IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Heat and Technology
Vol. 41, No. 5, October, 2023, pp. 1177-1186
Journal homepage: http://iieta.org/journals/ijht

Analysis of Critical Thermodynamic Parameters in Oil-Based Drilling Fluids: Implications for Wellbore Temperature Control

Yang Yu[1,2], Yinao Su[1,3*], Xuesong Zhao[2], Mengna Liang[1], Yongkang Li[1]

[1] Key Laboratory of Ministry of Education for Enhanced Oil and Gas Recovery, Northeast Petroleum University, Daqing 163318, China
[2] PetroChina Jilin Oilfield Company, China National Petroleum Corporation, Songyuan 138000, China
[3] CNPC Engineering Technology R & D Company Limited, China National Petroleum Corporation, Beijing 102206, China

Corresponding Author Email: 261980020409@nepu.edu.cn

https://doi.org/10.18280/ijht.410508

Received: 6 June 2023
Revised: 13 September 2023
Accepted: 20 September 2023
Available online: 31 October 2023

Keywords:
failure of rotary steering tools, wellbore temperature, oil-based drilling fluids, thermodynamic parameters, sensitivity analysis

ABSTRACT

In the quest to exploit unconventional oil and gas resources within China's borders, rotary steering tools have been increasingly utilized to enhance the drilling speed and ensure the precision of the drilling trajectory. Nevertheless, the prevalent high temperatures within the well have been identified as a primary cause of failure in these rotary steering tools, thereby impeding the drilling process significantly. Consequently, the real-time prediction and meticulous control of the wellbore temperature have emerged as pivotal elements in the enhancement of drilling efficiency. A myriad of factors contribute to the wellbore temperature, among which the thermodynamic parameters of the drilling fluid play a vital role. In this context, a comprehensive analysis has been conducted on various oil-based drilling fluids, with a focus on controlling their fundamental properties, and the thermodynamic parameters have been meticulously measured. Subsequently, the sensitivity of these parameters to various factors has been scrutinized based on the experimental outcomes. The findings delineate that within a drilling fluid oil-water ratio range of 0.75 to 0.9, the impact of the sensitive factors on thermodynamic performance is ranked as follows: solid content > oil-water ratio > plastic viscosity > apparent viscosity. It is noted that a one percentage unit augmentation in solid content results in a 0.01284 kJ/(kg·K) decrement in specific heat capacity, while the thermal conductivity experiences a 0.00528 W/(m·K) increment. Conversely, when the oil-water ratio ranges from 0.9 to 1, the impact hierarchy of sensitive factors transforms to: oil-water ratio > solid content > plastic viscosity > apparent viscosity, with a one percentage unit increase in oil-water ratio leading to a 0.04121 kJ/(kg·K) decrease in specific heat capacity and a 0.02669 W/(m·K) reduction in thermal conductivity. The findings underscore that variations in the oil-water ratio yield disparate impacts on the thermodynamic performance of oil-based drilling fluids.

1. INTRODUCTION

Amidst the dwindling reserves of easily accessible onshore oil and gas resources, the global focus of exploration and development activities has been shifting toward unconventional and intricate reserves, encompassing shale gas, ultra-deep layers, and ultra-deep water strata. The prevalence of high pressure/high temperature (HPHT) wells is noted predominantly in deep and ultra-deep drilling endeavors. In scenarios where water-based drilling fluids are rendered inadequate, oil-based drilling fluids have been progressively adopted due to their intrinsic benefits, such as thermal resistance, shale stabilization, hydrate suppression, and reservoir preservation [1-3]. These fluids have thus established themselves as the principal technology for drilling in complex formations, including high-temperature deep wells, highly deviated directional wells, and offshore deep water wells. In conjunction with the deployment of rotary steering tools, penetration rates in the horizontal sections of wellbores have been recorded at impressive levels, reaching up to 15.78m/h [4], thereby significantly enhancing both drilling speed and trajectory precision. However, an analysis of actual drilling scenarios reveals that bottom hole temperatures can exceed 140°C. The escalation of heat in the lower well, occasionally surpassing the original formation temperature, is attributed to the cumulative effects of friction from drilling fluid circulation, rotation of the drill string, and the rock-breaking action of the drill bit. This thermal increase often surpasses the heat dissipation capabilities of the circulating drilling fluid, potentially leading to the failure of rotary steering tools due to excessive temperatures, which paradoxically results in a reduction in drilling speed [5]. In light of these challenges, extensive research has been undertaken by various scholars, employing both indoor experiments and the development of wellbore temperature field models during drilling fluid circulation, with the aim of identifying and analyzing the sensitive factors influencing wellbore temperature. The outcomes of these studies are integral to the broader discourse and form the basis of the ensuing analysis.

In the realm of wellbore temperature analysis, a pivotal study was conducted by Zhong Bing et al. in 2000, utilizing a comprehensive data set derived from a three-dimensional numerical model to systematically assess the sensitivity of various factors influencing wellbore temperature [6]. The findings underscored the substantial impact of the thermophysical parameters of both drilling fluids and formations, highlighting the imperative of accurately determining these parameter values within the drilled area to facilitate precise wellbore temperature simulations. Subsequent to this, Wen et al. [7] embarked on a meticulous examination in 2008, exploring the influence of density variations in polymer and polysulfonate drilling fluids on their thermal conductivity. Employing consistent drilling fluid systems and temperature conditions, it was observed that an increase in density correlated with a rise in thermal conductivity. Furthermore, a comparative analysis of thermal conductivity measurements across different drilling fluid systems revealed distinct variations, elucidating the dependency of drilling fluid thermal conductivity on its compositional attributes.

In a similar vein, Guan et al. [8] conducted controlled laboratory experiments on polymer and polysulfonate drilling fluids in 2011, deploying the transient hot wire method to ascertain the thermal conductivity of the drilling fluids, whilst the specific heat capacity was determined through the application of the heat balance formula. The results indicated a direct correlation between increased drilling fluid density and elevated thermal conductivity, alongside a reduction in specific heat. This phenomenon was attributed to the relatively high thermal conductivity and low specific heat of barite, a commonly used additive in drilling fluids. As the density of the drilling fluid escalated, the proportion of barite increased, culminating in enhanced thermal conductivity and diminished specific heat capacity of the drilling fluid.

In 2017, an experimental investigation by Li et al. [9] revealed a notable correlation between the oil-water ratio in drilling fluid and its plastic viscosity. With a consistent dosage of treatment agent, a reduction in the oil-water ratio from 90:10 to 60:40 was observed to result in an increase of the plastic viscosity of oil-based drilling fluid from 16 mPa·s to 55 mPa·s. This finding illuminated the significant impact of the drilling fluid's oil-water ratio on its plastic viscosity. Concurrently, Wu et al. [10] developed a three-dimensional model capable of simultaneously calculating both the heat exchange and in-plane thermoelastic stress between the drilling fluid and the adjacent media, comprising drill pipes and rock layers. The results of this study suggested that prolonging the drilling fluid's circulation time contributes to a reduction in temperature at the bottom of the wellbore. Crucially, it was determined that the heat transfer coefficient of the drilling fluid is contingent upon its flow state, which is interrelated with its viscosity and density.

