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ORIGINAL ARTICLE

Nanoparticle-based cutting fluids in drilling: a recent review

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Abstract

The successful operations in the field of drilling requires high quality of the drilling fluids. The nanoparticle-based materials can be used in a variety of ways in the oilfield such as drilling fluids to enhance the efficiency of system. Drilling fluids play crucial role during the drilling operations. Nanoparticles (NPs) depict significant performance in the enhancement of the drilling fluid properties. The current manuscript summarizes the various types of nano-based drilling fluids for drilling operations. Nano-based drilling fluids are a new kind of fluids that are used to enhance the performance of working fluids. Graphene-based drilling fluids, carbon nanotube–based drilling fluid, and nanocellulose and its derivative-based drilling fluids investigated by various researchers are summarized in this review. Different reviews have been published on nano-based drilling fluids in literature, but few studies reported on nanoparticle-based fluids in drilling industry. Therefore, this review especially highlights the recent advances of nanoparticle-based fluids in drilling fluid system. The thermal conductivity, density, viscosity, and specific heat capacity of the nano-based drilling fluids are also critically discussed in this manuscript. Finally, this review indicates some future directions about nano-based drilling fluids in oil and gas exploration which will also give direction to young researchers to explore new kinds of drilling fluids in the drilling field.

Keywords Nanoparticles · Nanofluids · Drilling fluids · Thermophysical properties · Mechanical properties

Abbreviations

Al_2O_3	Aluminum oxide
AV	Apparent viscosity
CuO	Copper oxide
CNFs	Cellulose nanofibers
CMC	Carboxymethyl cellulose
CNTs	Carbon nanotubes
CGN	Carbon group nanoenhancer
CMQL	Cryogenic minimum quantity lubrication
DFs	Drilling fluids
DLS	Dynamic light scattering
ENP	Electrospun synthesized ZnTi O_3 nanoparticles
EG	Ethylene glycol
EDAG	Ethylene-diamine modified with graphene
FE-SEM	Field emission scanning electron microscopy
Fe_2O_3	Iron oxide
Glu-Gr	Glucopyranose grafted with graphene
GNPs	Graphene nanoplatelets
GBDF	Glycol-based drilling fluids
HBN	Hexagonal boron nitride
HTF	Heat transfer fluid
HCl	Hydrochloric acid

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HPHT	High pressure and high temperature
PANC	Polyacrylamide/clay nanocomposite
PAC	Polyanionic cellulose
PVP	Polyvinylpyrrolidone
PHPA	Partially hydrolyzed polyacrylamide
MgO	Magnesium oxide
MWCNTs	Multi-wall carbon nanotubes
MQL	Minimum quantity lubrication
MRM	Material removing mechanism
NWBM	Nanofluid-enhanced water-based drilling mud
NPs	Nanoparticles
NS	Nanosilica
NEBL	Nano-enhanced biolubricant
NMQL	Nanofluid minimum quantity lubrication
SDS	Sodium dodecyl sulfate
SDS-Gr	Sodium dodecyl sulfate modified with graphite
SWCNTs	Single-walled carbon nanotubes
WBDFs	Water-based drilling fluids
TEOS	Tetraethyl orthosilicate
TiO_2	Titanium dioxide
ZrO_2	Zirconium dioxide
ZnO	Zinc oxide

1 Introduction

The removal of drilled solids is the key to drill securely, quickly, and within less cost. Drilled solids raise drill expenses, harm reservoirs, and add to the expense of cleanup. Some of the issues with drilled solids are:

(1) Formations are harmed by filtrate,
(2) Limits on how fast you can drill,
(3) Issues with holes,
(4) Difficulties of stuck pipes,
(5) Complications with circulation,
(6) Direct expenses of drilling fluid, and
(7) Expenses of disposal rises.

The first most important purpose of a drilling mud is to reduce waste content around the drilling tool and throughout the hole. However, by doing so, the mud takes on the load of the clippings, and if the clippings are not cleared, the mud soon lacks the capacity to clear the hole, resulting in massive filter cakes. Clippings must always be continuously cleaned to allow on-site recyclability of the drilling mud. As the world develop, it prefers more modern, reliable, and eco-friendly processes as compared to classic old ones.

