

Review Paper

Advances in nanomaterial-enhanced thermal conductivity of drilling fluids: Current status and future perspectives

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ABSTRACT

Efficient heat transfer from the downhole environment to the surface is a key function of drilling fluids, essential for cooling drill bits and maintaining tool reliability. Enhancing the thermal conductivity of drilling fluids is an effective strategy to improve heat dissipation and support deep oil and gas development. Nanomaterials, owing to their nanoscale dimensions, large specific surface area, and high intrinsic thermal conductivity, have shown strong potential for improving drilling fluid thermal management. Recent studies demonstrate that incorporating nanomaterials can significantly increase drilling fluid thermal conductivity and enhance wellbore cooling efficiency during circulation. This review provides a systematic summary of advances in nanomaterial-enhanced drilling fluid heat-transfer performance, covering: (1) heat-transfer mechanisms during drilling; (2) high-temperature impacts on drilling fluid properties, wellbore stability, and tool reliability; (3) thermal-conductivity characteristics of nanomaterials and governing factors; (4) reported enhancement using diverse nanomaterials; and (5) underlying heat-transfer mechanisms. Findings indicate that one-dimensional (e.g., carbon nanotubes) and two-dimensional nanomaterials (e.g., graphene) are more effective in improving thermal conductivity than zero-dimensional nanomaterials. Moreover, enhancing thermal conductivity is generally more effective in water-based drilling fluids due to easier nanoparticle dispersion and lower interfacial thermal resistance, whereas oil-based fluids require extensive surface modification of nanomaterials and usually achieve comparatively smaller improvements. Critical challenges include improving nanomaterial dispersibility and stability under harsh conditions, balancing thermal-transfer enhancement with rheological and filtration performance, and addressing economic and environmental considerations. Future research should focus on hybrid-structure design, integration of low-dimensional nanomaterials, development of responsive intelligent additives, and exploration of sustainable bio-based options.

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Table of nomenclature

WBDF	Water-based drilling fluids
OBDF	Oil-based drilling fluids
SBF	Synthetic-based drilling fluids
0D	Zero dimension
1D	One dimension
2D	Two dimension
CNTs	Carbon nanotubes
SWCNTs	Single-walled carbon nanotubes
MWCNTs	Multi-walled carbon nanotubes
GO	Graphene oxide
GONPs	Graphene oxide nanoplatelets
BN	Boron nitride
h-BN	Hexagonal boron nitride
HTHP	High temperature and high pressure
PAM	Polyacrylamide
PEG	Polyethylene glycol
BNF	Boron nitride framework
MWD	Measurement-while-drilling

1. Introduction

As oil exploration and development advance, the focus has gradually shifted toward deeper and more complex formations (Liu et al., 2022a; Song et al., 2025; Sun et al., 2024b). These deep formations are often accompanied by harsh high-temperature and high-pressure (HTHP) environments, with formation temperatures frequently exceeding 150 °C and even surpassing 200 °C in certain areas. High-temperature conditions present multiple challenges to drilling operations. On one hand, elevated temperatures can cause thermal degradation of treatment agents (particularly polymer-based agents) in drilling fluids, disrupting their rheological properties (Seright and Wang, 2023). This makes it difficult to control critical parameters such as viscosity and gel strength, thereby impairing the fluid's cutting-carrying capacity and wellbore stability (Gautam et al., 2022; Mohamed et al., 2021; Noor et al., 2025; Sun et al., 2019). On the other hand, high temperatures intensify drilling fluid filtration, leading to thicker and less compact filter cakes, which increase the risks of wellbore collapse and formation fluid loss (Balaga and Kulkarni, 2022; Qiu and Zhao, 2013; Sun et al., 2024b). Furthermore, high-temperature environments impose greater demands on drilling equipment and tools, reducing their service life and increasing both operational costs and safety risks (Wang et al., 2021). Consequently, high formation temperatures have become a key factor limiting the efficient extraction of deep oil resources.

To address these multifaceted challenges posed by high-temperature environments, it is no longer sufficient for drilling fluids to merely support basic drilling functions (Gautam et al., 2025). Instead, they must evolve into multifunctional systems engineered specifically to endure and perform under extreme thermal conditions. In such demanding conditions, drilling fluids must rapidly dissipate frictional and geothermal heat to prevent critical downhole components, such as measurement-while-drilling (MWD) tools and drill bits, from exceeding their thermal tolerance thresholds. However, conventional water-based drilling fluids (WBDFs), though widely used, suffer from a significant reduction of approximately 40% in thermal conductivity under high temperatures due to the collapse of hydrogen-bonded water structures and the agglomeration of clay particles (Gudarzifar et al., 2020; Liu et al., 2022b; Sedaghatzadeh et al., 2012; Zheng

et al., 2023). Oil-based drilling fluids (OBDFs), while offering superior lubrication and shale inhibition, possess intrinsically low thermal conductivity (0.1–0.15 W/(m·K)), which is further exacerbated by oxidative degradation at elevated temperatures (Aftab et al., 2017). Adding antioxidants (such as 2,6-di-tert-butyl-p-cresol) to OBDF can alleviate its oxidative degradation and raise its thermal stability temperature, but it still fails to solve the problem of OBDF's inherent low thermal conductivity. Synthetic-based drilling fluids (SBFs) exhibit lower thermal stability than OBDFs and are prone to phase separation and viscosity instability under prolonged thermal stress, resulting in operational uncertainties (Razali et al., 2018). These systemic limitations underscore a critical technological gap between the capabilities of existing drilling fluids and the escalating thermal demands of modern deep and ultra-deep drilling operations.

To overcome these limitations, significant attention has been directed toward enhancing the thermal conductivity of drilling fluids using nanomaterials due to their unique physicochemical properties (Liang et al., 2022). Nanomaterials are defined as materials with at least one dimension in the nanoscale range (1–100 nm) or composed of such units, and they exhibit distinctive characteristics such as a large specific surface area, high surface energy, and quantum size effects (Wang et al., 2025; Jeevanandam et al., 2018; Pang et al., 2024). In particular, due to their small particle size, high surface atom ratio, reduced phonon scattering, and unique crystalline structures, nanomaterials possess excellent thermal conductivity compared with their bulk counterparts. Incorporating nanomaterials into drilling fluids can significantly enhance thermal conductivity, enabling more efficient heat transfer from the bottomhole to the surface (Evaristo et al., 2025). This reduces bottomhole temperature, thereby slowing the thermal degradation of drilling fluid additives and helping to maintain the performance of drilling equipment and tools.

Comprehensive analysis of existing research indicates that systematic advancement in this field still faces significant limitations. First, most current studies focus on a single type of nanomaterial or a specific drilling fluid system, lacking holistic integration of findings across different nanomaterial dimensions and base fluid types (Lysakova et al., 2024a; Maiti et al., 2021; Peng et al., 2025). Consequently, the performance advantages of nanomaterials with different dimensionalities and the compatibility rules of various base fluids cannot be effectively compared or correlated. Second, many studies examine heat conduction or heat convection in isolation, without clarifying their synergistic behavior or the regulatory effects of actual downhole environmental factors (Goyal and Sharma, 2021; Yang et al., 2019). Meanwhile, existing work provides insufficient analysis of how complex downhole conditions alter the relative contributions of the two mechanisms or how environmental parameters quantitatively influence heat-transfer pathways. In addition, under downhole HTHP conditions, some nanomaterials tend to lose their superior properties (e.g., nanoscale dimensions, large specific surface area and high intrinsic thermal conductivity), whereas most studies have neglected the structural changes of nanomaterials under HTHP conditions (Rana et al., 2021). Finally, although some studies mention individual challenges such as nanoparticle agglomeration, they lack a targeted and systematic discussion of core technical bottlenecks and future research directions (Ikram et al., 2020; Lyu et al., 2021; Sharma and Islam, 2021).

To address the identified research gaps, this paper systematically reviews the research progress on the application of thermally conductive nanomaterials for enhancing heat dissipation in drilling fluids (Fig. 1). First, it introduces the fundamental theories and consequences of heat transfer during drilling operation,

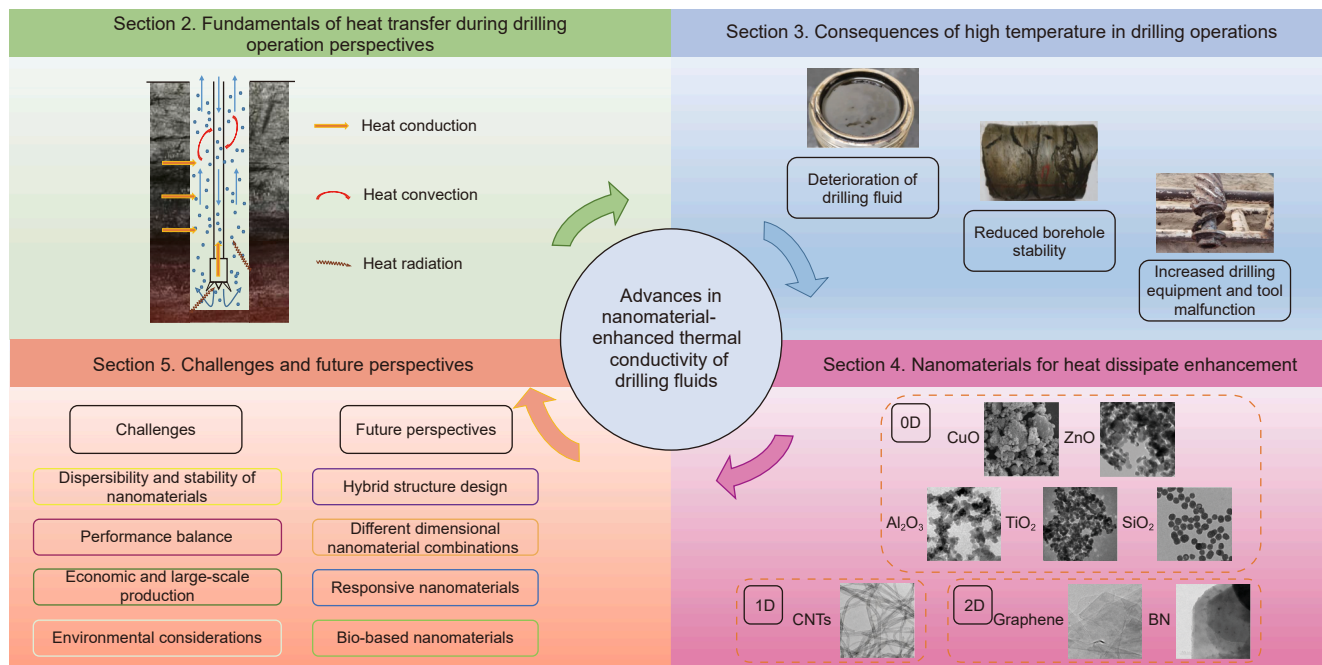


Fig. 1. A summary of the topic covered in the present review, including fundamentals of heat transfer during drilling operations, consequences of high temperature in drilling operations, nanomaterials for heat dissipation enhancement, and challenges and future perspectives.

elaborating on the mechanisms of heat conduction, convection, and radiation that underpin thermal management in high-temperature drilling environments. Subsequently, it provides an in-depth analysis of the thermal conductivity of various nanomaterials and their influencing factors. The review then summarizes the enhancement of drilling fluid thermal conductivity achieved using a broad range of nanomaterials, including zero-dimensional (0D), one-dimensional (1D), and two-dimensional (2D) nanomaterials, followed by a discussion of the underlying mechanisms. Finally, the current challenges and future research directions are provided. This work aims to provide theoretical support and technical pathways for the thermal management of drilling fluids in high-temperature deep-well drilling using thermally conductive nanomaterials, thereby promoting more efficient and safer oil and gas development.

2. Fundamentals of heat transfer during drilling operation

Heat transfer during drilling operation refers to the combined mechanisms of conduction, convection, and, to a lesser extent, radiation, by which thermal energy is exchanged between the drilling fluid, the drill string, the formation rock, and the wellbore environment (Fig. 2). Efficient heat transfer within drilling fluids is critical for maintaining the thermal stability of drilling fluids, protecting downhole tools, and preventing thermal degradation of additives. Understanding the heat transfer mechanism is essential for optimizing drilling fluid formulations and designing effective thermal management strategies to ensure safe and efficient drilling operations.

2.1. Heat conduction

Heat transfer follows the following mathematical laws:

$$Q_{\text{cond}} = -kA\nabla T \quad (1)$$

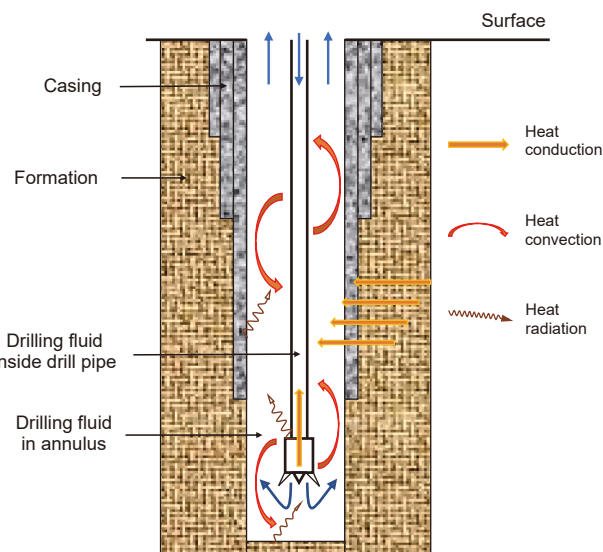


Fig. 2. Schematic diagram of heat transfer pathways during drilling operations: heat conduction, heat convection and heat radiation.

where Q_{cond} is heat transferred by conduction, W; k is thermal conductivity, W/(m·K); A is heat transfer area, m²; ∇T is temperature gradient, K/m. Among these parameters, thermal conductivity (k) is the most important, as it characterizes the ability of the material to conduct heat (Tan and Zhang, 2023).

During drilling operations, heat conduction takes place within solid components like the formation rock and the drill string, across the interfaces between the drilling fluid and the formation rock or drill string, and within the drilling fluid itself, especially when in contact with hot formations or equipment surfaces. In the drill string, thermal energy is conducted along the metallic structure from high-temperature zones at the bottomhole toward

the surface, potentially affecting tool performance and structural integrity. In the formation rock, heat conduction governs the transfer of geothermal energy toward the wellbore, contributing to the thermal load experienced by the circulating fluid. At the interfaces between the drilling fluid and the formation rock or drill string, heat flows according to the temperature gradient, playing a crucial role in the thermal exchange process. Within the drilling fluid, heat is transferred through molecular collisions, particularly in stagnant or low-flow regions, and is influenced by the fluid's thermal conductivity and composition. This comprehensive conduction process significantly impacts the thermal profile of the wellbore and the effectiveness of thermal management during high-temperature drilling.

2.1.1. Heat conduction in formation rock

In the heat exchange system between the formation and wellbore, thermal conduction of formation rocks is the primary heat source causing high wellbore temperatures. Due to the natural temperature gradient within the formation, deep formation rocks store substantial thermal energy because of high temperatures. This heat continuously transfers via thermal conduction from high-temperature formation rocks to the low-temperature wellbore wall, causing the wellbore temperature to rise.