In a study conducted in 2019, Zhang [11] established a numerical model to quantify the rate of change in bottom hole temperature under the influence of various factors, each adjusted by a single percentage unit. This work identified the specific heat capacity of the drilling fluid as the most influential factor on bottom hole temperature, with the exception of drilling fluid inlet temperature, geothermal gradient, and drilling fluid displacement. However, it is noteworthy that the drilling fluid considered in this model was exclusively saline-based. Further insights were provided in the same year by Yang et al. [12], who delved into the transient heat transfer mechanisms within various segments of the wellbore and formation. Their comprehensive analysis encompassed the thermal behaviour changes in these regions, culminating in the development and solution of a model that quantified the influence of each sensitive factor on bottom hole temperature. The findings underscored the paramount importance of drilling fluid properties, specifically its circulation time, specific heat capacity, and density, in determining wellbore thermal behaviour, accounting for influences of 19.98% and 12.219%, respectively.

In 2021, simulations employing Landmark software were conducted by Luo et al. [13], yielding results that underscored the impact of drilling fluid parameters on circulating temperatures. It was revealed that an increase in the drilling fluid's displacement led to a decrease in circulating temperature by 5.866℃, while an augmentation in drilling fluid density resulted in an elevation of the bottom hole circulating temperature, ranging from 1.944℃ to 4.154℃. Subsequently, Ruan et al. [14], within the same year, formulated a wellbore circulation temperature field model specifically for oil-based drilling fluids, grounded in the principles of solid-liquid heat conduction, energy, and material conservation. The finite difference numerical method was employed for solving the model. The results elucidated that the displacement and density of the drilling fluid, alongside the thermophysical parameters of the drilling fluid, which were found to be positively correlated with the solid volume fraction, emerged as principal influencing factors. A higher density of drilling fluid was associated with an increase in both the solid volume fraction and the constant pressure specific heat capacity of the drilling fluid.

Advancing into 2022, Lin et al. [15] demonstrated that alterations in the circulation time and displacement of drilling fluid, as well as a reduction in the inlet temperature of drilling fluid, exerted a pronounced influence on the cooling efficiency of drilling tools.

In 2023, a non-stationary heat transfer model, integrated with the temperature characteristics of drilling fluid, was applied to high-temperature geothermal wells by Wang [16]. The findings of this research delineated several factors as being particularly sensitive to wellbore temperature, including the specific heat capacity, thermal conductivity, volumetric flow rate, density, and viscosity of the drilling fluid.

Internationally and domestically, various surface cooling methodologies, including natural cooling, mixed low-temperature medium cooling, and forced cooling via cooling devices, have been predominantly employed [17-22] to mitigate the circulating temperature of drilling fluid by reducing the injection temperature at the wellhead. However, challenges such as substantial equipment investment, elevated energy consumption, and considerable utilization of cooling media have rendered these methods insufficient to satisfy the cooling demands of drilling fluid in high-temperature wells. In 2021, an innovative approach was introduced by Liu et al. [23], wherein phase change materials were incorporated into drilling fluids for the first time. This integration facilitated the creation of heat storage composite drilling fluid, enhancing the thermodynamic properties of the drilling fluid through the exploitation of its inherent capacity to absorb phase change latent heat and maintain temperature stability (phase change heat storage) during the phase transition. Subsequently, in 2022, Li [24] established a correlation between the density of drilling fluid and the performance of downhole drilling tools. It was observed that a reduction in drilling fluid density from 2.20 g/cm^3 to 1.82 g/cm^3 resulted in a decrease in the failure rate of rotary steering instruments from 50% to 30%, concurrently with an increase in the average mechanical drilling speed of the fourth spud section from 8 m/h to 11.44 m/h, constituting an enhancement of 43%. This evidence underscores the potential of adjusting the drilling fluid's density as a viable strategy to improve its thermodynamic performance and, consequently, facilitate the cooling of downhole drilling tools.

Analysis of both domestic and international research outcomes underscores the substantial influence exerted by the thermodynamic parameters of drilling fluid on wellbore temperature. Notably, a dearth of investigation into the thermodynamic parameters of oil-based drilling fluids is evident in the reviewed studies. In light of the insights garnered from previous research, this article has undertaken the regulation of the basic properties of oil-based drilling fluid. The sensitive factors and the extent of influence of the thermodynamic parameters of oil-based drilling fluid have been subjected to thorough examination. It has been ensured that the adjustment of the basic properties of oil-based drilling fluid, with the aim of altering its thermodynamic properties, aligns with the prerequisites of drilling technology. This strategic modification facilitates a reduction in drilling fluid temperature, even at a constant formation temperature. Such a methodology not only serves as a foundation for the proposition of optimization measures for the precise prediction of downhole temperature distribution but also contributes to the enhanced control of downhole temperature. This critical examination and subsequent adjustment of the oil-based drilling fluid’s properties underscore a significant advancement in thermal management within drilling operations.

2. EXPERIMENT

2.1 Materials, equipment, and parameters

The drilling fluid used in the experiment was oil-based drilling fluid, and its main components are listed in Table 1.

Table 1. Composition and content of oil-based drilling fluid

Composition	Content
Diesel oil	75%~100%
$CaCl_2$ aqueous solution with the concentration of 30%	0~25%
Main emulsifier, auxiliary emulsifier, filter loss reducer, organic soil	4% each
Quicklime (calcium oxide)	3%

For the determination of the apparent viscosity, plastic viscosity, density, and specific heat of the oil-based drilling fluid, the respective instruments used in the experimetn were a six-speed rotary viscometer, model ZNN-D6, and a densimeter, model YM-2, both sourced from Qingdao Hengtaida Electromechanical Equipment Co., Ltd. Additionally, a thermal constant analyzer, model TPS 2500 S from Hot Disk AB Company, and a solid content analyzer, model ZNG-A from Qingdao Hengtaida Electromechanical Equipment Co., Ltd., were employed. The stirring of the oil-based drilling fluid was facilitated by a GJ-B12K frequency conversion high-speed mixer from Qingdao Senxin Electromechanical Equipment Co., Ltd. An XGRL-4A high-temperature roller heating furnace from Qingdao Haitongda Special Instrument Co., Ltd. was utilized for the aging experiment of the oil-based drilling fluid, simulating the circulation process in the downhole annular space. This procedure ensures a homogeneous mixture of the drilling fluid components, culminating in a more stable system. To weigh the mass of each solid additive, a ZCS electronic balance from Ruian Haozhan Weighing Instrument Co., Ltd. was used.