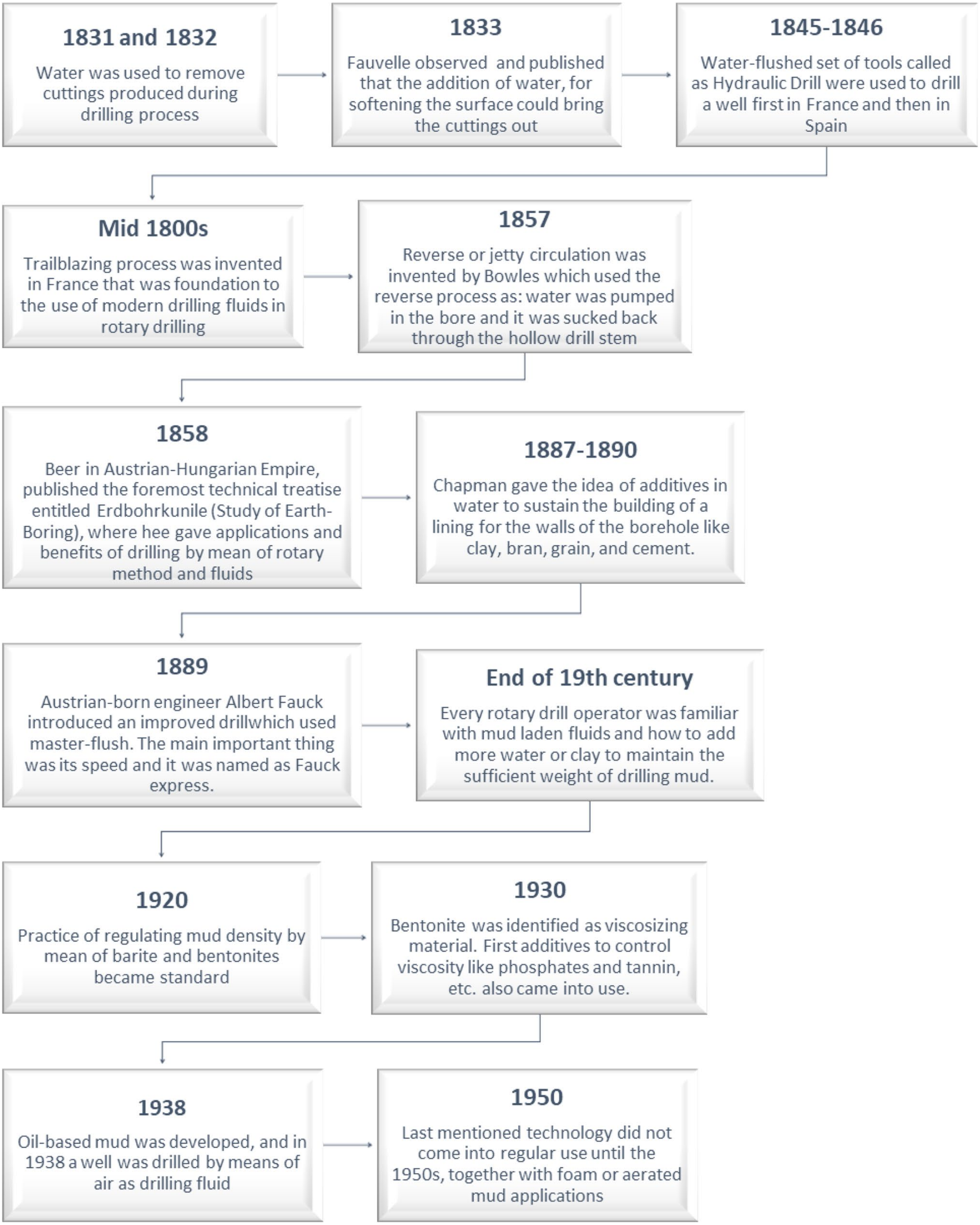
Using nanofluids in drilling fluids is one of the best methods to improve the performance. A lot of research can be found on this topic, and everyone gives 5 to 10 functions of drilling fluids/muds. But the major purposes that drilling fluids serve are as follows: (1) hold debris (drill materials); (2) extract waste from the bore's base and well hole, and let these to the top; (3) ensure wellbore strength while controlling pressure of formation; (4) permeable structures get sealed; (5) the drill unit is kept cool, lubricated, and supported; (6) fluid energy is transmitted to tools and bit; (7) reduce the amount of damage to the reservoir; (8) allow for proper assessment of formation; (9) corrosion is controlled; (10) allow for easier cementing and finishing; (11) reduce environmental effect as much as possible and stop the development of gas hydrates. The history chart of drilling fluids is shown in Fig. 1.

Hoelscher et al. [2] explained that in the last decade, nanotechnology has gained the attention of researchers, with various applications in a wide range of sectors. Hundreds of nanotechnology-based items are available, with the majority of them being used in the medical, defense, and coating sectors.

Mansoor et al. [3] studied that drilling issues are mostly solved by refining the properties related to filtration and rheology of drilling fluids based on water (WDFs). Researchers looked at nanofluid, prepared by using organic aloe vera as base fluid and CuO as nanoparticles, in WDF, to help deal with the issues related to drilling. For this investigation, a two-step approach was employed to create the nanofluids; aloe vera was used as the base fluid with 3 separate wt% of CuO nanoparticles. The characteristics related to rheology and loss of filtrate for produced drilling fluids were evaluated at a variety of temperatures. For WDF, the viscosity decreased by around 61.7% when it was heated at temperature of 90 °C.