The process of thermal conduction is influenced by multiple factors. From the perspective of rock physical properties, mineral composition is a core influencing factor. Rigid minerals such as quartz ($\sim 7.6 \text{ W/(m}\cdot\text{K)}$) and feldspar ($\sim 4.5 \text{ W/(m}\cdot\text{K)}$) exhibit significantly higher thermal conductivity than clay minerals ($\sim 1.6 \text{ W/(m}\cdot\text{K)}$) (Guo et al., 2020; Miao et al., 2013). Thus, igneous and metamorphic rocks rich in aluminosilicate minerals generally have higher thermal conductivity than clay-dominated mudstones. Porosity and pore structure act by altering the continuity of the solid skeleton and fluid occurrence state. Low-porosity rocks (e.g., tight sandstone) have smoother thermal conduction paths due to close contact between mineral grains (Bi et al., 2024). The thermal conductivity of high-porosity rocks depends not only on the type of pore fluid but also on pore connectivity. Isolated pores conduct heat only through the rock matrix, while connected pores allow fluids to form auxiliary thermal conduction channels (Cho et al., 2009).

Analyzing external environmental conditions, formation pressure modifies rock microstructure through compaction. Increased particle contact area and pore closure under high pressure enhance thermal conductivity. The geothermal gradient directly determines the driving force of thermal conduction. In high heat flow basins (geothermal gradient $> 4^\circ\text{C}/100 \text{ m}$), the heat input rate from the formation to the wellbore is over 30% higher than in normal geothermal regions ($3^\circ\text{C}/100 \text{ m}$) (Zhang et al., 2023). Rock water content and saturation are also critical. The thermal conductivity of fully water-saturated rocks can increase by 2–3 times compared to dry states, as water conducts heat far more efficiently than air and fills thermal resistance interfaces between mineral grains (Guo et al., 2020). Additionally, the degree of diagenesis affects rock compactness. Strongly cemented rocks (e.g., siliceous cemented sandstone) have significantly better thermal conductivity than loose uncemented formations due to superior thermal contact between mineral grains. Burial depth indirectly influences conduction efficiency by superimposing temperature and pressure effects. In deep HTHP environments, the rock thermal conduction mechanism may shift from single mineral skeleton conduction to

“mineral-fluid” coupled conduction, forming composite thermal conduction paths.

Numerous studies on formation rock thermal conduction have been conducted. Early scholars established basic thermal conduction parameter databases by experimentally measuring the thermal conductivity of different rock types (Chen et al., 2019; Jiang et al., 2021). With the development of numerical simulation technologies, researchers have used finite element, finite difference, and other methods to construct formation-wellbore thermal conduction coupling models, providing deeper insights into thermal conduction laws and their impact mechanisms on wellbore temperature fields (Tang et al., 2019; Yang et al., 2013). For instance, Tang et al. (2019) successfully modeled the close coupling between formation thermal conduction and wellbore thermodynamics using three methods. The study emphasized that one of the two core components of wellbore heat exchanger modeling is “heat conduction from geothermal formations to the wellbore”, explicitly identifying formation rock thermal conduction as a major heat source contributing to elevated wellbore temperatures. Furthermore, this heat conduction is influenced by factors such as the rock's thermal conductivity, the geothermal gradient, and the homogeneity of the formation.

2.1.2. Heat conduction in drill string

During the drilling process, thermal conduction within the drill string system originates primarily from frictional heat generated at the interface between the drill bit and the formation. Frictional heat is produced through the conversion of mechanical work into thermal energy. As the bit rotates at high speed to break the rock, friction at the contact interface between the cutting teeth and the formation, along with friction between the bit body and rock cuttings, constitute the primary mechanisms of heat generation. The rate of heat generation is closely related to several operational and geological parameters, including weight on bit (WOB), rotational speed, rock hardness, and bit wear status (Han et al., 2023; Mao et al., 2023; Song et al., 2021). WOB directly determines the normal pressure at the interface between the bit's cutting teeth and the rock, thereby intensifying frictional heat generation by increasing the contact load. Rotational speed influences heat generation by controlling the frequency of frictional contact and the relative sliding speed between the cutting teeth and the rock per unit time. Rock hardness (e.g., compressive strength and shear strength) reflects the rock's resistance to fragmentation, i.e., the higher the hardness, the more energy is required to break a unit volume of rock, leading to greater frictional heat generation. Bit wear (e.g., cutting tooth passivation and gauge wear) significantly reduces rock-breaking efficiency, resulting in a greater proportion of mechanical energy being converted into heat (Abbas, 2018).

Once generated, this heat is conducted axially through the drill string. The bit, acting as a high-temperature source, transfers heat into the connected drill pipe, establishing a temperature gradient along the drill string axis. The efficiency of this axial heat transfer depends largely on the thermal conductivity of the drill pipe material (Mao et al., 2023). Traditional carbon steel drill pipes have a thermal conductivity of approximately $45 \text{ W/(m}\cdot\text{K)}$, enabling moderate heat transfer. Aluminum alloy drill pipes offer significantly higher conductivity ($200\text{--}230 \text{ W/(m}\cdot\text{K)}$), facilitating rapid heat dissipation. Titanium alloy drill pipes, in contrast, have a much lower thermal conductivity ($6\text{--}7 \text{ W/(m}\cdot\text{K)}$), roughly one-tenth that of carbon steel, resulting in substantially reduced

axial heat transfer efficiency (Xiao et al., 2022). In addition, drill pipe geometric and surface characteristics influence thermal conduction. A thicker wall increases thermal resistance and reduces conduction efficiency. A larger joint contact area reduces interfacial thermal resistance, improving heat transfer. Moreover, smoother surfaces increase the actual-to-theoretical contact area ratio, enhancing heat transfer across interfaces by lowering interfacial thermal resistance (Song et al., 2024).

2.1.3. Heat conduction between drilling fluids and formation rock or drill string

The heat transfer process between drilling fluid and formation rock or drill string is primarily achieved through interfacial heat conduction, which follows Fourier's law and essentially relies on the thermophysical properties (such as thermal conductivity) between the two, the contact area at the interface, as well as the temperature difference. The thermal conductivity of formation rock and drill string is generally higher than that of the bulk drilling fluid. For instance, common rocks such as shale and sandstone have thermal conductivities of 1.7–3.1 W/(m·K), while carbonate rocks exhibit superior thermal conductivity of 2.0–5.6 W/(m·K) due to their dense structure (Xu and Shen, 2022). The thermal conductivity of conventional drill pipes is about 45 W/(m·K), while that of conventional WBDFs is only 0.5–0.7 W/(m·K) (Adil et al., 2024; Li et al., 2025b). Although the thermal conductivity of formation rock and drill string are high, a larger thermal conductivity difference leads to higher interfacial thermal resistance.

The contact area serves as the geometric basis for expanding heat transfer pathways, which is jointly determined by the wellbore diameter and well depth. A larger wellbore increases both the annulus cross-sectional area and contact perimeter, expanding the interface range involved in heat exchange per unit time. Bahonar et al. (2011) studied wellbore heat flow modeling and casing temperature prediction for steam injection wells, and found that a larger wellbore diameter directly increases the contact perimeter, thereby expanding the heat exchange interface. The temperature gradient, determined by the temperature difference between the formation and the drilling fluid, plays a dominant role, i.e., the larger the temperature difference, the more significant the heat transfer rate. Alimonti et al. (2018) found that heat conduction is driven by temperature gradients. When the temperature gradient increases from 25 °C/km to 45 °C/km, the exit fluid temperature rises significantly.

In addition to these three main factors, the deposition of filter cake from drilling fluid on the surface of formation rock plays a critical regulatory role. Due to the low thermal conductivity bentonite-based filter cake, it forms a thermal resistance barrier under static or low-velocity conditions, thereby reducing heat transfer efficiency. Furthermore, by adding thermal insulation materials, the overall thermal resistance of the filter cake can be enhanced, leading to improved insulation performance and further suppression of heat loss from the wellbore to the surrounding formation. For instance, Zhang et al. (2025) prepared polymer-coated SiO₂ aerogels (PC@SiO₂) via suspension polymerization. The thermal conductivity of filter cake containing 2 wt% PC@SiO₂ decreased by 33.8% after thermal rolling at 210 °C for 16 h, which can effectively reduce heat transfer from the formation rock to drilling fluid.

2.1.4. Heat conduction within drilling fluids

Heat conduction within drilling fluids involves the transfer of heat between suspended solid particles (e.g., weighting agents, bentonite, and cuttings) and the surrounding liquid phase due to molecular interactions (Yang et al., 2013). As the primary mode of

heat transfer within the solid skeleton, conduction is driven by temperature gradients, allowing heat to diffuse from high-energy, high-temperature regions to low-energy, low-temperature regions without requiring fluid movement (Han et al., 2012). Therefore, this mode of heat transfer is particularly significant when the drilling fluid is under static or low-flow conditions.

Drilling fluids are complex systems composed of water, bentonite, weighting agents, pH regulators, thickeners, fluid-loss reducers, lubricants, shale inhibitors, and other functional additives. Among these, water serves as the continuous phase and acts as the primary heat transfer medium due to its relatively high thermal conductivity (~0.6 W/(m·K)) and fluidity, especially through convective heat transfer. Owing to the low thermal conductivity (~0.4–0.6 W/(m·K)), bentonite impedes heat conduction (Hu et al., 2021). When dispersed in water, bentonite swells and forms a gel-like, colloidal structure. This network traps water within interlayer spaces and between platelets, further impeding molecular motion and heat diffusion. Weighting materials, such as barite (BaSO₄) and hematite (Fe₂O₃), are commonly used in drilling fluids to increase fluid density and maintain wellbore stability under high-pressure conditions. Unlike bentonite or water, most weighting materials possess moderately high thermal conductivity (e.g., barite ~2.2 W/(m·K), hematite ~6.5 W/(m·K)), which is significantly higher than that of the base fluid (typically water at ~0.6 W/(m·K)). These materials thus act as thermal bridges, enabling more efficient transfer of heat within the fluid system, especially under static or low-convection conditions. Furthermore, the addition of nanomaterials, particularly 1D and 2D nanomaterials, can enhance the thermal conduction network, further increasing the thermal conductivity of drilling fluids. Polymers are widely used in drilling fluids to control viscosity, fluid loss, lubrication, and shale inhibition. Polymers are inherently poor thermal conductors, with typical thermal conductivities in the range of 0.15–0.4 W/(m·K), which is significantly lower than water and weighting agents. As such, polymers do not directly enhance the thermal conductivity of the drilling fluid. Moreover, due to the high surface absorption capacity, polymers may interrupt the formation of an effective solid conduction network, leading to reduced heat conduction.

In HTHP formations, a large amount of weight materials is added to drilling fluids to maintain wellbore stability and counterbalance formation pressure. Under such conditions, heat conduction becomes the dominant mode of heat transfer within the fluid system, as convective effects are often suppressed by increased fluid viscosity and limited flow velocity. The high solid content forms a thermally conductive particle skeleton, primarily composed of weighting materials, which facilitates the transfer of heat through solid-to-solid contact pathways and thermal bridging between particles (Han et al., 2012, 2013). This conductive network is especially critical under static or low-flow conditions, such as during pump shutdowns, bit trips, or well logging operations, where fluid circulation ceases or significantly slows down. In these scenarios, convection becomes negligible, and conduction serves as the sole mechanism for heat transfer within the drilling fluid and between the fluid and surrounding wellbore environment (Wong-Loya et al., 2017). For WBDFs weighted with high concentrations of inorganic salts (e.g., NaCl, KCl, CaCl₂), salt ions disrupt the hydrogen-bonded network of water molecules and compress the electric double layer of clay particles, which reduces the thermal conductivity of the base fluid and weakens the heat conduction path constructed by solid particles (Le et al., 2024; Liu et al., 2022b). Therefore, the type, concentration, and thermal properties of the weighting materials used play a crucial role in determining the overall heat conduction efficiency of the drilling fluid under HTHP conditions.

2.2. Heat convection

Convection is the dominant heat transfer mechanism in dynamic environments and is significantly more efficient than conduction. Key factors influencing convective heat transfer include fluid viscosity, flow velocity, and flow pattern (Roshan and Rahman, 2013; Santoyo et al., 2001; Wu et al., 2017). The primary mathematical principle governing heat convection in drilling fluids is Newton's law of cooling:

$$Q_{\text{conv}} = hA(T - T_{\infty}) \quad (2)$$

where Q_{conv} is heat transferred by convection, W; h is convective heat transfer coefficient, $\text{W}/(\text{m}^2 \cdot \text{K})$; A is heat transfer area, m^2 ; T is temperature, K; and T_{∞} is the constant temperature of the surrounding environment, K. Among them, the convective heat transfer coefficient (h) is the most critical parameter, as it represents the fluid's ability to transfer heat and indicates the rate of convective heat transfer. A higher convective heat transfer coefficient corresponds to faster heat transfer and lower thermal resistance. Changing the flow pattern of drilling fluid can alter the efficiency of convective heat transfer. For example, turbulent flow (characterized by a high Reynolds number) increases the heat transfer coefficient, whereas laminar flow has the opposite effect (Yin and Jia, 2007; Gao et al., 2017). Pumping parameters (e.g., flow rate and pressure) can be dynamically adjusted to maintain optimal turbulence (Sorgun et al., 2013).

The rheological performance is one of the most critical parameters influencing the flow pattern of drilling fluid. Within drilling fluids, water as a base fluid has low viscosity and supports efficient convection. Bentonite, weighting materials, and polymers can increase the viscosity of drilling fluids, which reduce flow velocity and may cause laminar or stagnant flow, particularly in the annulus or during low circulation periods, and thereby suppresses convective heat transport. Therefore, drilling fluid design must carefully balance rheological performance with thermal management goals. In high-temperature wells, where cooling is critical, optimizing viscosity is essential to sustain sufficient convective heat removal. Moreover, it is worth noting that the viscosity of drilling fluids is also influenced by environmental conditions such as temperature, pressure, and salinity. For instance, in deep reservoirs with high temperatures, the viscosity of the drilling fluid typically decreases, thereby enhancing convective heat transport (Lysakova et al., 2024a).

2.3. Heat radiation

Although heat conduction and convection are the primary modes of heat transfer in most drilling scenarios, the role of thermal radiation cannot be ignored in extremely high-temperature, low-flow-rate environments. In drilling environments, high-temperature formation rock walls, casings, drill strings, and other components exchange heat with surrounding objects or fluids through thermal radiation.

High-temperature surfaces (such as rock walls) emit electromagnetic waves, and energy propagates through space. When electromagnetic waves impinge on the surfaces of other objects (such as casings, drill strings, or particles in drilling fluid), part of the energy is absorbed and converted into heat, while the rest is reflected or transmitted. Therefore, thermal radiation is a dynamic process of emission, propagation, and absorption. Thermal radiation in drilling follows the Stefan-Boltzmann law:

$$Q_{\text{rad}} = \varepsilon \sigma A T^4 \quad (3)$$

where Q_{rad} is heat transferred by radiation, W; ε is emissivity, σ is Stefan-Boltzmann constant, $5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$; A is surface area, m^2 ; T is thermodynamic temperature, K. Among them, the radiant heat exchange is proportional to the fourth power of temperature, so temperature is the core factor determining the radiant energy. The higher the temperature of an object, the stronger its radiation power. Meanwhile, the temperature difference directly affects the direction and rate of radiant heat exchange. High-temperature objects transfer energy to low-temperature objects, and the greater the temperature difference, the higher the heat exchange. Additionally, emissivity is the ability of an object to emit radiant energy and depends on material type, surface conditions (such as roughness, oxidation level), and temperature. Finally, the larger the surface area, the more energy is radiated or absorbed.