2.2 Methods and procedures

A range of oil-based drilling fluids were prepared, varying in solid content, oil-water ratio, solid particle size, and viscosity. The components-diesel oil, main emulsifier, auxiliary emulsifier, filtrate reducer, quicklime, $CaCl_2$ aqueous solution, and organic soil-were sequentially introduced into a stirring cup. Each component was subjected to high-speed stirring for 10 minutes using a frequency conversion high-speed stirrer, except for the $CaCl_2$ aqueous solution and organic soil, which were stirred for 30 minutes and 1 hour, respectively. Following this, the oil-based drilling fluid was placed in a high-temperature roller heating furnace, maintained at 120°C for 16 hours, to undergo aging. This was succeeded by high-speed stirring at 12000r/min for 10 minutes. Only upon completion of these procedures was the performance of the drilling fluid assessed. It is critical to underscore that the preparation and measurement of the oil-based drilling fluid adhered strictly to predefined procedural steps, ensuring the precision and comparability of the measurement results.

3. RESULTS AND DISCUSSION

3.1 Influence of drilling fluid’s solid content on its thermodynamic properties

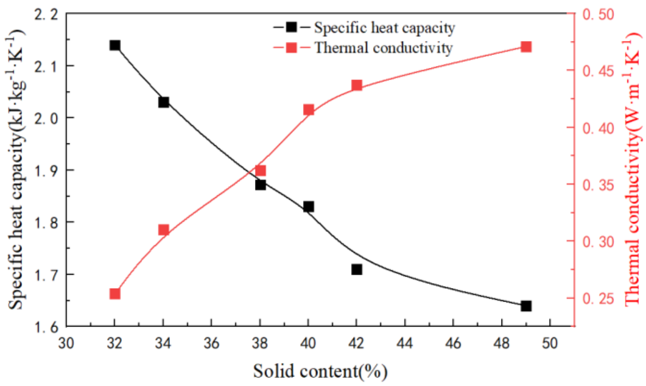


Figure 1. Effect of solid content on specific heat capacity and thermal conductivity of drilling fluid

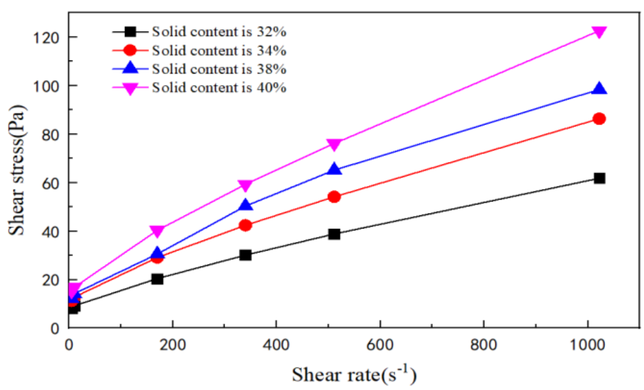


Figure 2. Rheological curves of drilling fluid with different solid contents

In the context of short-term circulation of drilling fluid, it has been observed that the majority of cuttings transported to the surface by the drilling fluid are efficiently removed via solid control equipment, thereby exerting minimal impact on the solid content of the drilling fluid. Nevertheless, as the circulation time of the drilling fluid extends, certain cuttings that are not promptly eliminated by the solid control equipment may re-enter the wellbore, subsequently participating in the circulation of the drilling fluid. It is, therefore, more representative of actual drilling conditions to take into account the influence of drilling cuttings. The examination of thermodynamic properties of the drilling fluid, regulated by diverse solid contents, offers a more precise depiction of the thermodynamic properties' variation over extended circulation periods than experiments conducted under varied drilling fluid densities.

In scenarios where the solid content of the drilling fluid was altered, both the thermophysical parameters and the rheological curve of the drilling fluid were subjected to measurement. The ensuing results are depicted in Figures 1 and 2, respectively.

In the conducted experiment, the solid content of the drilling fluid was intentionally designed to range between 30% and 50%, reflecting the actual conditions of a drilling site. Referring to Figure 1, a decline in specific heat capacity and a simultaneous increase in thermal conductivity were observed as the solid content of the drilling fluid increased. A scatter plot, correlating the solid phase content with the thermophysical parameters of the drilling fluid, was constructed using SPSS software. The overall trend of the data was analyzed, and the functional form was deduced based on the empirical observations. Subsequent regression analysis led to the determination of function expressions, revealing a decreasing trend in the specific heat of the drilling fluid as a function of Eq. (1).

$$c = 0.0014x^2 - 0.1452\,x + 5.3237 \qquad (1)$$

Eq. (2) gives the increasing trend in thermal conductivity.

$$k = -0.0007\,x^2 + 0.0697\,x - 1.2555 \qquad (2)$$

Figure 2 illustrates an upward trend in both apparent viscosity and plastic viscosity of the drilling fluid with increasing solid content.

$$Q = cm\Delta T \qquad (3)$$

The data presented in Table 2 facilitates a comparative analysis between the colloidal solution of oil-based drilling fluid and solid particles. It is observed that the latter possesses a reduced specific heat capacity and an elevated thermal conductivity. An increase in the proportion of solid particles within the drilling fluid correlates with an enhanced volumetric occupancy by these particles, culminating in a diminished specific heat capacity and an augmented thermal conductivity of the drilling fluid. In scenarios where the heat transferred from the formation to the drilling fluid per unit area remains constant. According to heat transfer Eq. (3), with the reduction in the drilling fluid's specific heat capacity, there is a corresponding decrease in its ability to absorb heat. This phenomenon leads to a heightened temperature increase per unit mass of the drilling fluid. Consequently, a more pronounced temperature gradient is established between the drill bit and the drill pipe, culminating in an enhanced driving force for heat transfer. Similarly, an escalation in the solid content of the drilling fluid is correlated with an increase in both thermal conductivity and diffusivity, facilitating a more rapid internal heat transfer within the drilling fluid to the drill rod and bit. This rapid heat transfer has the potential to precipitate the failure of rotary steering tools due to the onset of high temperatures.

