling fluid was reduced by up to 20℃, which highlights the potential of PCMs to significantly enhance drilling fluid thermal management, particularly in high-temperature deep wells with bottom-hole temperatures exceeding 180℃.

## Data Availability

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

## Conflicts of Interest

The authors declare no conflict of interest.

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