2.4. Combined effects

In real drilling environments, especially in high-temperature and high-flow conditions, heat conduction, heat convection and heat radiation usually work together, with the total heat transfer following:

$$Q = Q_{\text{cond}} + Q_{\text{conv}} + Q_{\text{rad}} \quad (4)$$

where Q is total heat transfer, W; Q_{cond} is heat transferred by conduction, W; Q_{conv} is heat transferred by convection, W; and Q_{rad} is heat transferred by radiation, W. Heat conduction and heat convection remain the twin cornerstones of drilling fluid thermal management, with their synergistic interaction driving the bulk of heat transfer essential for efficient thermal regulation. While heat radiation may exert a supplementary effect, particularly in extreme high-temperature scenarios where thermal emissions from wellbore surfaces become non-negligible, it typically plays a secondary role compared to the dominant conductive and convective mechanisms.

3. Consequences of high temperature in drilling operations

As discussed previously, heat conduction from the deep formation and drilling string to the drilling fluid, together with heat convection through fluid circulation, represent the primary sources of temperature rise in drilling fluids. Elevated temperatures can impair drilling fluid performance, compromise borehole stability, reduce equipment safety, leading to several critical challenges.

3.1. Deterioration of drilling fluid

In drilling operations, high-temperature environments have a pronounced negative impact on drilling fluid performance (Hu et al., 2012; Prajapati et al., 2025). Drilling fluids contain various polymeric additives (e.g., thickeners and fluid-loss reducers), which are prone to thermal degradation under elevated temperatures (Noor et al., 2025; Sun et al., 2019).

For instance, the thermal degradation of thickeners can cause unfavorable changes in drilling fluid rheology, such as abnormal reductions in viscosity, yield stress, and shear-thinning behavior (Fig. 3(a)) (Davoodi et al., 2024). Consequently, the fluid becomes less capable of effectively transporting cuttings, thereby increasing the risk of incidents such as pipe sticking. Moreover, elevated temperatures significantly reduce the effectiveness of fluid-loss reducers, which are designed to minimize filtration losses by forming a dense filter cake on the wellbore wall (Khan et al., 2025a). However, when their structure is compromised by thermal degradation, they fail to form an effective barrier with

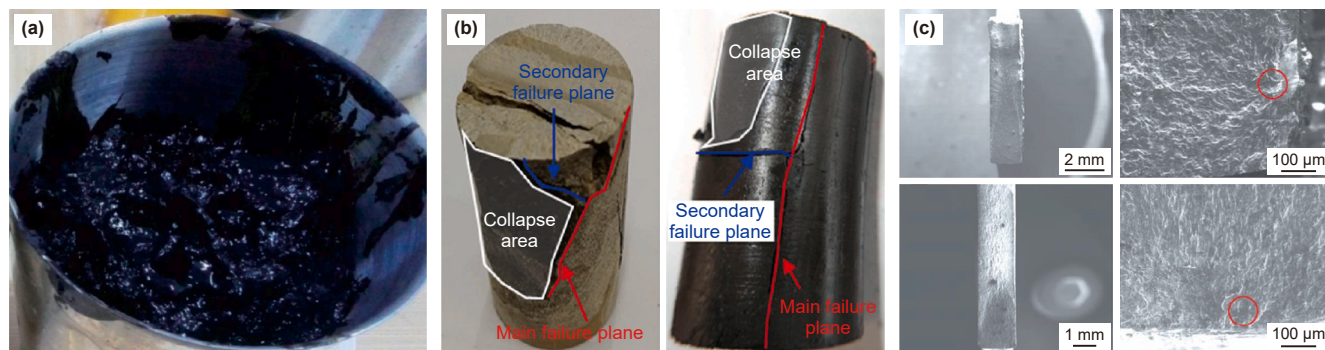


Fig. 3. Consequences of high temperatures in drilling operations: (a) high-temperature thickening of drilling fluid (Xu et al., 2019), (b) shale collapse (Zhao et al., 2024), and (c) accelerated metal corrosion (Liu et al., 2014).

bentonite, leading to excessive filtration loss (Li et al., 2024). The uncontrolled invasion of drilling fluid filtrate into the formation not only contaminates reservoirs, harming subsequent oil and gas recovery, but may also induce wellbore shrinkage and collapse (Khan et al., 2025b). Collectively, these effects severely compromise the efficiency of drilling fluids and disrupt the smooth progress of drilling operations.

3.2. Reduced borehole stability

Excessively high temperatures pose a serious threat to wellbore integrity and stability, with the impact being particularly pronounced in shale-rich formations and hard-brittle formations (Magzoub et al., 2020).

Shale contains abundant clay minerals, such as montmorillonite, which are highly sensitive to thermal and hydration effects. Elevated temperatures alter the pore pressure of shale formations, while the temperature gradient between the drilling fluid and shale enhances the infiltration of filtrate (Sun et al., 2024a). Clay minerals tend to hydrate and swell upon filtrate absorption, whereas high temperatures accelerate the loss of internal moisture, leading to shale shrinkage. This alternating cycle of swelling and shrinkage drastically reduces the mechanical strength of shale, making it prone to spalling and collapse (Fig. 3(b)). Studies indicate that when wellbore temperature exceeds 150 °C, the probability of shale collapse increases sharply compared to normal conditions, posing serious safety risks to drilling operations (Zhang et al., 2021).

The impact of temperature on wellbore stability in hard-brittle formations is equally critical. Hard-brittle formations, such as tight sandstones and carbonate rocks, exhibit high compressive strength but low toughness and often contain primary microfractures. When low-temperature drilling fluid circulates through wellbores in high-temperature formations, a significant temperature gradient quickly develops between the drilling fluid and the wellbore wall. This sharp thermal gradient induces rapid temperature changes in the near-wellbore rock. As the wellbore wall cools abruptly, the surface layer undergoes pronounced thermal contraction (Wang and Dusseault, 2003). However, the high-temperature rock in the interior restricts this contraction, generating substantial tensile stress in the near-wellbore region (Gomar et al., 2015). Once this tensile stress exceeds the tensile strength of the hard-brittle rock, new fractures form along the wellbore wall, and existing microfractures expand and interconnect. This process compromises the structural integrity of the wellbore wall, increasing the risks of wellbore enlargement, pipe sticking, and lost circulation, thereby posing serious threats to the safety and efficiency of drilling operations.

3.3. Increased drilling equipment and tool malfunction

High-temperature conditions also shorten the service life and impair the performance of drilling equipment and tools, triggering a series of operational challenges (Li et al., 2025b; Liu et al., 2025). From a materials perspective, elevated temperatures accelerate oxidation and corrosion of metals, decreasing the fatigue strength of equipment components (Fig. 3(c)) (Nabifo et al., 2025). For instance, the wear rate of drill bits increases markedly when operating in high-temperature environments, thereby reducing their effective service time (Ji et al., 2021). Electronic monitoring devices are also highly susceptible to thermal interference. Under high temperatures, sensors are prone to malfunction or data drift, which compromises the accuracy of drilling parameter measurements and complicates operational control (Kirschbaum et al., 2020).

The increased frequency of tool and equipment failures necessitates the deployment of additional standby units to maintain operational continuity, thereby driving up procurement costs. Furthermore, frequent failures demand more maintenance shut-downs, prolonging drilling cycles and substantially increasing repair expenditures. Statistics indicate that in high-temperature drilling environments, equipment maintenance costs are significantly higher than under normal conditions, which severely impacts the economic efficiency of drilling operations (Kirschbaum et al., 2020).

4. Nanomaterials for heat dissipation enhancement

The above discussion highlights that elevated downhole temperatures exert multifaceted negative effects on drilling operations. Enhancing the thermal conductivity of drilling fluids using nanomaterials has emerged as an effective strategy to improve heat dissipation and mitigate temperature-induced risks. Currently, a wide range of nanomaterials have been applied to enhance heat transfer in drilling fluids (Table 1).

4.1. Thermal conductivity of nanomaterials

Thermal conductivity is a physical property that characterizes the ability of a material to transfer heat. It is defined as the amount of heat transferred through a unit area per unit time under a unit temperature gradient (Qian et al., 2021; Tan and Zhang, 2023). As a key parameter affecting the heat-transfer efficiency of drilling fluids, thermal conductivity largely determines the temperature distribution in the wellbore. Drilling fluids with high thermal conductivity can dissipate heat rapidly, thereby slowing thermal degradation of polymer-based agents (Rafati et al., 2018). Thermal conductivity can be expressed in terms of Fourier's law as follows:

Table 1
Thermal conductivity of nanomaterials.

Nanomaterials	Morphology	Thermal conductivity, W/(m·K)	Ref.
CuO	Polyhedral particles/nanowires	5–10	Zhang et al. (2024)
ZnO	Hexagonal wurtzite structure	10–30	Igamberdiev et al. (2012)
Al ₂ O ₃	Spherical/polygonal particles	5–35	Kalhuri et al. (2023b)
TiO ₂	Anatase/rutile type crystal	1–10	Maheshwary et al. (2017)
SiO ₂	Spherical/rod-shaped	1.2–2.0	Kalhuri et al. (2023b)
Carbon nanotubes	Hollow tubular	1500–6000	Nieto de Castro et al. (2012); Gao et al. (2007)
Graphene	Single-layer/multi-layer honeycomb 2D films	5000–18000	Dong et al. (2017); Wang et al. (2023)
Boron nitride	Hexagonal crystal	20–550	Yuan et al. (2019); Zeng et al. (2017)

$k = \alpha \rho c \tag{5}$

where α is thermal diffusivity, m²/s; ρ is material density, kg/m³; c is specific heat capacity, J/(kg·K).

Nanomaterials are defined as materials with at least one dimension in the range of 1–100 nm. At this scale, their thermal conduction properties differ significantly from those of bulk materials, primarily due to the combined effects of quantum confinement, surface and interface scattering, and structural dimensionality (Wang et al., 2020). These factors can either enhance thermal conductivity, for instance through long-range phonon transport in highly rigid lattices, or reduce it by shortening the phonon mean free path via scattering, such as the impediment to low-frequency phonons at boundary defects. Therefore, the thermal conductivity of nanomaterials is highly tunable and influenced by various factors, including particle size, shape, structural continuity, specific surface area and so on (Fig. 4).

Taking 0D materials as an example, their thermal conductivity exhibits common characteristics significantly different from those of bulk materials, while there are specific differences due to the intrinsic properties of the materials. From an overall perspective, the thermal conductivity of such nanomaterials is generally lower than that of their bulk counterparts and shows strong size dependence. When the particle size decreases from the micrometer scale to the nanoscale, the thermal conductivity undergoes a significant decrease, with the reduction mostly exceeding 30% and even higher for some materials (such as Al₂O₃). This phenomenon is mainly attributed to the strengthened phonon scattering mechanisms at the nanoscale: enhanced boundary scattering

caused by small particle sizes, intensified surface phonon scattering induced by high specific surface areas, and shortened phonon mean free paths due to lattice distortion inside the nanoparticles. These factors together constitute the core reasons for the reduced thermal conductivity. Beyond these common rules, material specificity also leads to differences in thermal conductivity performance. For instance, the thermal conductivity of ZnO nanoparticles exhibits a unique non-monotonic size dependence.

In 1D materials, carbon nanotubes (CNTs) often exhibit thermal conductivities exceeding 1500 W/(m·K) along the tube axis. However, their thermal conductivity is sensitive to diameter. Smaller-diameter CNTs experience increased surface scattering of low-frequency phonons due to the presence of more boundaries, leading to reduced thermal conductivity (Lysakova et al., 2024b). This illustrates the synergistic influence of dimensionality (one-dimensional), structure (diameter), and surface scattering, where surface effects directly affect thermal conductivity through interfacial defects.

2D materials, e.g., graphene and hexagonal boron nitride (h-BN), exhibit thermal conduction behavior that more clearly demonstrates the complex coupling of multiple factors. The in-plane thermal conductivity of graphene can reach values between 5000 and 18000 W/(m·K), while that of single-layer h-BN at room temperature also exceeds 400 W/(m·K) (Ikram et al., 2020). This appears to contradict the conventional understanding that “high specific surface area reduces thermal conductivity due to surface scattering”. The high specific surface area of two-dimensional materials arises from their atomic-scale thickness, which suggests a large number of surfaces. However, the key lies in their

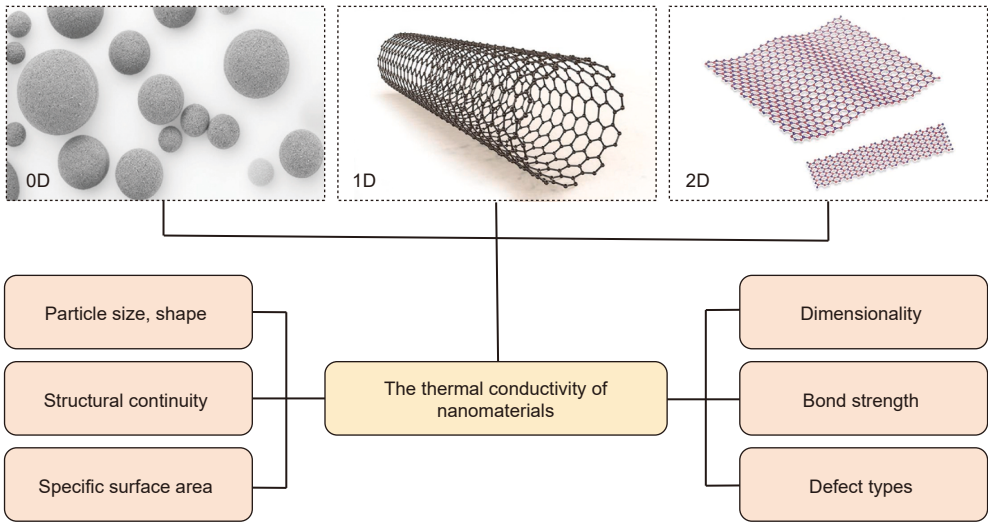


Fig. 4. Schematic diagrams of 0D, 1D, and 2D nanomaterial structures, and factors affecting the thermal conductivity of nanomaterials.

structural continuity. Unlike other nanomaterials composed of stacked discrete particles, two-dimensional materials are continuous single-crystal layers. Their high specific surface area results from their dimensional characteristics (atomic thickness) rather than from the external surfaces of individual particles. Consequently, phonon scattering mainly originates from internal defects rather than from outer surfaces. Moreover, the layered hexagonal lattice structure of these materials imparts extremely low defect densities and strong covalent bonding. The highly rigid lattice enables phonons to travel with high group velocities and long mean free paths. The two-dimensional confinement effect localizes phonon vibrations within the in-plane direction, minimizing scattering in the out-of-plane (vertical) direction. This combination of structural continuity, strong bond energy, and dimensional confinement allows the in-plane covalent bond network to conduct heat with minimal disruption from interfaces, ultimately achieving ultra-high thermal conductivity. However, their out-of-plane thermal conductivity remains limited due to vertical-direction scattering, another manifestation of dimensional regulation.