Table 2. Thermophysical parameters of each component of oil-based drilling fluid

Component	Specific Heat Capacity ($J\cdot g^{-1}\cdot {}^\circ C^{-1}$)	Thermal Conductivity ($W\cdot m^{-1}\cdot {}^\circ C^{-1}$)
Diesel oil	2.4	0.12
Water	4.2	0.60~0.68 (20~100°C)
Barite	0.6	2.00
Drill cuttings	0.8~1.2	1.50~3.00

3.2 Influence of oil-water ratio of drilling fluid on its thermodynamic properties

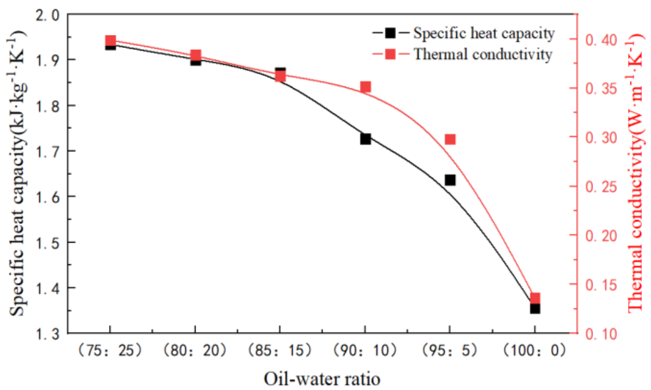


Figure 3. Effect of oil-water ratio on specific heat capacity and thermal conductivity of drilling fluid

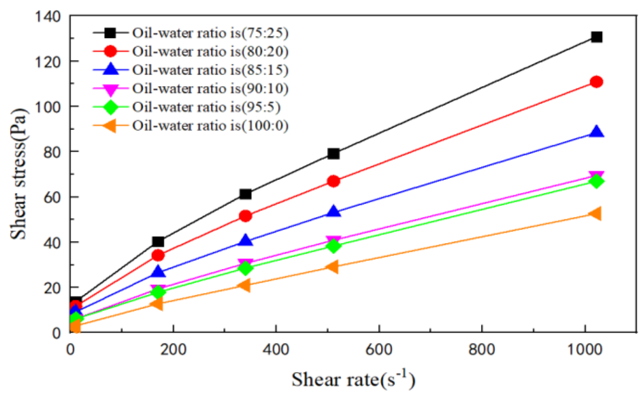


Figure 4. Rheological curves of drilling fluid under different oil-water ratios

In the context of varying the oil-water ratio within the oil-based drilling fluid, measurements were taken of both the thermophysical parameters and the rheological properties of the fluid. The outcomes of these measurements are respectively depicted in Figures 3 and 4.

In the experiment, the designed oil-water ratio was between 75:25 to a pure oil phase of 100:0. Figure 3 shows the relationship between the oil-water ratio and the thermophysical properties of the drilling fluid, that an increase in the oil content correlates with a decrease in both the specific heat capacity and the thermal conductivity of the drilling fluid. With an increment in the oil-water ratio of the drilling fluid, a diminishing trend in the specific heat capacity was discerned, adhering to the functional relationship delineated by Eq. (4). In instances where the oil-water ratio stood at 75:25, the variable x was assigned a value of 0.75, exemplifying this observed trend.

$$c = -34.2222x^3 + 79.2333x^2 - 61.8090x + 18.1612 \tag{4}$$

The thermal conductivity exhibited a downward trajectory, conforming to the functional form presented in Eq. (5). Notably, a pronounced acceleration in the reduction of both the specific heat capacity and thermal conductivity of the drilling fluid was observed when the oil-water ratio surpassed 0.9.

$$k = -278x^4 + 923.4148x^3 - 1148.3439x^2 + 633.3086x - 130.2437 \tag{5}$$

In Figure 4, a discernible trend is observed wherein an increase in the oil-water ratio of the drilling fluid correlates with a reduction in both its apparent viscosity and plastic viscosity.

Water possesses a specific heat capacity nearly twice that of diesel oil, and its thermal conductivity approximately quintuples that of diesel oil. As the oil-water ratio escalates, resulting in a heightened proportion of base oil within the drilling fluid, a subsequent diminution in both the specific heat capacity and thermal conductivity of the drilling fluid is witnessed. Although a reduced thermal conductivity diminishes the drilling fluid's capacity for heat transfer, it is noteworthy that the specific heat capacity experiences a more rapid rate of decrease. Thus, it becomes apparent that an augmentation in the oil-water ratio of the drilling fluid leads to a diminished specific heat capacity, thereby attenuating its ability to absorb heat. Correspondingly, in accordance with the principles outlined in heat transfer Eq. (3), such conditions heighten the susceptibility of rotary steering tools to failure due to excessive temperatures.

3.3 Influence of solid particle size distribution on thermodynamic properties of drilling fluid

Variations in the size distribution of solid particles within the drilling fluid were explored, with subsequent measurements taken of both the thermodynamic parameters and rheological behavior of the drilling fluid. The findings from these measurements are presented in Figures 5 and 6, respectively.

The initial barite powder was segregated into distinct particle size intervals, encompassing 20-50 mesh, 50-100 mesh, 100-150 mesh, and beyond 150 mesh. A laser particle size analyzer was employed to quantify the particle size of the barite powder, revealing that the barite powder utilized in the experiments predominantly fell within the 12-16μm range (where 1μm=1000 nm). Analysis of Figures 5 and 6 indicates that variations in the particle size of the barite powder incorporated into the drilling fluid did not markedly influence its specific heat capacity, thermal conductivity, or viscosity. This observation suggests that alterations in the particle size of barite powder utilized for on-site slurry formulation exert minimal impact on the thermodynamic performance of the drilling fluid within its conventional particle size spectrum.

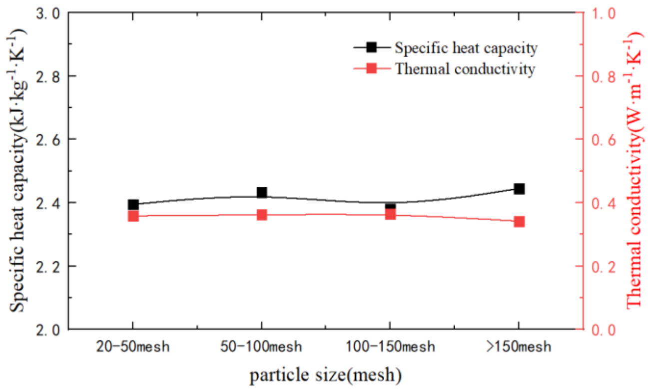


Figure 5. Effect of particle size on specific heat capacity and thermal conductivity of drilling fluid

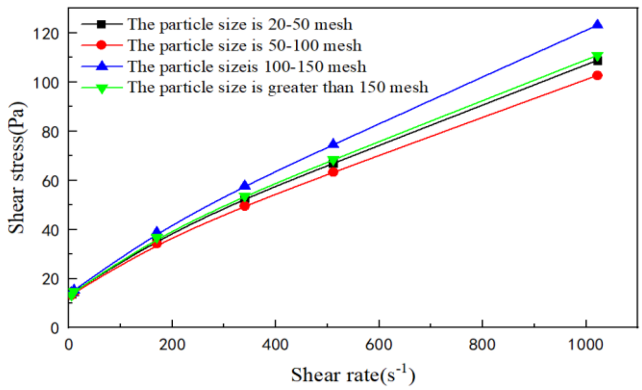


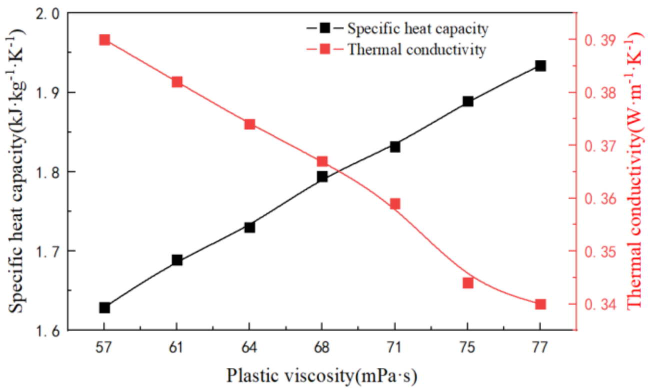
Figure 6. Rheological curves of drilling fluids with different particle sizes

Contrastingly, a considerable body of literature on nanoparticles [25-30] articulates that these minute particles, with dimensions ranging from 1 to 100 nm, hold the potential to substantially enhance the heat transfer efficacy of conventional drilling fluids, optimize the cooling of drilling instruments, and find extensive applications in HPHT drilling scenarios. This enhancement is attributable to the nanoparticles' expansive total surface area, relative to particles of larger dimensions, under equivalent volume conditions. An increased total surface area facilitates a more substantial contact interface with the drilling fluid colloid solution. Consequently, nano drilling fluids, in comparison to their conventional oil-based counterparts, exhibit pronounced improvements in both thermal conductivity efficiency and specific heat capacity. Furthermore, as the particle size of the nanoparticles diminishes, these enhancements in the thermophysical properties of the drilling fluid become increasingly pronounced. The barite particles subjected to screening in this study, characterized by their larger particle size, limited total surface area, and reduced contact interface with the drilling fluid colloid solution, did not exhibit significant variations in thermodynamic parameters upon alteration of barite particle size.

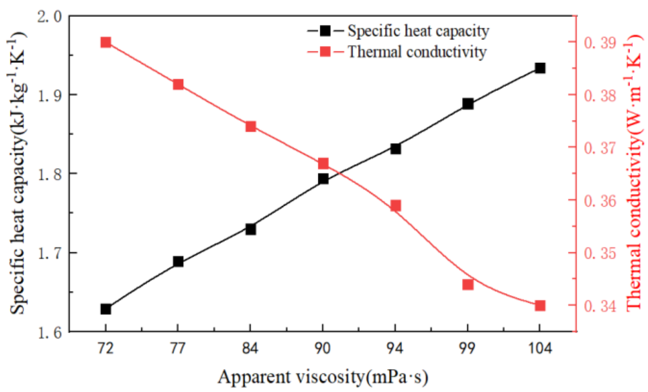
It is crucial to elucidate that while changes in the solid content and oil-water ratio of the drilling fluid do indeed impact its viscosity, the alterations in the thermodynamic properties of the drilling fluid primarily stem from shifts in its physical properties and compositional ratios (specifically, oil-water and solid-liquid ratios), rather than from modifications in its viscosity per se. Section 3.4 of this paper delves into experiments wherein viscosity modifiers-either reducers or increasers-are introduced to the drilling fluid, thereby altering its flow characteristics. This adjustment, in turn, facilitates an analysis of the corresponding variations in the thermodynamic properties of the drilling fluid.

3.4 Influence of drilling fluid viscosity on its thermodynamic properties

Modifications to the viscosity of the oil-based drilling fluid were achieved through the introduction of either viscosity-reducing or viscosity-increasing agents. Subsequent to these alterations, the thermophysical properties of the drilling fluid were meticulously measured and quantified. The results of these measurements are comprehensively presented in Figure 7.



(a) The influence of plastic viscosity on the thermophysical parameters of drilling fluid



(b) The effect of apparent viscosity on the thermophysical properties of drilling fluids

Figure 7. The effect of viscosity on the specific heat capacity and thermal conductivity of drilling fluid

Figure 7 elucidates the relationship between the drilling fluid's viscosity and its thermophysical properties. It is observed that an increase in the drilling fluid's viscosity correlates with an increase in specific heat capacity, while simultaneously witnessing a reduction in thermal conductivity. Furthermore, a positive trend is discerned in the specific heat capacity in concordance with the escalation of viscosity, adhering to the functional relationship delineated by Eq. (6), where μ_1 represents the apparent viscosity (measured in mPa·s), and μ_2 denotes the plastic viscosity (also expressed in mPa·s).

$$c = 0.8183 + 0.0022\mu_1 + 0.0115\mu_2 \tag{6}$$

The thermal conductivity exhibited a decreasing trajectory, conforming to the relationship outlined in Eq. (7).

$$k = 0.5498 + 0.0008\mu_1 - 0.0037\mu_2 \tag{7}$$

As the viscosity of the drilling fluid escalated, both the thickness and the thermal resistance of the boundary layer in flow-established between the drilling fluid and the formation, as well as between the drilling fluid and the drill string wall-experienced an increase. This phenomenon impeded the flow and heat transfer of the drilling fluid, resulting in a diminished efficiency of convective heat transfer. Consequently, an augmented viscosity of the drilling fluid led to a reduction in the heat absorbed by the drilling fluid from the formation within the annulus, culminating in a corresponding decrease in the bottom-hole temperature.

3.5 Determination of principal influencing factors on the thermophysical properties of drilling fluid

The thermophysical properties of a drilling fluid are characterized by its specific heat capacity and thermal conductivity. The specific heat capacity denotes the capacity of a unit mass of drilling fluid to absorb or release heat upon undergoing a unit change in temperature. A higher specific heat capacity reflects a more robust capacity of the drilling fluid to absorb or release heat. Conversely, a higher thermal conductivity indicates a more efficient heat transfer capability of the drilling fluid. The findings of this study elucidate that the thermodynamic behavior of oil-based drilling fluids is contingent upon a myriad of factors, including the solid content, oil-water ratio, apparent viscosity, and plastic viscosity of the drilling fluid. This section aims to identify the predominant factors influencing the thermophysical parameters of the drilling fluid, drawing upon the experimental data encapsulated in Tables 3-5. Given the disparate units and orders of magnitude associated with oil-water ratio, solid content, viscosity, specific heat capacity, and thermal conductivity, it becomes imperative to neutralize the impact of dimensionality and magnitude variance among the variables to render them comparable. Consequently, this section computes the variations in the specific heat capacity and thermal conductivity of the drilling fluid, attributable to a one percentage unit augmentation in each independent variable, as delineated in Tables 6 to 11.