It is evident that the thermal conductivity of nanomaterials is not governed by a single factor, but by the combined effects of dimensionality, structural continuity, bond strength, and defect types. The influence of any single factor (such as surface effects) must be interpreted in the context of material morphology (e.g., 0D, 1D and 2D) and the types of scattering mechanisms involved (e.g., surface boundaries vs. internal defects). This interaction formed by the coupling relationship between multiple factors such as dimensionality, structural continuity, bond strength, and defect types constitutes the fundamental source of the uniqueness and tunability of the thermal conductivity of nanomaterials.

4.2. Types of nanomaterials used in drilling fluids

In recent years, nanomaterials with high thermal conductivity have demonstrated exceptional potential for enhancing heat transfer efficiency in drilling operations. As shown in Table 2, a broad range of nanomaterials, including 0D, 1D, and 2D types, have been applied.

Table 2
Enhancement of drilling fluid thermal conductivity using different nanomaterials.

Nanomaterials	Dimensions	Size	Drilling fluid	Content	Increase rate, %	Ref.
CuO	0D	Diameter: ~45 nm	WBDF	0.9 wt%	10	Veisi et al. (2020)
CuO	0D	Diameter: ~50 nm	WBDF	0.5 wt%	38	William et al. (2014)
CuO	0D	Diameter: ~55.4 nm	WBDF	0.3 wt%	69.68	Saboori et al. (2019)
ZnO	0D	Diameter: <20 nm	WBDF	2 vol%	23	Hassani et al. (2016)
ZnO	0D	Diameter: ~50 nm	WBDF	0.5 wt%	34	William et al. (2014)
Al ₂ O ₃	0D	Diameter: 30 ± 5 nm	OBDF	3 wt%	9.41	Wang et al. (2024)
Al ₂ O ₃	0D	Diameter: ~5 nm	WBDF	1 wt%	26	Kalhari et al. (2023b)
Al ₂ O ₃	0D	Length: 10–20 nm				
Al ₂ O ₃	0D	Diameter: ~70 nm	WBDF	0.5 wt%	35	Kalhari et al. (2023a)
TiO ₂	0D	Diameter: 10–15 nm	WBDF	2 wt%	25	Parizad et al. (2018)
TiO ₂	0D	N/A	OBDF	0.4 wt%	18.1	Wang and Zou (2023)
SiO ₂	0D	N/A	WBDF	2 vol%	16.9	Hassani et al. (2016)
SiO ₂	0D	Diameter: ~10 nm	WBDF	1 wt%	22	Kalhari et al. (2023b)
SiO ₂	0D	Diameter: 15 ± 5 nm	OBDF	3 wt%	8.54	Wang et al. (2024)
Carbon nanotubes	1D	Diameter: 10 ± 10 nm	OBDF	3 wt%	7.79	Wang et al. (2024)
Carbon nanotubes	1D	N/A	WBDF	1 wt%	12.2	Biaż et al. (2024)
Carbon nanotubes	1D	Diameter: 54–76 nm	WBDF	0.002 wt%	14.7	Farahbod (2021)
Carbon nanotubes	1D	Diameter: ~15 nm	WBDF	1 vol%	31.8	Fazelabdolabadi et al. (2015)
		Length: ~20 µm	OBDF	1 vol%	40.3	
Carbon nanotubes	1D	Diameter: ~25 nm	WBDF	0.5 vol%	442	Malika et al. (2023)
Graphene	2D	Lateral size: 60–100 nm	OBDF	0.01 wt%	14.41	Chai et al. (2017)
		Thickness: 2–5 nm				
GONPs	2D	Thickness: ~2.71 nm	WBDF	0.08 wt%	57.9	Gudarzifar et al. (2020)
Boron nitride	2D	Lateral size: ~100 nm	WBDF	6 wt%	7	Soares et al. (2025)
		Thickness: ~15.2 nm				

4.2.1. 0D nanomaterials

(a) CuO

Copper oxide (CuO) nanoparticles (Fig. 5(a)), with thermal conductivities ranging from 5 to 10 W/(m·K) depending on crystallinity and particle size, enhance heat transfer in drilling fluids through several unique mechanisms. Their monoclinic crystal structure facilitates efficient phonon transport, while surface oxygen vacancies improve interfacial thermal coupling with polar base fluids by enhancing charge interactions.

Although CuO has been historically used in drilling operations, systematic studies quantifying its thermal conductivity enhancement in drilling fluid remain limited. Experimental investigations show concentration-dependent improvements in thermal performance of nanofluid. Veisi et al. (2020) reported a linear increase in thermal conductivity for nanofluids containing less than 1 wt% CuO, achieving a 10% enhancement at 0.9 wt% concentration (Fig. 5(b)). William et al. (2014) observed thermal conductivity increases ranging from 28% to 53% in base nanofluids and from 20% to 38% in CuO-modified drilling fluids as nanoparticle concentrations increased.

Preparing CuO as part of composite nanomaterials further enhances drilling fluid performance via synergistic effects. Saboori et al. (2019) developed CuO/polyacrylamide (PAM) nanocomposites that increased drilling fluid thermal conductivity by 16.06% to 69.68% when the additive concentration increased from 1 g to 10 g. This approach mitigates CuO's tendency to agglomerate, improving dispersion stability. Simultaneously, the inclusion of PAM imparts viscosity-enhancing and filtration-control properties, leading to a synergistic improvement in overall fluid performance (Saboori et al., 2019). Based on existing research, CuO is more suitable for WBDF. These findings highlight CuO's dual role as a thermal enhancer and chemical stabilizer, although precise control over nanoparticle dispersion and surface chemistry remains essential for optimizing performance in downhole thermal management applications.

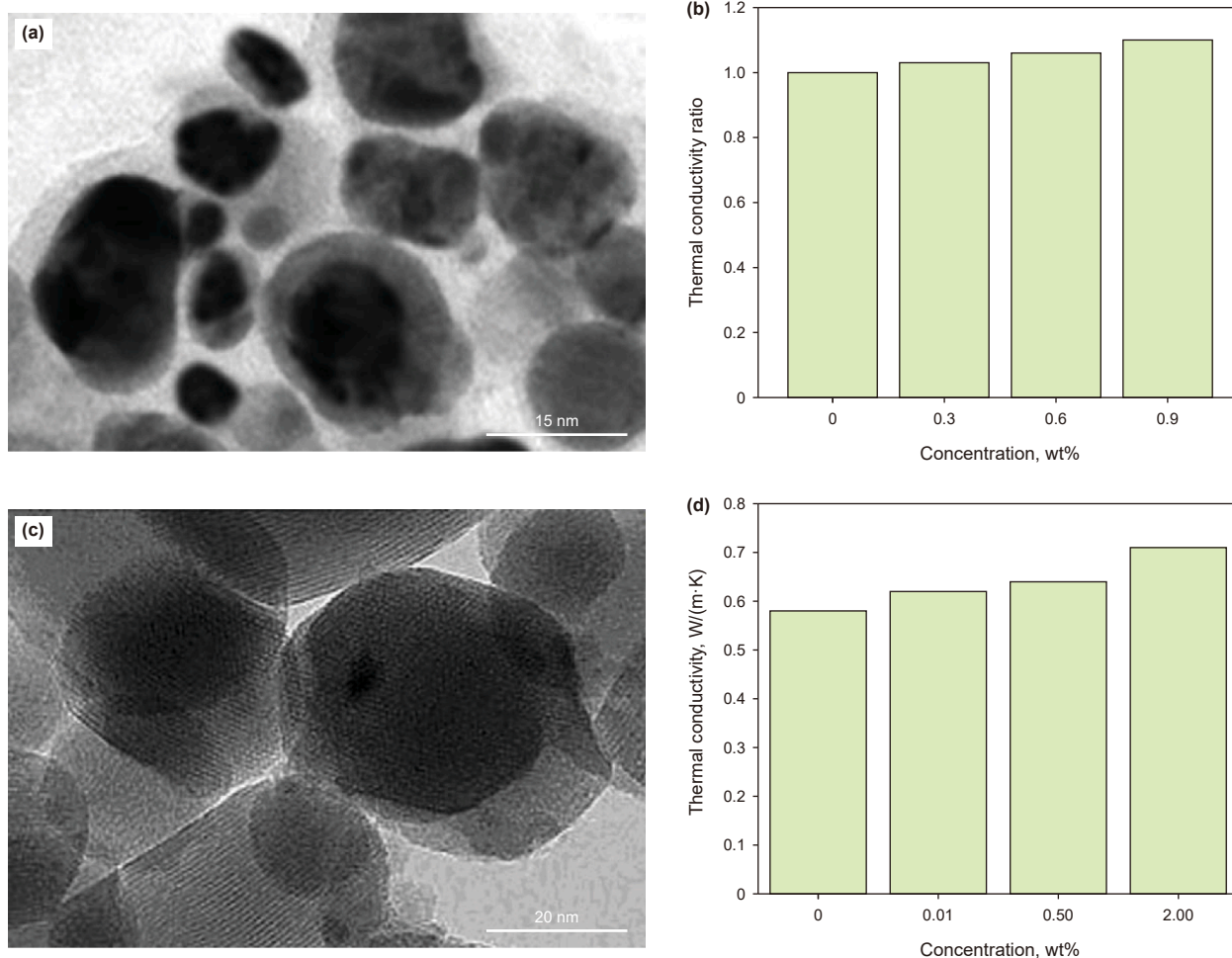


Fig. 5. Effect of copper oxide and zinc oxide on the thermal conductivity of drilling fluids: (a) TEM image of copper oxide (Gunalan et al., 2012), (b) thermal conductivity of drilling fluids containing copper oxide (Veisi et al., 2020), (c) TEM image of zinc oxide (Zak et al., 2011), and (d) thermal conductivity of drilling fluids containing zinc oxide (Hassani et al., 2016).

(b) ZnO

Zinc oxide (ZnO) nanoparticles exhibit anisotropic thermal conductivity, with values ranging from 10 to 30 W/(m·K). Their microscopic morphology is mostly a mutually agglomerated granular structure (Fig. 5(c)). Their inherent piezoelectric properties enable shear-induced polarization alignment in flowing fluids, thereby enhancing convective heat transfer efficiency. However, practical implementation is limited by thermal instability above 220 °C, due to crystal phase transitions, and by viscosity elevation resulting from dipole–dipole interactions. These factors confine their applicability primarily to shallow well operations.

Recent experimental studies have demonstrated the potential of ZnO nanoparticles to enhance the thermal conductivity of drilling fluids. For instance, Hassani et al. (2016) used ZnO nanoparticles synthesized via spray pyrolysis, reported a 22% increase in thermal conductivity at 40 °C for drilling fluids containing 2 vol% ZnO (Fig. 5(d)). William et al. (2014) compared various nanoparticle concentrations and observed thermal conductivity increases in ZnO nanofluids from 12% to 23%. In WBDFs, the addition of ZnO increases the thermal conductivity from approximately 17% to 34%,

depending on the concentration of ZnO. Based on existing research, ZnO is more suitable for WBDF, with good dispersion stability at low-to-medium temperatures. These findings confirm the concentration-dependent thermal optimization capability of ZnO nanoparticles. However, their operational temperature limitations necessitate careful thermal management strategies in downhole environments. Despite these constraints, the combination of heat transfer enhancement and auxiliary functionalities positions ZnO nanoparticles as multi-functional additives for shallow well drilling systems, provided that high-temperature stability issues are addressed through advanced material engineering.

(c) Al₂O₃

Aluminum oxide (Al₂O₃) nanoparticles (Fig. 6(a)) exhibit a thermal conductivity of 5–35 W/(m·K) via phonon-dominated heat transfer mechanisms, enhanced by their high specific surface area. Their amphoteric surface chemistry ensures broad pH compatibility, achieving optimal dispersion stability within the pH range of 6–8. Advanced material engineering approaches, such as Janus configurations (e.g., Al₂O₃–TiO₂ hybrids), show promise for multimodal heat transfer enhancement. However, the intrinsic

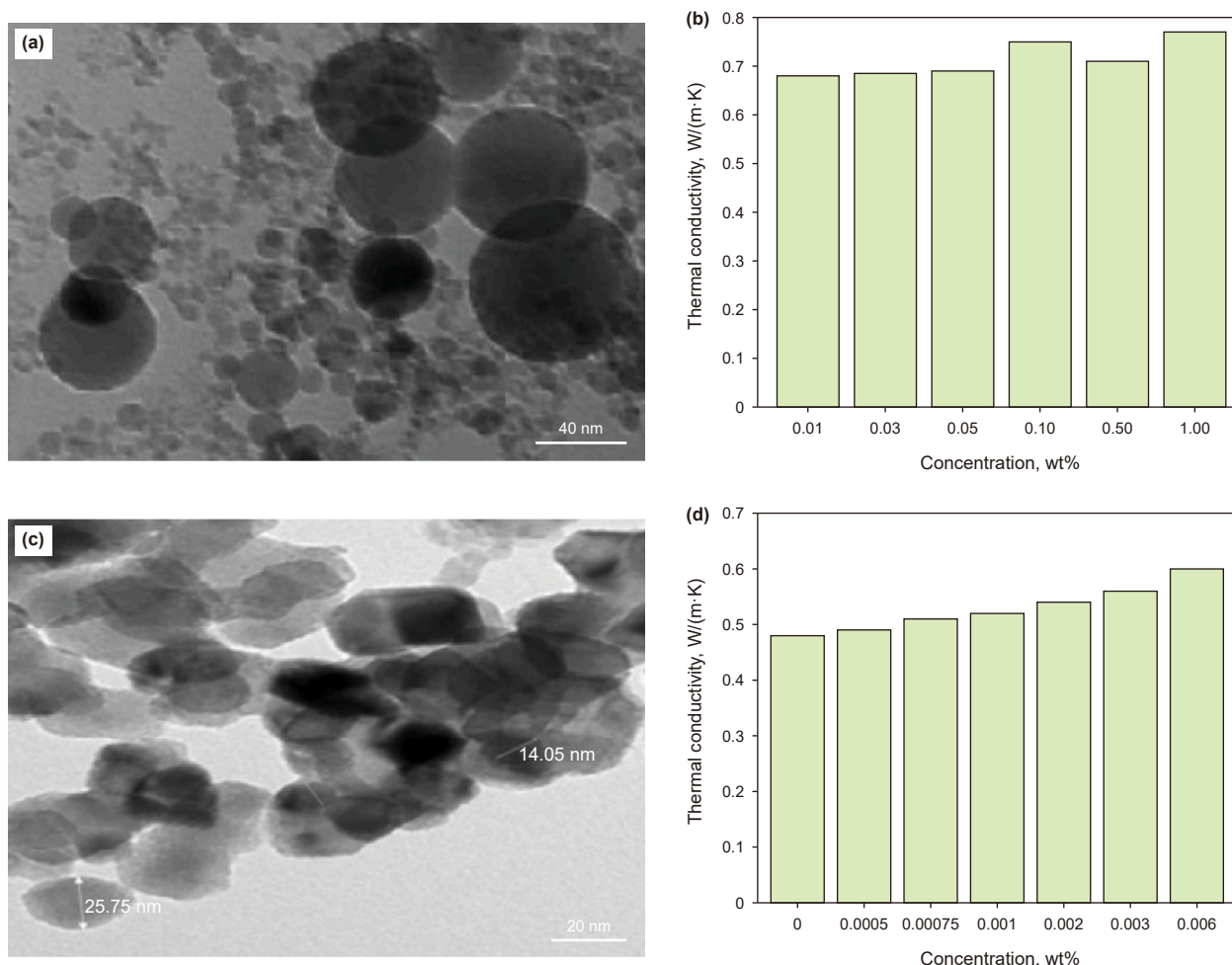


Fig. 6. Effect of aluminum oxide and titanium dioxide on the thermal conductivity of drilling fluids: (a) TEM image of aluminum oxide (Wagner et al., 2007), (b) thermal conductivity of drilling fluids containing aluminum oxide (Kalhori et al., 2023b), (c) TEM image of silicon titanium dioxide (Haider et al., 2019), and (d) thermal conductivity of drilling fluids containing titanium dioxide (Parizad et al., 2019).

hardness of Al_2O_3 nanoparticles introduces operational trade-offs, functioning both as friction modifiers and potential wear accelerators for drilling equipment.