Table 3. Changes of viscosity and thermodynamic parameters of drilling fluid under different solid content

Solid Content (%)	Plastic Viscosity (mPa·s)	Apparent Viscosity (mPa·s)	Specific Heat Capacity (kJ·kg^{-1}·K^{-1})	Thermal Conductivity (W·m^{-1}·K^{-1})
32	45	60.5	2.140	0.2539
34	63	84.5	2.030	0.3101
38	69	86.5	1.872	0.3622
40	91	120.0	1.831	0.4158

Table 4. Changes of viscosity and thermodynamic parameters of drilling fluid under different oil-water ratios

Oil-Water Ratios	Plastic Viscosity (mPa·s)	Apparent Viscosity (mPa·s)	Specific Heat Capacity ($kJ·kg^{-1}·K^{-1}$)	Thermal Conductivity ($W·m^{-1}·K^{-1}$)
0.75	101	128.0	1.934	0.3988
0.80	86	108.5	1.901	0.3839
0.85	69	86.5	1.872	0.3622
0.90	56	68.0	1.727	0.3515
0.95	56	65.5	1.637	0.2980
1.00	46	51.5	1.356	0.1361

Table 5. Changes of thermodynamic parameters of drilling fluid under different viscosities

Plastic Viscosity (mPa·s)	Apparent Viscosity (mPa·s)	Specific Heat Capacity ($kJ·kg^{-1}·K^{-1}$)	Thermal Conductivity ($W·m^{-1}·K^{-1}$)
57	72	1.629	0.39
61	77	1.689	0.382
64	84	1.73	0.374
68	90	1.794	0.367
71	94	1.832	0.359
75	99	1.889	0.344
77	104	1.934	0.34

3.5.1 Influence of basic performance parameters on specific heat capacity of drilling fluid

Referencing Table 6, it is observed that a one percentage unit augmentation in solid phase content correlates with an approximate reduction of 0.01284 kJ/(kg·K) in the specific heat capacity.

Table 7 reveals that in the oil-water ratio range of 0.75 to 0.9, a one percentage unit increment in the oil-water ratio corresponds to a reduction of approximately 0.01128 kJ/(kg·K) in the specific heat capacity. This rate of change is smaller than that associated with a similar increase in solid content, indicating a predominant influence of solid content over the oil-water ratio in this specific range. Conversely, when the oil-water ratio ranges from 0.9 to 1, the specific heat capacity experiences a more substantial decrease of approximately 0.04121 kJ/(kg·K) per percentage unit increase in the oil-water ratio. In this interval, the oil-water ratio exerts a more significant impact on the specific heat capacity of the drilling fluid than the solid content does. This phenomenon can be attributed to the markedly higher specific heat capacity of water compared to diesel oil. As the oil-water ratio surpasses 0.9, there is a substantial increment in the proportion of diesel oil in the oil-based drilling fluid, leading to an accelerated decline in the specific heat capacity of the drilling fluid. Consequently, the influence of the oil-water ratio on the specific heat capacity becomes more pronounced, surpassing that of the solid content.

As discerned from Table 8, plastic viscosity exerts a more substantial impact on the specific heat capacity of the drilling fluid compared to apparent viscosity. The data in Table 8 illustrates that for every percentage unit increase in plastic viscosity, the specific heat capacity of the drilling fluid augments by approximately 0.01011 kJ/(kg·K).

From this analysis, it becomes evident that in the oil-water ratio range of 0.75 to 0.9, the hierarchy of influence on the specific heat capacity of oil-based drilling fluid is as follows: solid content > oil-water ratio > plastic viscosity > apparent viscosity. Conversely, when the oil-water ratio ranges from 0.9 to 1, the order of impact shifts to: oil-water ratio > solid content > plastic viscosity > apparent viscosity.

Table 6. Variation in the specific heat capacity of drilling fluid with a one percentage unit alteration in solid content

The Solid Content Before Changing (%)	The Specific Heat Capacity Before Changing ($kJ·kg^{-1}·K^{-1}$)	The Solid Content After Changing (%)	The Specific Heat Capacity After Changing ($kJ·kg^{-1}·K^{-1}$)	Difference (After Change-Before Change)
32	2.11090	32.32	2.09325	-0.01765
34	2.00530	34.34	1.98846	-0.01684
38	1.82770	38.38	1.81316	-0.01454
40	1.75570	40.4	1.74264	-0.01306
42	1.69490	42.42	1.68355	-0.01135
49	1.57030	49.49	1.56672	-0.00358

Table 7. Variation in the specific heat capacity of drilling fluid with a one percentage unit alteration in oil-water ratio

The Oil-Water Ratio Before Changing	The Specific Heat Capacity Before Changing ($kJ·kg^{-1}·K^{-1}$)	The Oil-Water Ratio After Changing	The Specific Heat Capacity After Changing ($kJ·kg^{-1}·K^{-1}$)	Difference (After Change-Before Change)
0.75	1.93569	0.7575	1.93048	-0.00521
0.8	1.90155	0.808	1.89540	-0.00614
0.85	1.85290	0.8585	1.84134	-0.01156
0.9	1.76409	0.909	1.74186	-0.02223
0.95	1.60944	0.9595	1.57050	-0.03894
1	1.36330	1.01	1.30083	-0.06247

Table 8. Variation in the specific heat capacity of drilling fluid with a one percentage unit alteration in plastic viscosity

The Plastic Viscosity Before Changing (mPa·s)	The Apparent Viscosity Before Changing (mPa·s)	The Plastic Viscosity After Changing (mPa·s)	The Apparent Viscosity Before Changing (mPa·s)	The Specific Heat Capacity Before Changing ($kJ \cdot kg^{-1} \cdot K^{-1}$)	The Specific Heat Capacity After Changing ($kJ \cdot kg^{-1} \cdot K^{-1}$)	Difference (After Change-Before Change)
57	72	57.57	72.82	1.63220	1.64057	0.00837
61	77	61.61	79.19	1.68920	1.70102	0.01182
64	84	64.64	83.96	1.73910	1.74637	0.00727
68	90	68.68	90.32	1.79830	1.80682	0.00852
71	94	71.71	95.09	1.84160	1.85216	0.01056
75	99	75.75	101.45	1.89860	1.91262	0.01402
77	104	77.77	104.63	1.93260	1.94284	0.01024

3.5.2 Influence of basic performance parameters on thermal conductivity of drilling fluid

Referring to Table 9, it is observed that an incremental percentage unit rise in solid content correlates with an approximate increase of 0.00528 W/(m·K) in the thermal conductivity of the drilling fluid.

Table 10 reveals a relationship between the oil-water ratio and the thermal conductivity of the drilling fluid. In the oil-water ratio range of 0.75 to 0.9, an increase of one percentage unit in the oil-water ratio corresponds to a decrease in thermal conductivity of approximately 0.00285 W/(m·K). During this interval, the solid content exerts a more substantial impact on the thermal conductivity than the oil-water ratio. Conversely, as the oil-water ratio escalates from 0.9 to 1, each additional percentage unit contributes to a more pronounced decrease in thermal conductivity, approximately 0.02669 W/(m·K). This shift in influence is attributed to the thermal conductivity of water being nearly five times greater than that of diesel. Beyond the 0.9 threshold, the prevalence of diesel in the oil-based drilling fluid markedly increases, hastening the reduction in thermal conductivity. In this regime, the oil-water ratio becomes a more dominant factor affecting the thermal conductivity than the solid content.

Table 11 demonstrates that plastic viscosity has a more substantial impact on the thermal conductivity of the drilling fluid compared to apparent viscosity. The variations in thermal conductivity in response to changes in plastic viscosity are quantified in Table 11, indicating a decrease of approximately 0.00165 W/(m·K) in thermal conductivity for each one percentage unit increase in plastic viscosity.

Table 9. Variation in the thermal conductivity of drilling fluid with a one percentage unit alteration in solid content

Solid Content Before Changing (%)	Thermal Conductivity Before Changing ($W \cdot m^{-1} \cdot K^{-1}$)	Solid Content After Changing (%)	Thermal Conductivity After Changing ($W \cdot m^{-1} \cdot K^{-1}$)	Difference (After Change-Before Change)
32	0.25810	32.32	0.26600	0.00790
35	0.30510	35.35	0.31253	0.00743
38	0.38230	38.38	0.38847	0.00617
41	0.41250	41.41	0.41787	0.00537
44	0.43710	44.44	0.44155	0.00445
47	0.47910	47.47	0.47947	0.00037

Table 10. Variation in the thermal conductivity of drilling fluid with a one percentage unit alteration in oil-water ratio

The Oil-Water Ratio Before Changing	Thermal Conductivity Before Changing ($W \cdot m^{-1} \cdot K^{-1}$)	The Oil-Water Ratio After Changing	Thermal Conductivity After Changing ($W \cdot m^{-1} \cdot K^{-1}$)	Difference (After Change-Before Change)
0.75	0.39899	0.7575	0.39800	-0.00099
0.8	0.38266	0.808	0.37927	-0.00340
0.85	0.36452	0.8585	0.36220	-0.00232
0.9	0.34907	0.909	0.34437	-0.00470
0.95	0.29913	0.9595	0.27992	-0.01920
1	0.13580	1.01	0.07965	-0.05615

Table 11. Variation in the thermal conductivity of drilling fluid with a one percentage unit alteration in plastic viscosity

Plastic Viscosity Before Change (mPa·s)	Apparent Viscosity Before Change (mPa·s)	Modified Plastic Viscosity (mPa·s)	Modified Apparent Viscosity (mPa·s)	Thermal Conductivity Before Change ($W \cdot m^{-1} \cdot K^{-1}$)	Thermal Conductivity After Change ($W \cdot m^{-1} \cdot K^{-1}$)	Difference (After Change-Before Change)
57	72	57.57	72.82	0.39650	0.39505	-0.00145
61	77	61.61	79.19	0.38570	0.38520	-0.00051
64	84	64.64	83.96	0.38020	0.37780	-0.00240
68	90	68.68	90.32	0.37020	0.36794	-0.00226
71	94	71.71	95.09	0.36230	0.36055	-0.00176
75	99	75.75	101.45	0.35150	0.35069	-0.00082
77	104	77.77	104.63	0.34810	0.34576	-0.00235

From this analysis, it is evident that the relative influence of various factors on the thermal conductivity of oil-based drilling fluids shifts with the oil-water ratio. In the range of 0.75 to 0.9 for the oil-water ratio, the factors influencing thermal conductivity rank in the following order: solid content > oil-water ratio > plastic viscosity > apparent viscosity. However, as the oil-water ratio increases, spanning from 0.9 to 1, this ranking changes to: oil-water ratio > solid content > plastic viscosity > apparent viscosity. This shift highlights the nuanced interplay between the oil-water ratio and other properties of the drilling fluid, underscoring their collective impact on thermal conductivity.

4. CONCLUSION

In the pursuit of enhancing the precision in predicting downhole circulating temperatures and devising apt cooling strategies, the factors influencing the thermodynamic parameters of oil-based drilling fluids have been meticulously analyzed in this study. The following conclusions have been drawn:

(1) The thermodynamic parameters of oil-based drilling fluids are predominantly affected by the solid content, oil-water ratio, plastic viscosity, and apparent viscosity. It has been observed that the particle size distribution of the solid particles exerts a negligible impact on these thermodynamic parameters.

(2) Within the oil-water ratio range of 0.75 to 0.9 for oil-based drilling fluids, the influence hierarchy of the aforementioned sensitive factors on their thermodynamic parameters is established as: solid content > oil-water ratio > plastic viscosity > apparent viscosity. An increment of one percentage unit in the solid content corresponds to a decrease of approximately 0.01284 kJ/(kg·K) in the specific heat capacity, alongside an increase of about 0.00528 W/(m·K) in the thermal conductivity of the drilling fluid.

(3) Conversely, when the oil-water ratio spans from 0.9 to 1, the degree of influence of these sensitive factors shifts, presenting the following order: oil-water ratio > solid content > plastic viscosity > apparent viscosity. Under these conditions, a one percentage unit rise in the oil-water ratio results in a decrease of approximately 0.04121 kJ/(kg·K) in the specific heat capacity and a reduction of about 0.02669 W/(m·K) in the thermal conductivity of the drilling fluid.

ACKNOWLEDGMENT

This work is sponsored by Heilongjiang Province Natural Science Foundation of China (LH2022E026); Project funding of CNPC (2021ZZ01-04).

REFERENCES

[1] Wang, Z.H. (2023). Current situation and development suggestions for drilling fluid technologies in China. Petroleum Drilling Technology, 51(4): 114-123. https://doi.org/10.11911/syztjs.2023028

[2] Sun, J.S., Jiang, G.C., He, Y.B., Shi, H., Du, M.L., Dong, P.F., Yang, L.L. (2023). Technical difficulties and challenges faced by oil-based drilling fluids. Journal of China University of Petroleum (Edition of Natural Science), 47(5): 76-89. https://doi.org/10.3969/j.issn.1673-5005.2023.05.008

[3] Wang, Z.H. (2022). A review of oil-based drilling fluid research and application in China. Sino-Global Energy, 27(8): 29-36.

[4] Wu, P.C., Wang, Y., Fu, L., Chen, Y., Wang, Y., Zhang, Z., Zhang, H. (2023). Exploration and practice of "One Trip" technology for deep shale gas horizontal wells. China Petroleum Machinery, 51(8): 26-33. https://doi.org/10.16082/j.cnki.issn.1001-4578.2023.08.004

[5] Chu, Q.L., Wen, W., Jiao, C. (2023). Control method for circulating cooling of high temperature directional wells in Shunbei oil and gas field. China Petroleum and Chemical Standards and Quality, 43(6): 137-138. https://doi.org/10.3969/j.issn.1673-4076.2023.06.048

[6] Zhong, B., Fang, D., Shi, T.H. (2000). Sensitivity analysis of the factors affecting temperature in well bore. Natural Gas Industry, 20(2): 57-60.