Experimental validations confirm the thermal performance advantages of Al_2O_3 . Kalhori et al. (2023b) found that Al_2O_3 at all concentrations increased the thermal conductivity of the drilling fluid, with the maximum effect achieved at 80 °C, and the presence of 1 wt% Al_2O_3 nanoparticles increased the thermal conductivity of the base fluid by approximately 26% (Fig. 6(b)). Ghasemi et al. (2018) reported that the addition of Al_2O_3 and TiO_2 nanoparticles significantly improved the thermal conductivity and cooling efficiency of drilling fluids, with Al_2O_3 demonstrating superior thermal performance compared to TiO_2 and more effective drill bit cooling. Wang et al. (2024) evaluated the thermal conductivity enhancement effects of CNTs, SiO_2 , and Al_2O_3 in ODBFs. At a 3% nanoparticle concentration, Al_2O_3 yielded the highest thermal conductivity enhancement, with a 9.41% increase.

Furthermore, Kalhori et al. (2023a) synthesized $\text{CeVO}_4/\text{Al}_2\text{O}_3/\text{rGO}$ nanocomposites via a one-step hydrothermal method and observed that all samples exhibited notable improvements in thermal conductivity and gel strength. Specifically, in the presence of 0.5 wt% Al_2O_3 nanoparticles, the thermal conductivity of drilling fluid increased from 0.60 to 0.81 W/(m·K) at 80 °C. Based on existing research, Al_2O_3 is compatible with WBDF/OBDF, showing optimal compatibility in pH 6–8 systems and being more suitable

for WBDF. These studies collectively demonstrate Al_2O_3 's capacity to enhance thermal management in high-temperature drilling operations while also contributing to fluid stabilization. However, mitigation strategies are necessary to address the wear induced by particle hardness for long-term operational viability.

(d) TiO_2

Titanium dioxide (TiO_2) nanoparticles (Fig. 6(c)), primarily existing in anatase and rutile crystalline phases, exhibit a thermal conductivity of 1–10 W/(m·K). The rutile phase supports optimized axial phonon transport, enabling directional heat flux regulation. Characterized by high specific surface area, chemical stability, and ultraviolet absorption capacity, TiO_2 nanoparticles require ultraviolet shielding in surface systems to mitigate photocatalytic activity, while their enhanced oxidation resistance is advantageous in downhole environments. Their incorporation into drilling fluids improves operational stability, lubricity, plugging capacity, and environmental compatibility, particularly beneficial in complex geological formations (Sarokolai and Shiri, 2025).

Parizad et al. (2019) found that the thermal conductivity of WBDFs continuously increased with the concentration of TiO_2 nanoparticles. Through synergistic effects with potassium chloride salts, they achieved a maximum thermal conductivity enhancement of 25% and also improved the rheological properties of the WBDFs

(Fig. 6(d)). In another study, they reported a temperature-dependent enhancement in thermal conductivity for WBDFs containing TiO_2 nanoparticles. Specifically, in potassium chloride-based drilling fluids with added TiO_2 , the thermal conductivity enhancement increased with temperature, reaching 28% at 70 °C. This improvement was attributed to the functionalization of TiO_2 , which enhances its dispersion and stability in the fluid, thereby improving thermal conductivity and overall performance under high-temperature, high-pressure conditions (Parizad et al., 2018). Meanwhile, different forms of modification corresponding to different application scenarios also yield different results. Wang and Zou (2023) developed β -cyclodextrin-modified TiO_2 nanoparticles (β -CD/ TiO_2), which increased the thermal conductivity of OBDFs by 18.1%. Based on existing research, TiO_2 is compatible with WBDF/OBDF, achieving synergy between thermal conductivity. These findings position TiO_2 nanoparticles as multifunctional additives capable of addressing thermal management challenges while simultaneously enhancing fluid stability in demanding drilling environments. However, the requirement for ultraviolet shielding necessitates careful material handling during surface operations.

(e) SiO_2

Silicon dioxide (SiO_2) nanoparticles (Fig. 7(a)), available in both amorphous and crystalline forms (Heng et al., 2025), offer unique thermal management capabilities despite their inherently low thermal conductivity (1.2–2.0 W/(m·K)). The amorphous form features a high specific surface area and mesoporous architecture with pore sizes up to 50 nm, enabling structurally mediated optimization of heat transfer. Their thixotropic behavior facilitates the formation of shear-thinning fluids that enhance convective heat transfer, while surface hydroxyl groups allow for facile chemical functionalization to improve interfacial thermal coupling, particularly in oil-based systems.

In drilling fluid applications, SiO_2 nanoparticles serve multiple functions, including fluid loss control, foam stabilization, and wellbore strengthening. However, their thermal performance is highly dependent on advanced structural engineering strategies (Tchameni et al., 2025). Wang et al. (2024) observed an 8.54% increase in thermal conductivity in OBDFs at a 3% SiO_2 concentration, outperforming carbon nanotubes under specific operational conditions. Kalhori et al. (2023b) developed WBDFs incorporating SiO_2 nanoparticles, observing the thermal conductivity of the composite system increases by 22% at room temperature, but the enhancement decreases to 12% when the temperature rises to 80 °C (Fig. 7(b)). Building on the thermal enhancement potential of

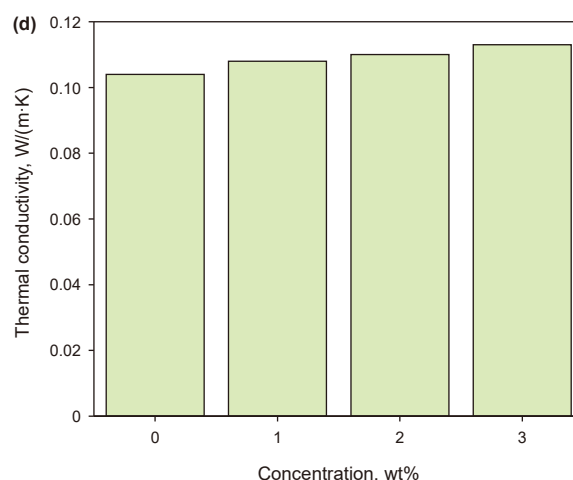
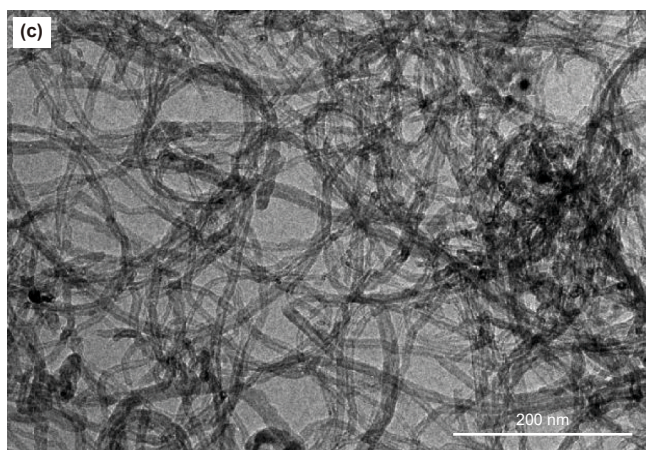
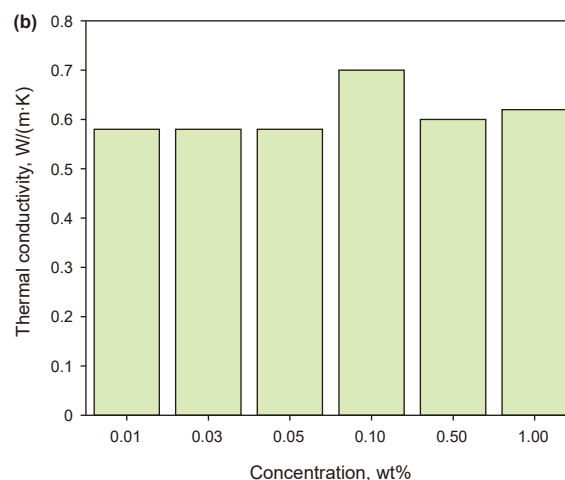
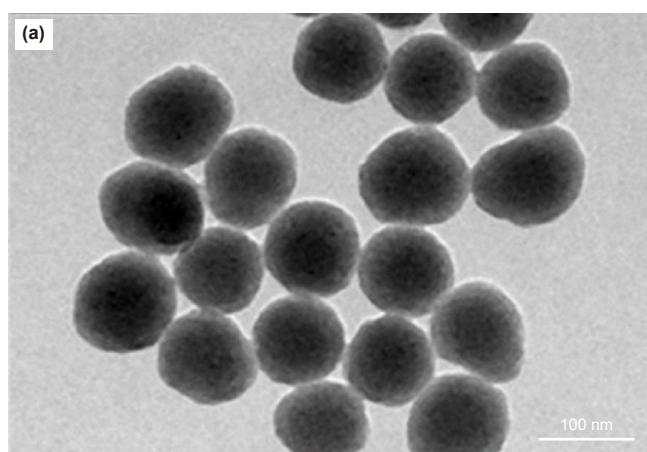


Fig. 7. Effect of silicon dioxide and carbon nanotubes on the thermal conductivity of drilling fluids: (a) TEM image of silicon dioxide (Elrai et al., 2025), (b) thermal conductivity of drilling fluids containing silicon dioxide (Kalhori et al., 2023b), (c) TEM image of carbon nanotubes (Li et al., 2021), and (d) thermal conductivity of drilling fluids containing carbon nanotubes (Wang et al., 2024).

SiO₂, researchers developed hybrid composites to exploit synergistic interactions and optimize heat transfer performance. For instance, [Hassani et al. \(2016\)](#) synthesized SiO₂ nanoparticles via sol-gel methods and designed a functionalized hybrid structure by chemically bonding carboxylated MWCNTs to SiO₂, forming SiO₂-CNT hybrids. Under conditions of 40 °C and 2 vol% SiO₂, the thermal conductivity of WBDFs increased by 16.9%. These findings highlight the versatility of SiO₂-based nanomaterials, whether used alone or in combination with other nanostructures, in enhancing thermal performance across different drilling fluid systems.

4.2.2. 1D nanomaterials

(a) Carbon nanotubes

Carbon nanotubes ([Fig. 7\(c\)](#)), cylindrical macromolecules formed by rolling single-layer carbon atom sheets (graphene), exhibit a distinctive one-dimensional tubular morphology with diameters ranging from 0.5 to 20 nm and micrometer-scale lengths. These black fibrous materials possess exceptional mechanical strength, up to 100 times greater than steel, and exhibit unique anisotropic thermal transport properties ([Minakov et al., 2025](#)). Classified as single-walled (SWCNTs) or multi-walled (MWCNTs), CNTs display remarkable axial thermal conductivities, i.e., SWCNTs can reach up to 3500 W/(m·K), while MWCNTs typically range from 1500 to 3000 W/(m·K). Notably, MWCNTs combine high thermal conductivity with electrical insulation along their longitudinal axis ([Ospanov and Kudaikulova, 2025](#)). Their high aspect ratios (100–1000) enable low percolation thresholds for thermal network formation via enhanced mechanical interlocking within fluid matrices.

In drilling fluid applications, CNTs offer multifunctional advantages beyond thermal management, including emulsion stabilization, enhanced cuttings transport, and antistatic effects. Their tubular geometry complements the planar structure of graphene but may introduce electrochemical limitations in reactive downhole environments and potential interference with fluid additives. Current industrial applications primarily favor MWCNTs due to their balanced performance characteristics and availability. [Wang et al. \(2024\)](#) compared the thermal conductivity enhancement effects of three types of nanomaterials on OBDF and found that at the minimum concentration (1%), CNTs exhibited the best performance, with the enhancement rate reaching 3.36% ([Fig. 7\(d\)](#)). [Blaž et al. \(2024\)](#) reported a 12.2% increase in thermal conductivity of WBDFs upon adding 1 wt% CNTs, with stable rheological properties maintained after heating. [Farahbod's \(2021\)](#) research indicates that the thermal conductivity of drilling fluids increases as the size of carbon nanotubes decreases, with a maximum enhancement reaching 14.7%. [Malika et al. \(2023\)](#) mixed MWCNT and Fe₂O₃ at an 80:20 vol ratio and found the 0.5 vol% hybrid nanofluid drilling fluid's thermal conductivity increased by 442% at 70 °C, far exceeding single nanofluids and proving carbon nanotubes' outstanding effect on enhancing drilling fluid thermal conductivity.

Surface functionalization plays a critical role in improving CNTs dispersion in drilling fluids, thereby enhancing thermal conductivity, rheological behavior, and filtration control. Acid treatment introduces hydrophilic functional groups (e.g., carboxyl groups) onto CNTs surfaces via nitric acid reflux, improving their compatibility with polar WBDFs. Ball milling, a mechanical dispersion technique, helps disintegrate aggregates and improve distribution uniformity, especially effective in WBDFs. Silane modification introduces hydrophobic functional groups onto CNTs surfaces, enhancing their compatibility with nonpolar OBDFs.

Babak's study reported thermal conductivity enhancements of 31.8% in WBDFs and 40.3% in OBDFs through combined chemical modification and ball milling treatment ([Fazelabdolabadi et al., 2015](#)). These advancements position CNTs as versatile nano-additives for the simultaneous improvement of thermal conductivity, fluid rheology, and operational efficiency in both WBDFs and OBDFs.

4.2.3. 2D nanomaterials

(a) Graphene and graphene oxide

Graphene ([Fig. 8\(a\)](#)), a two-dimensional carbon allotrope with an sp²-hybridized atomic layer structure ([Han et al., 2025](#)), has emerged as a key research focus in drilling fluid thermal management due to its revolutionary physicochemical properties, despite its deceptively simple carbon composition. This monoatomic-layer material appears as a black flaky powder with a distinctive hexagonal lattice structure and exhibits exceptional in-plane thermal conductivity (5000–18000 W/(m·K) at room temperature), the highest among known materials. Its unique crystal architecture enables efficient phonon transport, while its extraordinary specific surface area (2630 m²/g) enhances interfacial heat transfer. When incorporated into drilling fluids, graphene forms a percolation network structure, thereby improving axial and radial heat dissipation performance.

Despite these advantages, practical implementation is hindered by challenges such as high production costs and poor dispersibility in drilling fluids, which limit its direct application ([Zhang et al., 2024](#); [Li et al., 2026](#)). Consequently, graphene oxide (GO) offers superior applicability in drilling systems compared to pristine graphene. Experimental studies have shown that hydrogenated oil-based nanofluids containing graphene nanoplatelets achieve a 14.41% increase in thermal conductivity at a concentration of 100 ppm at 50 °C ([Fig. 8\(b\)](#)), while WBDFs incorporating graphene oxide nanosheets (GONPs) demonstrate a 57.9% enhancement in thermal conductivity ([Chai et al., 2017](#); [Gudarzifar et al., 2020](#)). Furthermore, recent advancements indicate that GO-based nanocomposites can significantly improve thermal performance. For example, GO_{0.5}/PAM nanocomposites in WBDFs exhibit a progressive increase in thermal conductivity from 5.95% to 19.6% ([Gudarzifar et al., 2020](#)). These findings underscore the transformative potential of graphene derivatives in optimizing heat transfer characteristics.

(b) Boron nitride

Boron nitride (BN) nanoparticles ([Fig. 8\(c\)](#)), a two-dimensional inorganic material with structural and mechanical similarities to graphene, appear as white flaky powders exhibiting exceptional thermal conductivity and mechanical robustness. Distinguished by their excellent chemical stability and corrosion resistance, BN nanoparticles are particularly well-suited for deep-well drilling fluid formulations, especially in high-temperature and highly corrosive environments. Among the crystalline forms of BN, hexagonal boron nitride is the most thermodynamically stable, consisting of sp²-hybridized boron and nitrogen atoms arranged in a hexagonal lattice. With in-plane thermal conductivity up to 400 W/(m·K) and oxidation resistance up to 850 °C, h-BN holds significant promise for high-temperature drilling fluid applications.

Although current research on BN-enhanced drilling fluids remains limited, preliminary studies have shown promising results. [Soares et al. \(2025\)](#), demonstrated that the thermal conductivity of the base fluid increased with increasing concentrations of oxidized

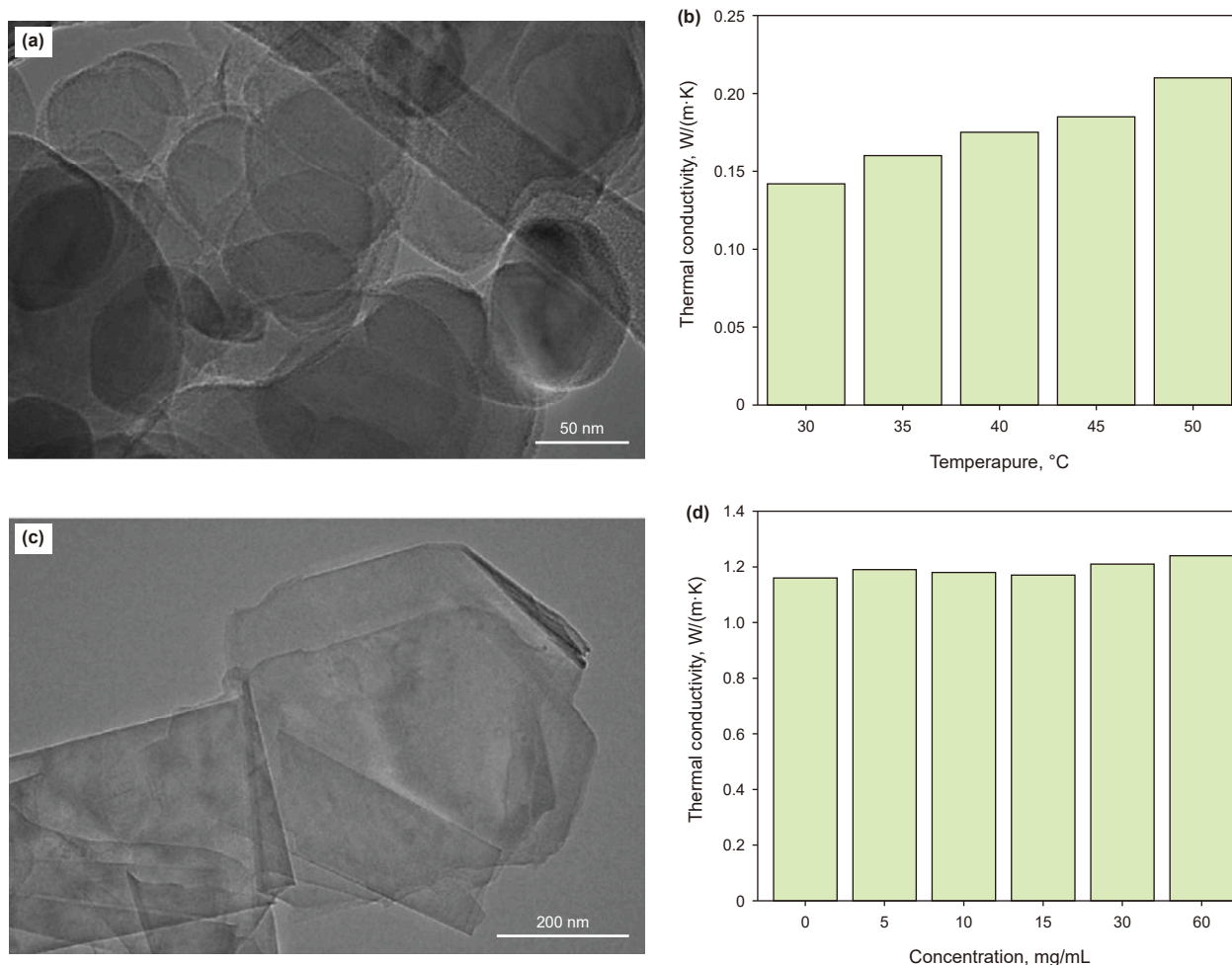


Fig. 8. Effect of graphene and boron nitride on the thermal conductivity of drilling fluids: (a) TEM image of graphene (Arain et al., 2022), (b) thermal conductivity of drilling fluids containing graphene (Chai et al., 2017), (c) TEM image of boron nitride (Arain et al., 2022), and (d) thermal conductivity of drilling fluids containing boron nitride (Soares et al., 2023).

h-BN (hBN-oxi). Additionally, the system exhibited temperature-dependent enhancement of thermal conductivity while maintaining stable fluid rheology. It was observed that the thermal conductivity increased with temperature up to 50 °C, after which it began to decline. Furthermore, Arain and Ridha (2025) investigated the synergistic effects of BN and graphene nanoplatelets (GNPs) in OBDs, identifying optimal performance at 0.2 ppb nanoparticle concentration with enhanced rheological properties and thermal stability under elevated temperatures.

The use of xanthan gum, with its unique molecular structure forming a stable three-dimensional network in solution, facilitates uniform dispersion of hBN-oxi nanosheets, reduces aggregation, and enhances the expression of their thermal properties. The development of xanthan gum-based hBN-oxi dispersions achieved a thermal conductivity increase from 1.163 W/(m·K) to 1.236 W/(m·K) in aqueous suspensions, suggesting hBN-oxi as a promising additive for WBDFs (Fig. 8(d)) (Soares et al., 2023). At ultra-high temperatures above 200 °C, its oxidation resistance and electrical insulation are more critical, making it suitable for deep corrosive operating conditions. These findings collectively highlight BN's potential to address multiple operational challenges through tailored nanoengineering approaches, although further systematic investigations are necessary to fully realize its application in downhole thermal management systems.

4.3. Mechanisms of heat transfer enhancement by nanomaterials

In deep, high-temperature drilling scenarios, the enhancement of heat transfer performance in drilling fluids using nanomaterials relies on multiscale and multiphysical field synergistic effects. Compared to traditional drilling fluids, nanomaterials enable effective thermal management through conduction and convection. These mechanisms not only reveal the scientific principles underlying efficient heat transfer in nanofluids but also provide a theoretical foundation for the thermal stability design of drilling fluids under extreme operating conditions.

4.3.1. Heat conduction mechanisms

(a) Phonon interfacial scattering suppression mechanism

The mechanism by which nanomaterials enhance thermal conduction in drilling fluids through the small-size effect is inherently linked to phonon transport characteristics and interfacial interactions. In solid nanoparticles, thermal conduction occurs through the propagation of phonon vibrations, but interfacial scattering can lead to phonon energy dissipation and a reduction in thermal conductivity (Xie et al., 2018). When the size of nanoparticles is smaller than the phonon mean free path (typically

10–100 nm), the dominant phonon scattering mechanism transitions from disordered bulk scattering to low-loss surface scattering. Moreover, the high surface energy of nanoparticles promotes an ordered arrangement of interfacial atoms, which reduces the phonon scattering probability caused by lattice distortion (Choudhary et al., 2022).

In the liquid medium of drilling fluids, the random thermal motion of liquid molecules typically leads to strong phonon scattering (Beck et al., 2009). However, the introduction of nanoparticles mitigates this effect through a dual mechanism. First, interactions between small-sized particles and surrounding liquid molecules, such as hydrogen bonding and van der Waals forces, restrict the motion of liquid molecules near the nanoparticle surface, forming an ordered liquid layer that reduces phonon scattering at the solid–liquid interface. Second, the network structure formed by the uniform dispersion of nanoparticles shortens the thermal conduction path, encouraging phonons to propagate through the low-scattering solid particles rather than through the highly scattering liquid medium (Fig. 9(a)) (Wang et al., 2012). Together, these effects optimize phonon transport pathways within the nanoparticle phase and reduce scattering losses at the solid–liquid interface, thereby constructing efficient thermal conduction channels across the two-phase (solid–liquid) system in drilling fluids.

(b) Static thermal conductive network construction mechanisms

In drilling fluids, nanomaterials form three-dimensional thermally conductive networks spanning nano-to micro-scales through physical adsorption, chemical bonding, or van der Waals interactions (Wan et al., 2016). The core mechanisms include

cross-dimensional structural coupling, interfacial bonding reinforcement, and regulation of self-assembly behavior, all of which contribute to the construction of efficient heat conduction pathways at the static structural level (Fig. 9(b)) (Hamade et al., 2020).

The incorporation of nanomaterials (especially the 1D and 2D) into drilling fluids enables the formation of three-dimensional thermal networks via dimensional complementarity. 1D materials (e.g., carbon nanotubes, CNTs) function as conductive bridges, spanning the continuous phase of the base fluid (water or oil), linking discrete nodes and establishing long-range heat transfer pathways (Zhu et al., 2019). 2D materials (e.g., graphene and boron nitride) possess high thermal conductivity and nanoscale thickness, allowing them to form parallel-stacked or wrinkled interconnected structures within the base fluid, which facilitate rapid heat conduction along the planar (XY) direction of their sheets (Cong et al., 2017).

Interfacial bonding reinforcement refers to the mechanism by which physical or chemical interactions at the nanomaterial–base fluid interface enhance bonding strength, optimize interfacial structure, reduce interfacial thermal resistance, and improve the overall thermal performance of the composite (Zhang et al., 2022). This is typically achieved through surface modification of nanomaterials, which improves dispersion stability in the base fluid and increases energy transfer efficiency at the interface. In drilling fluid systems, interfacial bonding reinforcement is a critical step in establishing effective static thermal networks and directly affects heat conduction between nanomaterials and the surrounding fluid.

In static or low-shear environments, nanomaterials in drilling fluids can spontaneously self-assemble via charge matching, hydrophobic/hydrophilic interactions, or functional group specificity (Ke and Wei, 2008). Optimizing this self-assembly process can

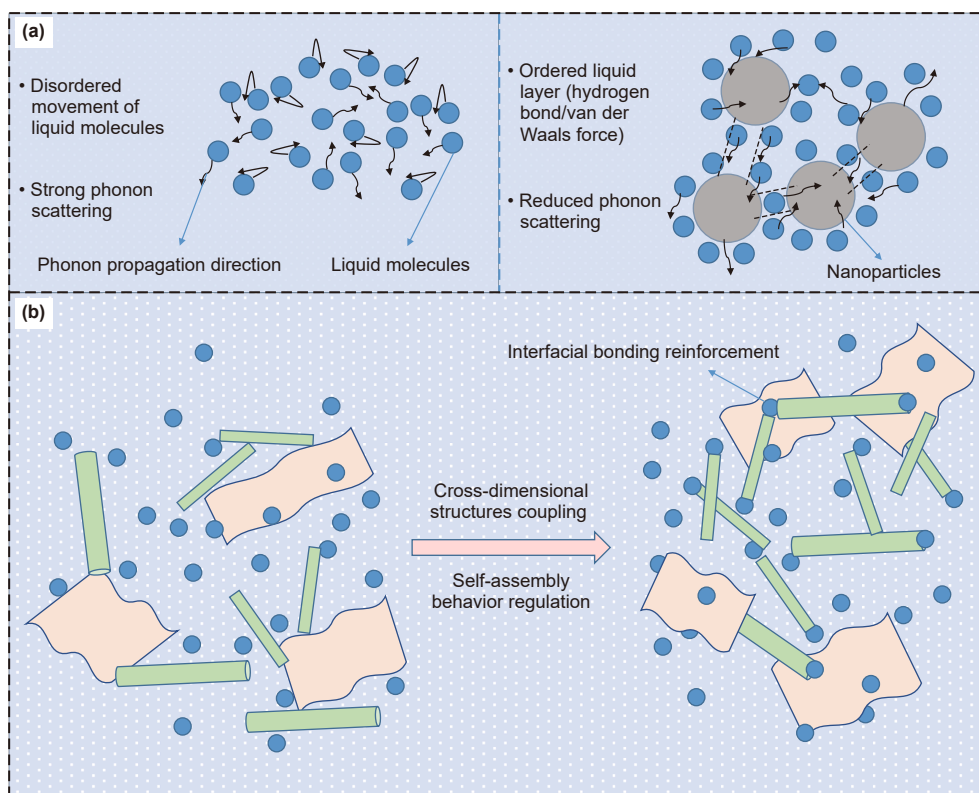


Fig. 9. Schematic diagram of heat conduction enhancement mechanisms by nanomaterials: (a) phonon interfacial scattering suppression mechanism and (b) static thermal conductive network construction mechanisms.

directionally enhance heat conduction by promoting the transition from disordered dispersion to ordered alignment. Spontaneous self-assembly involves the specific interaction of nanoparticles with the base fluid and with each other to form ordered nanostructures without the need for external energy input. This static network formation does not rely on external dynamic fields (e.g., shear flow or temperature gradients) but rather on the inherent surface properties of the nanomaterials.

4.3.2. Heat convection mechanisms

The heat conduction mechanisms are dominant under moderate-to-low temperature conditions ($<150\text{ }^{\circ}\text{C}$), as well as static or low-shear environments. In contrast, under high-shear conditions (e.g., circulating flow) and intense Brownian motion activity, heat convection mechanisms are more effective (Khan et al., 2025c). Importantly, synergistic effects exist between conduction and convection mechanisms, i.e., heat conduction establish foundational thermal conduction pathways, while Brownian motion and high-shearing

further activates heat transfer. During drilling fluid circulation, the heat convection of nanomaterials overcomes the limitations of static conduction, enabling real-time optimization of heat transfer through Brownian motion-induced microconvection, shear-field-responsive structural reorganization, and temperature-gradient-driven thermophoretic migration (Gieseler and Millen, 2018; Suganthi and Rajan, 2017).