[7] Wen, Q.B., Liang, D.C., Ren, M., Deng, S.H. (2008). Laboratory study on drilling fluid heat conductivity. Petroleum Drilling Technology, 2008(1): 30-32. https://doi.org/10.3969/j.issn.1001-0890.2008.01.009

[8] Guan, Z.C., Li, Q.D., Ning Liwei, Ke, K., Zhao, X.F., Liang, H.M. (2011). Study on drilling fluid thermal properties measurement and influence on wellbore temperature field. Drilling Fluid & Completion Fluid, 28(3): 1-4. https://doi.org/10.3969/j.issn.1001-5620.2011.03.001

[9] Li, S., Xia, B.R., Han, X.Z., Wang, X.G., Li, Z.J. (2017). Study on the effect of oil water ratio on the performance of oil based drilling fluids. Oilfield Chemistry, 34(2): 196-200. https://doi.org/10.19346/j.cnki.1000-4092.2017.02.02.002

[10] Wu, B., Liu, T., Zhang, X., Wu, B., Jeffrey, R.G., Bunger, A.P. (2017). A transient analytical model for predicting wellbore/reservoir temperature and stresses during drilling with fluid circulation. Energies, 11(1): 42. https://doi.org/10.3390/en11010042

[11] Zhang, Z. (2019). Research on wellbore temperature distribution under complex working conditions during drilling process. Southwest Petroleum University, 2019. https://doi.org/10.27420/dccnki.gxsyc.2019.001111

[12] Yang, M., Luo, D., Chen, Y., Li, G., Tang, D., Meng, Y. (2019). Establishing a practical method to accurately determine and manage wellbore thermal behavior in high-temperature drilling. Applied Energy, 238: 1471-1483. https://doi.org/10.1016/j.apenergy.2019.01.164

[13] Luo, Z., Cao, Q., Shen, X.Y., Guo, J.H., Yang, Q. (2021). Analysis and application of circulating temperature sensitivity factors in drilling process. Unconventional Oil and Gas, 2021(5): 93-99. https://doi.org/10.19901/j.fcgyq.2021.05.13

[14] Ruan, B., Huang, H., Xu, X.N., Gan, R.Z., Zhang, W., Yang, H. (2021). Wellbore circulating temperature field model for ultra-high density oil-based drilling fluid. China Petroleum Machinery, 49(11): 10-16. https://doi.org/10.16082/j.cnki.issn.1001-4578.20211.002

[15] Lin, R.Y., Yu, C.H., Yang, H.L., Lv, X.Y., Feng, M., Zhu, T.X. (2022). Temperature field simulation and analysis of drilling fluid circulation in super deep horizontal wells. Chemical Engineering of Oil and Gas, 51(3): 91-97. https://doi.org/10.3969/j.issn.1007-3426.2022.03.014

[16] Wang, Z.Q. (2017). Numerical simulation and analysis of wellbore temperature in geothermal wells coupled with drilling fluid temperature characteristics. China University of Geosciences (Beijing).

[17] Li, S.Z., Zhang, T.Y., Nie, J., Yang, Z.Y., Lv, H.J., Bao, Q.M. (2022). Development and application of ZLZY310 high temperature drilling fluid cooling system. China Petroleum Machinery, 2022(8): 46-51. https://doi.org/10.16082/j.cnki.issn.1001-4578.2022.08.007

[18] Többen, B.J. (2010). Apparatus for the cooling of drilling liquids. US7819205B2. Washington, DC, U.S. Patent and Trademark Office.

[19] Vrielink, H., Bradford, J.S., Basarab, L., Ubaru, C.C. (2008). Successful application of casing-while-drilling technology in a Canadian arctic permafrost application. In SPE/IADC Drilling Conference and Exhibition, Orlando, Florida, USA, pp. SPE-111806. https://doi.org/10.2118/111806-MS

[20] Liang, X.Y., Zhao, C., Zhao, X.Y., Zhang, Y.Z., Bai, Y.Y., Yang, M. (2023). Development of a drilling fluid surface cooling system based on heat pipe technology. China Petroleum Machinery, 51(3): 24-32. https://doi.org/10.16082/j.cnki.issn.1001-4578.2023.03.004

[21] Ma, Q.F. (2016). Overview of drilling fluid cooling technology and equipment. China Petroleum Machinery, 2016, 44(10): 42-46. https://doi.org/10.16082/j.cnki.issn.1001-4578.2016.10.10

[22] Kabir, C.S., Hasan, A.R., Kouba, G.E., Ameen, M.M. (1996). Determining circulating fluid temperature in drilling, workover, and well control operations. SPE Drilling & Completion, 11(2): 74-79. https://doi.org/10.2118/24581-PA

[23] Liu, J.Y., Chen, E.D, Li, G.Q., Yuan, L. (2021). Experimental study of drilling fluid cooling in deep wells based on phase change heat storage. Petroleum Drilling Technology, 49(1): 53-58. https://doi.org/10.11911/syztjs.2020131

[24] Li, K. (2022). Key technologies for accelerating drilling speed in the horizontal section of deep shale gas in Luzhou. Drilling Engineering, 49(5): 100-105. https://doi.org/10.12143/j.ztgc.2022.05.014

[25] Zhong, J.P. (2023). Experimental study on thermophysical properties of nanoparticle drilling fluids. Energy and Chemical Engineering, 44(1): 53-56. https://doi.org/10.3969/j.issn.1006-7906.2023.01.011

[26] Ghasemi, N., Mirzaee, M., Aghayari, R., Maddah, H. (2018). Investigating created properties of nanoparticles based drilling mud. Heat and Mass Transfer, 54: 1381-1393. https://doi.org/10.1007/s00231-017-2229-7

[27] Ponmani, S., Nagarajan, R., Sangwai, J.S. (2016). Effect of nanofluids of CuO and ZnO in polyethylene glycol and polyvinylpyrrolidone on the thermal, electrical, and filtration-loss properties of water-based drilling fluids. SPE Journal, 21(2): 405-415. https://doi.org/10.2118/178919-PA

[28] Ahmadi, M.H., Mirlohi, A., Nazari, M.A., Ghasempour, R. (2018). A review of thermal conductivity of various nanofluids. Journal of Molecular Liquids, 265: 181-188. https://doi.org/10.1016/j.molliq.2018.05.124

[29] Pan, Y.D., Yu, P.Z. (2019). The effect of density on the performance of oil-based drilling fluids. Drilling and Completion Fluids, 36(3): 273-279 http://doi.org/10.3969/j.issn.1001-5620.2019.03.002

[30] Cheraghi, M., Hajipour, M., Emamzadeh, A. (2022). Enhancement of the heat capacity of water-based drilling fluids for deep drilling applications. Brazilian Journal of Chemical Engineering, 39(1): 77-86. https://doi.org/10.1007/s43153-021-00201-7