The continuous random Brownian motion of nanoparticles in the base fluid (with velocities on the order of $\sim 10^{-6}\text{ m/s}$) can directly perturb the boundary layer and disrupt laminar flow (Fig. 10(a)). As nanoparticles move, viscous drag induces localized microconvection in the surrounding fluid, reducing the thickness of the thermal boundary layer from a static range of $100\text{--}500\text{ }\mu\text{m}$ to $50\text{--}150\text{ }\mu\text{m}$, thereby significantly lowering thermal resistance. Concurrently, frequent collisions between nanoparticles and fluid molecules facilitate energy exchange via phonon scattering and molecular collisions. This leads to a diffusion-convection synergy with the fluid's macroscopic flow, enhancing the radial thermal

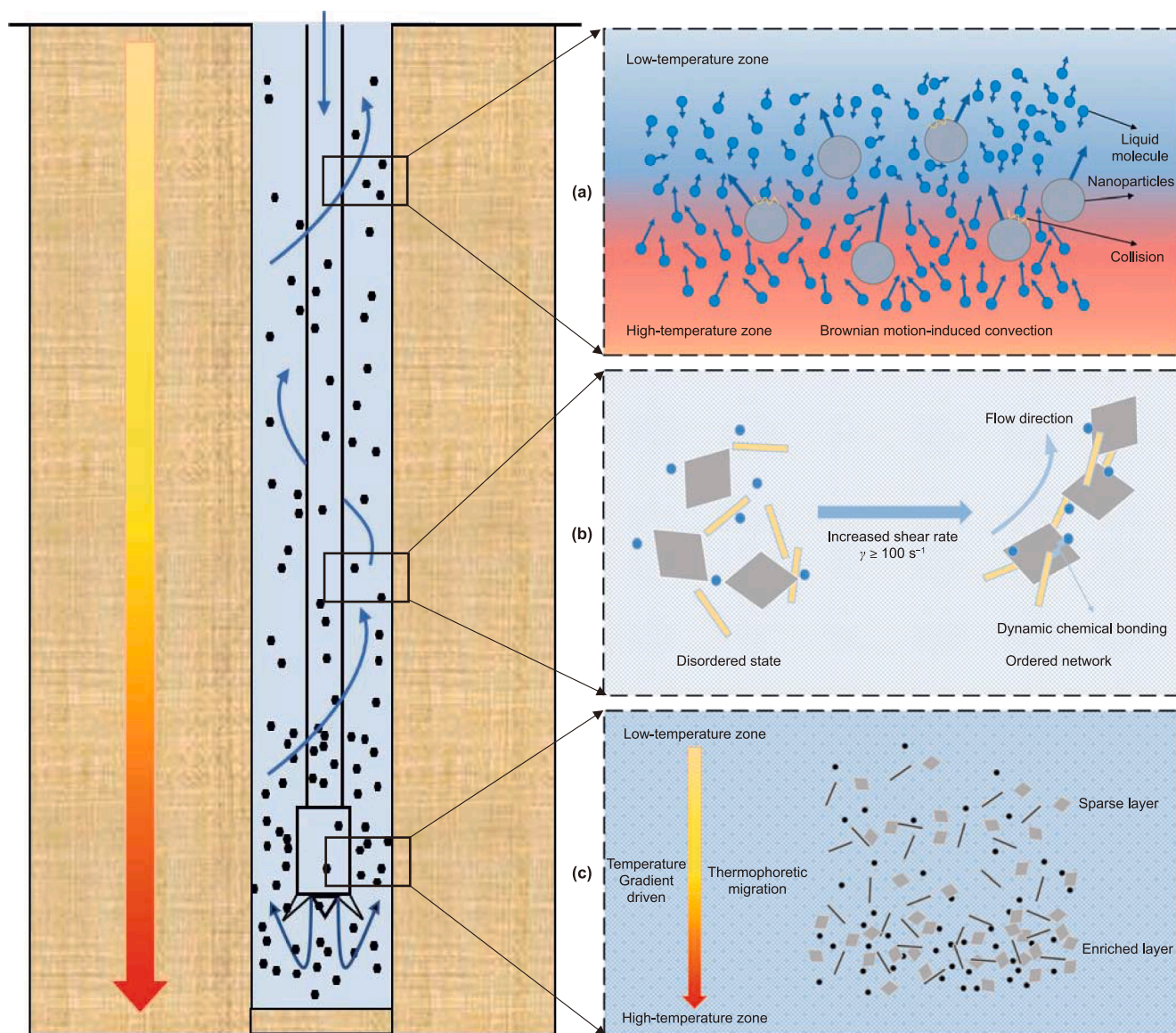


Fig. 10. Schematic diagram of heat convection enhancement mechanisms by nanomaterials: (a) Brownian motion-induced microconvection mechanisms (Gokapai et al., 2024), (b) shear-field-responsive structural reorganization mechanisms and (c) temperature-gradient-driven thermophoretic migration mechanisms.

diffusion coefficient and overall heat transfer efficiency in confined regions such as the narrow annulus (Hussain et al., 2024; Soltani et al., 2022).

Moreover, during fluid circulation, shear fields generated by flow cause anisotropic nanomaterials to align directionally along the flow path, forming shear-induced ordered networks that significantly improve thermal conductivity in the flow direction (Fig. 10(b)). At moderate-to-high shear rates ($\gamma \geq 100 \text{ s}^{-1}$), the orientation of 1D and 2D nanomaterials increases, network porosity decreases, and the straightness of thermal conduction pathways improves. Moreover, high shear stress promotes dynamic chemical bonding between particles or between particles and base fluid molecules, enhancing interfacial heat transfer (Liang, 2007). Additionally, structural disaggregation of nanomaterials under shear reduces drilling fluid viscosity and increases macroscopic flow velocity, further improving convective heat transfer. At the same time, temperature gradients between high-temperature bottomhole zones and low-temperature annular regions drive thermophoretic migration of nanomaterials, leading to the formation of high-concentration enrichment layers near the wellbore (Fig. 10(c)). These layers form thermally conductive paths with gradient distribution characteristics. Together, these mechanisms operate synergistically under complex, high-temperature, high-shear conditions, significantly enhancing the convective heat transfer efficiency and thermal responsiveness of drilling fluids (Vallejo et al., 2022).

4.3.3. Influence of actual drilling fluid environment on heat transfer mechanisms

The heat transfer mechanisms of nanomaterials in drilling fluids (conduction and convection) are not isolated, but are significantly regulated by the actual downhole environment. These environmental factors either enhance or suppress the basic mechanisms, ultimately affecting the improvement in thermal conductivity of drilling fluids.

In drilling fluid systems, there are factors related to the heat transfer mechanism, such as high shear rates, extreme pressures, and other additives. High shear rates disrupt the static thermal conduction network of nanomaterials, yet they facilitate the oriented alignment of thermally conductive nanomaterials and enhance the convective heat transfer efficiency of drilling fluids (Gautam et al., 2022). Meanwhile, high shear stress aids in dispersing small agglomerates, thereby mitigating the thermal resistance induced by agglomeration. Extreme pressures compress the interparticle spacing and elevate the risk of agglomeration, but they can strengthen interparticle contact and reduce interfacial thermal resistance, which offset a portion of the adverse effects arising from agglomeration (Ali et al., 2020). Other additives in drilling fluids, such as polymer-based additives, adsorb onto the surface of nanoparticles, which is detrimental to the formation of thermal conduction networks (Li et al., 2025c; Seright and Wang, 2023). In contrast, bentonite exerts a synergistic effect with nanoparticles, thereby contributing to the enhancement of dispersion stability (Saboori et al., 2019).

This indicates that the thermal enhancement effect of nanomaterials in actual drilling fluids is the result of the combined action of basic heat transfer mechanisms and environmental regulatory factors. Therefore, the selection and concentration optimization of nanomaterials must fully consider the actual downhole environmental parameters to achieve the best thermal management effect.

5. Challenges and future perspectives

Despite the breakthrough potential of nanomaterials in drilling fluid thermal management, their large-scale application still faces challenges arising from contradictions between material properties and engineering requirements. Current technical bottlenecks are concentrated in areas such as nanoparticle dispersibility and stability, performance balance, economic and large-scale production, and environmental considerations. Addressing these issues requires interdisciplinary and innovative strategies, including hybrid structure design, different dimensional nanomaterial combinations, responsive nanomaterials, and bio-based nanomaterials (Fig. 11).

5.1. Challenges

5.1.1. Dispersibility and stability of nanomaterials under elevated temperature conditions

Efficient dispersion and long-term stability of nanomaterials in drilling fluids are fundamental prerequisites for achieving high thermal conductivity (Gokapai et al., 2024). However, due to the intrinsic physicochemical properties of nanomaterials and the harsh operating conditions encountered in drilling, especially under elevated temperature conditions, several technical bottlenecks arise.

The most critical issue is aggregation, which is more pronounced under elevated temperature conditions. Aggregation refers to the spontaneous formation of large clusters of nanoparticles due to physical or chemical interactions, resulting in a reduced effective surface area, loss of active sites, and disruption of the thermal conductive network (Zhao et al., 2019). Owing to their high specific surface area and the influence of van der Waals forces, nanomaterials are particularly prone to physical aggregation, with this tendency being further enhanced when exposed to elevated temperature conditions (Fang et al., 2017). Typically, nanoparticles in the 1–100 nm range possess a high surface-area-to-volume ratio and a large fraction of surface atoms. According to the Lennard-Jones potential model, van der Waals attractions decay with the sixth power of distance, but at distances less than 10 nm, the attractive force far exceeds the thermal kinetic energy, triggering spontaneous aggregation (Inui, 2019; Ma et al., 2019). For example, graphene sheets without surface treatment tend to form graphite-like structures, thereby causing a significant reduction in their theoretical thermal conductivity in practical applications (Sang et al., 2019). Additionally, during fluid circulation, exposure to high shear rates ($>1000 \text{ s}^{-1}$) and extreme temperature fluctuations (up to $>200 \text{ }^{\circ}\text{C}$) further intensifies particle collisions and promotes aggregation, especially under sustained elevated temperature conditions (Bouguerra et al., 2023; Heyhat et al., 2012).

Furthermore, density differences between nanomaterials and the base fluid lead to sedimentation during long-term static storage, compromising dispersion uniformity and resulting in thermal conductivity degradation over time, and this sedimentation process is notably accelerated under elevated temperature conditions (Zhao et al., 2019). Long-term stability refers to the ability of nanomaterials to remain uniformly dispersed in drilling fluids and encompasses resistance to sedimentation, phase separation, and chemical degradation. According to Stokes' law:

$$\nu = \frac{2(\rho_p - \rho_f)gr^2}{9\eta} \quad (6)$$

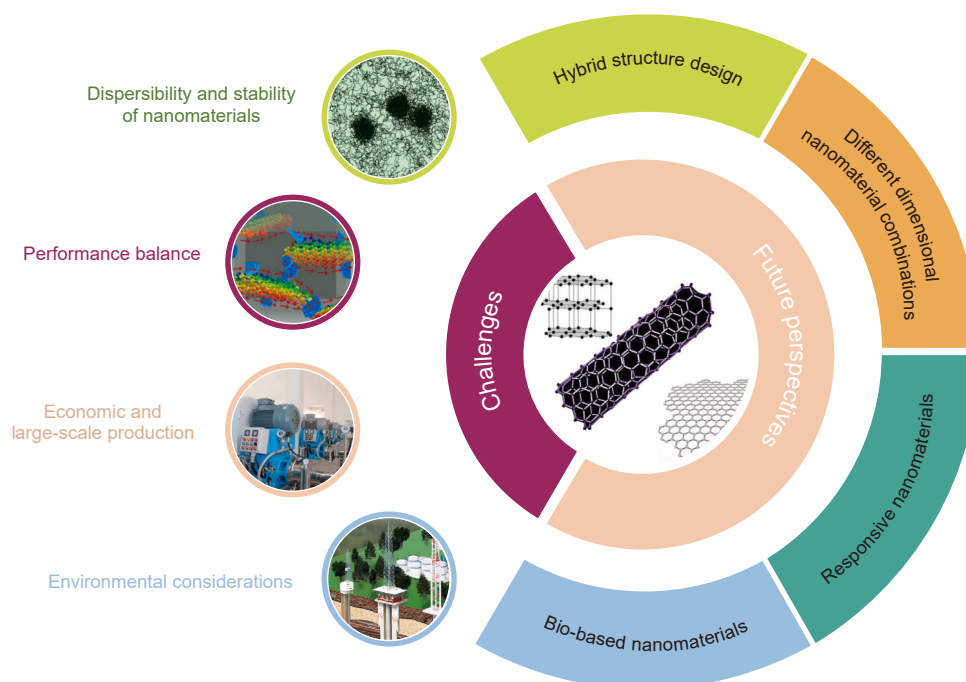


Fig. 11. Proposed critical challenges and future perspectives.

where v is sedimentation velocity of particles, m/s; ρ_p is density of particles, kg/m³; ρ_f is density of fluid, kg/m³; g is gravitational acceleration, m/s²; r is radius of spherical particles, m; η is dynamic viscosity of fluid, Pa·s. Sedimentation velocity is directly proportional to the density difference and the square of particle size, and inversely proportional to the fluid's viscosity. When nanomaterials aggregate, their effective particle size increases, further accelerating sedimentation. In practice, due to Brownian motion and aggregation effects, the sedimentation rate of nanomaterials in WBDFs increases nonlinearly, leading to significantly shorter settling times than those predicted theoretically (Jiao et al., 2022; Parsai and Kumar, 2019), with this discrepancy becoming larger under elevated temperature conditions. Long-term sedimentation causes an uneven particle distribution and the formation of high-concentration deposits at the bottom, ultimately leading to a substantial reduction in the thermal conductivity of the upper fluid. For example, it has been reported that after 72 h of static storage, the density of the upper layer of drilling fluid decreased by up to 60%, while the convective heat-transfer coefficient dropped by as much as 25.8%, resulting in a significant decline in the heat-transfer performance of the upper drilling fluid (Ueki et al., 2018; Yang et al., 2020). Although agitation during drilling circulation can temporarily re-disperse particles, the interruption of the thermal conduction network remains unavoidable.

In addition, some nanomaterials undergo lattice distortion, oxidation, or phase transitions at elevated temperatures, leading to irreversible losses in thermal conductivity (Andrievski, 2014). At temperatures above 150 °C, the concentration of surface oxygen vacancies increases, promoting grain growth, which enlarges particle size, reduces surface area, and weakens thermal transport. The structural deterioration of nanomaterials not only weakens their dispersion stability but also reduces their thermal conductivity enhancement effect (Wang and Zou, 2023). Only a few thermally stable nanomaterials (e.g., h-BN) can maintain relatively effective thermal transport performance at ultra-high

temperatures above 200 °C. Electrolytes (e.g., Ca²⁺ and Cl⁻) and acidic or alkaline components in drilling fluids can chemically corrode nanomaterial surfaces (Verma and Quraishi, 2022). For instance, certain metal-based nanoparticles dissolve in acidic environments (pH < 4), releasing ions and reducing particle integrity, thereby impairing the thermal conduction network. Moreover, the long-term stability of nanomaterials is further influenced by coupled factors such as mechanical stress, degradation of surface modifications, competition among multiple fluid components, and environmental oxidation (Li et al., 2025a). These mechanisms collectively undermine the effectiveness of the thermal conduction network by altering particle size, interfacial interactions, and structural integrity over time.

However, the effect of elevated temperature on the thermal conductivity of drilling fluids is still lacking. Most of these data are obtained under low temperature conditions. The lack of systematic validation on thermal enhancement effectiveness at high temperatures further restricts the reliable application of nanomaterials in deep well drilling. Therefore, future research should investigate how the elevated temperature can affect the thermal conductivity of drilling fluids. In addition, future work should focus on developing thermally stable surface functionalization strategies, designing core-shell or encapsulated nanostructures to prevent aggregation, and exploring synergistic hybrid systems that combine different dimensional nanomaterials to enhance both thermal conductivity and long-term dispersion stability. Additionally, advanced in-situ monitoring techniques and modeling approaches could provide real-time insight into nanoparticle behavior under downhole conditions, guiding the formulation of nanofluids optimized for ultra-deep and high-temperature drilling environments.

5.1.2. Performance balance

Drilling fluids are required to meet multiple performance criteria simultaneously, including thermal management, rheology,

and filtration performance. However, the incorporation of nanomaterials often leads to trade-offs or conflicts between these properties, necessitating precise formulation design and synergistic optimization strategies.

One of the most prominent conflicts arises between rheology and thermal conductivity. These two properties often contradict each other in terms of nanomaterial loading and structural configuration. Nanoparticles can increase viscosity through two primary mechanisms: the hard-sphere effect and the formation of three-dimensional particle networks. High loadings of nanomaterials (such as nano-SiO₂ or Al₂O₃) significantly increase fluid viscosity, impairing pumpability, while the efficiency ratio between thermal conductivity enhancement and viscosity increase remains low (Ghasemi et al., 2018; Veisi et al., 2020). For optimal performance, drilling fluids must exhibit shear-thinning behavior (i.e., power-law flow with a flow index $n < 1$) to minimize pumping resistance. However, certain nanomaterials, such as rod-like nano-TiO₂, tend to form rigid network structures under shear that are difficult to disentangle, causing the flow index n to approach 1 (Newtonian behavior), thereby reducing fluidity and dramatically increasing the required pumping power. In addition, thermal conduction networks require close particle contact to establish continuous pathways for heat transfer, while rheological optimization demands moderate dispersion to reduce interparticle friction, presenting another structural contradiction (Lalji et al., 2024). These issues illustrate the inherent physical limitations associated with both nanomaterials loading and structural design.

Moreover, the requirement for a stable and dense filter cake to ensure effective fluid control (i.e., a good seal) is inherently contradictory to the requirement for high thermal conductivity of drilling fluids (i.e., efficient heat transfer). From a microstructural perspective, the integrity of the filter cake depends on the tightly packed arrangement of solid particles. However, the direct incorporation of nanomaterials with mismatched sizes may disrupt the optimized particle-size distribution that is essential for forming a low-permeability filter cake. This disruption can lead to increased porosity, weakened sealing capacity, and reduced structural robustness of the filter cake under downhole pressure conditions. Conversely, when nanomaterials deposit and accumulate within the filter cake, they can reduce the overall thermal conductivity of the drilling fluid system. Therefore, simultaneously enhancing the thermal conductivity of drilling fluids and maintaining high-quality filter-cake performance presents a substantial materials-engineering challenge.

5.1.3. Economic and large-scale production

The transition of nanomaterials from laboratory research to industrial-scale application in drilling fluids requires overcoming challenges related to cost and production efficiency. The synthesis of nanomaterials aimed at enhancing the thermal conductivity of drilling fluids is typically expensive, often involving high energy consumption and low production yields, which hinder their widespread industrial adoption (Fan et al., 2025). In addition, most existing drilling fluid production lines are not equipped with specialized dispersion systems suitable for nanomaterials. As a result, the direct addition of unmodified nanomaterials can lead to issues such as equipment blockages, poor dispersion, and reduced operational efficiency (Dutta and Das, 2021). Furthermore, OBDFs possess non-polar characteristics, which requires nanomaterials to undergo multi-step chemical modification (e.g., grafting long-chain alkyl groups or fluorinated hydrophobic groups) to enhance their oil-phase compatibility. This modification process not only requires the consumption of expensive chemical reagents and precise reaction conditions (e.g., temperature control, inert gas protection) but also increases process complexity, thereby

further raising production costs and reducing production efficiency.

5.1.4. Environmental considerations

Environmental impact and waste management must also be taken into account. The use and disposal of nanomaterials raise concerns regarding potential ecological toxicity, long-term accumulation in the environment, and the lack of standardized treatment processes (Sarvepalli et al., 2025). Ensuring safe handling, recovery, and disposal is essential for the sustainable implementation of nanomaterials in drilling operations.

The small size of nanoparticles enables them to easily penetrate the physiological barriers of organisms, readily causing cellular damage to plankton, interfering with soil microbial metabolism, and even accumulating through the food chain. Meanwhile, most nanomaterials used in drilling are difficult to be microbially degraded in the natural environment and are not easily converted into harmless substances via physicochemical processes. Their excellent chemical stability further exacerbates risks through long-term environmental accumulation. Currently, there are no unified global standards for the classification, detection, and disposal of nano-waste. The lack of standardized disposal processes makes these issues difficult to regulate, essentially due to the lag in industry norms and technologies. The superposition of these problems, coupled with the industry's research and regulation on environmental impacts lagging behind the pace of application, keeps environmental risks at a persistently high level.

5.2. Future perspectives

5.2.1. Hybrid structure design

Hybrid structure design involves integrating nanomaterials with distinct functionalities into “core-shell” or “heterojunction” architectures using chemical bonding or physical encapsulation (Yang et al., 2019). This strategy enables synergistic optimization of properties, particularly balancing thermal conductivity with dispersion stability. Furthermore, surface modification can enhance the compatibility between nanomaterials and the drilling fluid matrix and improve high-temperature dispersion stability (Rong et al., 2023). For instance, the lipophilic outer shell can enhance dispersion stability in oil-based systems, and grafting silane coupling agents can effectively improve high-temperature dispersion stability. Simultaneously, chemical bonding reduces defects at the core-shell interface, enhances phonon/electron transport, and lowers interfacial thermal resistance (Wong et al., 2023).

In composite nanomaterials designed with this approach, the core typically provides high thermal conductivity, while the shell contributes auxiliary functions such as lubrication, plugging, or corrosion resistance, overcoming the limitations of single-component materials (Ren et al., 2022; Zhang et al., 2019). For example, grafting oleophilic functional groups onto graphene significantly improves its dispersibility in OBDFs, while boron nitride-coated nanoparticles (e.g., BN@Cu) retain chemical inertness under high-temperature conditions (Huang et al., 2015). These designs achieve synergistic performance by combining the high thermal conductivity of the core with the multifunctionality of the shell, while minimizing interfacial thermal resistance.

Additionally, a thin boron nitride layer can be deposited onto graphene via chemical vapor deposition, or atomic layer deposition can be employed to precisely control shell thickness, enabling a balance between thermal conductivity and dispersibility (Galligan et al., 2023). The core significance of this strategy lies in surpassing the performance limits of individual materials, providing feasible methods for maintaining the dispersion

Table 3

Application fields, scopes and limitations of different dimensional nanomaterials in drilling fluids.

Nanomaterials	Compatible with drilling fluid types	Concentration range	Applicable temperature range, °C	Thermal conductivity enhancement capacity	Limitations
CuO (0D)	WBDF	0.3–0.9 wt%	<150	Low	High temperature intolerance
ZnO (0D)	WBDF	0.5–2 vol%	<200	Medium	Viscosity increase at high concentrations
Al ₂ O ₃ (0D)	WBDF/OBDF	1–3 wt%	<150	Medium	High hardness
TiO ₂ (0D)	WBDF/OBDF	0.4–2 wt%	<200	Medium	Easy dissolution in acidic environments
SiO ₂ (0D)	WBDF/OBDF	1–3 wt%	<150	Low	Low thermal conductivity
CNTs (1D)	WBDF/OBDF	0.1–1 vol%	<220	High	Poor dispersion
Graphene (2D)	WBDF/OBDF	0.01–0.1 wt%	<250	High	High cost
BN (2D)	WBDF/OBDF	0.2–3 wt%	<300	Medium	Low thermal conductivity enhancement rate

stability of nanomaterials under high-temperature or even ultra-high-temperature conditions, and offering integrated solutions for thermal management in complex downhole environments.

5.2.2. Different dimensional nanomaterial combinations

Different dimensional nanomaterials exhibit markedly different physicochemical properties, leading to varying applicable drilling scenarios, advantages, and inherent limitations (Table 3). The strategic combination of nanomaterials with different dimensionalities enables the construction of three-dimensional, interpenetrating thermal-conduction networks. By integrating 1D nanomaterials (e.g., carbon nanotubes), 2D nanomaterials (e.g., boron nitride nanosheets), and 0D nanoparticles (e.g., CuO), such hybrid systems can leverage the unique thermal, mechanical, and interfacial characteristics of each component. This multidimensional synergy offers enhanced thermal pathways, improved dispersion stability, and more robust heat-transfer performance compared with single-dimensional additives, while also providing greater flexibility in tailoring rheological, filtration, and sedimentation properties for specific drilling environments.

For example, combining the axial thermal conductivity of 1D carbon nanotubes with the in-plane thermal conductivity of 2D boron nitride nanosheets results in an efficient “highway + branch” conduction pathway. Boron nitride nanosheets can bridge gaps between carbon nanotubes, enhancing the continuity of thermal pathways. Implementation methods include vacuum filtration self-assembly of alternating carbon nanotube/boron nitride nanosheets layered structures or in-situ chemical vapor deposition to grow boron nitride nanosheets directly on carbon nanotube surfaces, forming heterojunctions. These combinations not only optimize phonon transport but also improve the mechanical robustness of the fluid system (e.g., through the fiber-toughening effect of carbon nanotubes), making them especially suitable for high-pressure, deep-well drilling environments (Li et al., 2019).

5.2.3. Responsive nanomaterials

Responsive nanomaterials are nanoparticles engineered through molecular design to exhibit dynamic responses to external stimuli such as temperature, pH, and pressure, thereby enabling on-demand regulation of thermal conductivity (Liu et al., 2017). For example, combined with the double-crosslinked boron nitride framework (BNF) in the polyethylene glycol (PEG) phase change matrix, when the temperature exceeds the phase change temperature of PEG, the thermal conductive network of BNF unfolds, achieving a heat dissipation effect with $\Delta T_{\max} = 10\text{ }^{\circ}\text{C}$ (Jiang et al., 2019). Similarly, for the boron nitride/graphene/polyethylene glycol composite phase change material prepared by the water-based emulsion method, when the temperature exceeds the

phase change temperature of PEG, the composite material transforms from a solid state to an elastomer, and the honeycomb network formed by two-dimensional fillers increases the thermal conductivity from 0.2 to 1.09 W/(m·K) (Sun et al., 2024c).

The significance of responsive nanomaterials lies in their ability to enable adaptive thermal management, automatically enhancing thermal conductivity in high-temperature downhole zones while minimizing heat loss in low-temperature regions, thus optimizing heat distribution along the wellbore (Liu et al., 2025). Moreover, they activate high-conductivity modes only when needed, reducing energy consumption and minimizing mechanical wear under standard conditions (Fan et al., 2024).

In addition, many responsive nanomaterials exhibit self-healing capabilities (Jamil et al., 2024). For instance, damage to the responsive shell can trigger self-repair mechanisms (e.g., recombination of polymer chains), restoring the structural and functional integrity of the thermal conduction network (Bisht et al., 2024). The application of these responsive nanomaterials can achieve real-time regulation and on-demand control, reduce the loss of nanomaterials to save costs, and lay a foundation for intelligent and adaptive drilling fluid systems.

5.2.4. Bio-based nanomaterials

Bio-based nanomaterials are sustainable nanomaterials derived from natural biomass sources (e.g., cellulose, chitosan) through processes such as nanosizing, carbonization, and functional modification (Li et al., 2023; Zhong et al., 2025). These materials combine high thermal conductivity with environmental sustainability. Functional groups naturally present in biomass (e.g., hydroxyl and amino groups) are amenable to chemical modification, enabling the incorporation of multiple functionalities such as thermal conductivity, antibacterial activity, and pH responsiveness. For example, acid hydrolysis of wood pulp yields cellulose nanofibers, which can be converted into graphitized carbon nanofibers with high thermal conductivity through high-temperature carbonization (Yeamsuksawat et al., 2024). Similarly, the compounding preparation of chitosan with boron nitride can endow the composite materials with dual characteristics of environmental friendliness and high thermal conductivity (Tu et al., 2023).

The significance of these materials lies in their use of renewable resources to replace petroleum-based nanomaterials, contributing to carbon emission reduction, sustainable development, and reduced long-term ecological impact due to their biodegradability. Technical development pathways include biomass nanosizing, hybrid functionalization, and scalable processing techniques, which together support the reduction of material costs and the improvement of green standards for drilling fluid formulations.

6. Conclusions

In deep formation drilling, reducing the circulation temperature of drilling fluids is a crucial strategy to ensure the safe and efficient operation of drilling fluids, drilling tools, and logging-while-drilling equipment. Enhancing the thermal conductivity of drilling fluids provides an effective means of rapidly dissipating heat from the wellbore to the surface. This review systematically summarizes recent research progress on the application of nanomaterials to improve the thermal conductivity of drilling fluids. Studies have shown that 0D, 1D, and 2D nanomaterials can all effectively enhance the heat-transfer performance of drilling fluids and can be tailored to different base fluid systems and temperature scenarios through appropriate surface modification. Compared with 0D nanomaterials, 1D and 2D nanomaterials are generally more efficient at enhancing thermal conductivity and exhibit broader applicability, with graphene and carbon nanotubes demonstrating the optimal overall performance. For instance, carbon nanotubes can achieve a maximum thermal conductivity enhancement of up to 442% in WBDFs. Moreover, thermal conductivity enhancement is generally easier in WBDFs due to superior nanoparticle dispersion, whereas oil-based fluids typically require surface modification and achieve comparatively smaller improvements. The underlying enhancement mechanisms involve two synergistic pathways: (i) thermal conduction optimization, achieved through reduced phonon scattering and the formation of continuous thermal conduction networks; and (ii) thermal convection optimization, facilitated by micro-convection induced by Brownian motion, oriented particle alignment under shear fields, and thermophoretic migration. Notably, the actual downhole environment significantly influences these mechanisms, and the observed thermal enhancement results from the interplay of fundamental heat-transfer principles and environmental factors.

Despite the many advantages of nanomaterial applications in drilling fluids, significant challenges remain, including poor dispersion stability, difficulty in balancing multiple performance requirements, economic and large-scale production constraints, and environmental considerations. Furthermore, although this review systematically summarizes research progress in this field, it has certain limitations. Most studies reported are at the laboratory scale and lack long-term field validation under actual complex downhole conditions, making it difficult to fully evaluate the stability and reliability of nanomaterials in practical applications. To overcome these limitations and address existing technical bottlenecks, future research should focus on hybrid structure design, dimensional complementarity of different nanomaterials, development of stimuli-responsive intelligent systems, and exploration of bio-based nanomaterials. Progress in these directions will facilitate the transition from laboratory research to field applications, ultimately supporting safer, more efficient, and more economical exploitation of deep oil and gas resources.

CRedit authorship contribution statement

Hao Yan: Writing – original draft, Investigation, Formal analysis. **Zi-Qing Liu:** Formal analysis, Data curation. **Na-Na Song:** Formal analysis. **Kai-He Lv:** Resources. **Jin-Sheng Sun:** Project administration, Funding acquisition. **Chao-Zheng Liu:** Formal analysis. **Mei-Chun Li:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

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

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