Farahbod [4] used digital densitometer, digital viscometer, digital calorimeter, and portable electromagnetic handheld current meter to measure density, viscosity, heat capacity, and velocity respectively of nano-based drilling fluids. In this work, the thermal and the physical characteristics of fluids used when drilling were altered using carbon nanotubes and titanium dioxide nanoparticles. The results demonstrated that particles of titanium dioxide showed size reduction 76 to 54 nm, and the quantity of specific heat increases by approximately 1.26%. Additionally, according to the findings of the experiments, mixing of carbon nanotubes in the drilling fluid had a convective heat to conductive heat ratio that was about 30% greater as compared to the addition of titanium dioxide nanoparticles.

Moraveji et al. [5] studied the rheological properties of glycol-based drilling fluids (GBDFs) after the addition of amorphous silica nanoparticles in it. For the purpose of measuring the rheological characteristics at high temperatures, an OFFITE E900 viscometer was also employed.



1831 and 1832

Water was used to remove cuttings produced during drilling process

1833

Fauvelle observed and published that the addition of water, for softening the surface could bring the cuttings out

1845-1846

Water-flushed set of tools called as Hydraulic Drill were used to drill a well first in France and then in Spain

Mid 1800s

Trailblazing process was invented in France that was foundation to the use of modern drilling fluids in rotary drilling

1857

Reverse or jetty circulation was invented by Bowles which used the reverse process as: water was pumped in the bore and it was sucked back through the hollow drill stem

1858

Beer in Austrian-Hungarian Empire, published the foremost technical treatise entitled Erdbohrkunile (Study of Earth-Boring), where hee gave applications and benefits of drilling by mean of rotary method and fluids

1887-1890

Chapman gave the idea of additives in water to sustain the building of a lining for the walls of the borehole like clay, bran, grain, and cement.

1889

Austrian-born engineer Albert Fauck introduced an improved drillwhich used master-flush. The main important thing was its speed and it was named as Fauck express.

End of 19th century

Every rotary drill operator was familiar with mud laden fluids and how to add more water or clay to maintain the sufficient weight of drilling mud.

1920

Practice of regulating mud density by mean of barite and bentonites became standard

1930

Bentonite was identified as viscosizing material. First additives to control viscosity like phosphates and tannin, etc. also came into use.

1938

Oil-based mud was developed, and in 1938 a well was drilled by means of air as drilling fluid

1950

Last mentioned technology did not come into regular use until the 1950s, together with foam or aerated mud applications

Fig. 1 Background of drilling fluids [1]

After the nanoparticles were added, the glycol fluid's apparent viscosity, plastic viscosity, yield point, and gel strength all rose. The characteristics of GBDF related to rheology got enhanced by increasing the percentage weight of nanoparticles. Perween et al. [6] investigated the impact of ageing on rheological and filtration capabilities. The mud samples were aged in an oven at temperature of 110 °C for 16 h in hot rolling test to measure thermal stability. The experimental findings demonstrated that $ZnTiO_3$ nanoparticles have a considerable impact on the characteristics of drilling fluids, substantially reduced the loss of filtrate, thermally stabilized the DF, and enhanced the characteristics related to rheology.

The mud functions are to effectively block the flow of water in the wellbore. The approach of using traditional drilling fluid results in decrease fluid loss, or leak off cannot be utilized in shale formations. Like the Marcellus, because of low permeability of the shale there is formation of the filter cake. Nanoparticle's suspensions in fluids are known as nanofluids that exhibit substantial property improvement even at low nanoparticle concentrations. The use of nanoparticles as a drilling fluids was shown to be useful by many researchers [7–14]. Hence, nanoparticle-based drilling fluids have been summarized in this review. Therefore, this paper introduces the various nano-based drilling fluids in detail to make drilling fluids more efficient along with thermal and mechanical properties. This review also gives some future recommendations to investigate new kinds of nanoparticles in drilling fluids which will help in fighting severe problems in the process of drilling operations.

2 Nanoparticles in drilling fluids

Various types of nanoparticles have been investigated as drilling fluids by different authors. Vryzas and Kelessidis [15] specified that nanoparticles are regarded to be ideal choices for smarter drilling fluid composition, i.e., fluids with tailored rheological and filtration characteristics, because of their distinctive physico-chemical characteristics. Nevertheless, because of the high risk of adopting new technology, their use in the oil and gas sector has yet to be completely realized. Numerous researchers have investigated the use of different nanoparticles, ranging from commercial to user particles, to establish drilling fluids with improved properties that can resist extreme downhole climates, especially at high pressure and high temperature (HPHT) situations, over the last few years.

The kind, dimension, and form of nanoparticles, as well as the volumetric concentration, the inclusion of various surfactants, and the use of an external magnetic field, are all essential elements to consider. According to the findings of numerous research, nanoparticles offer a great deal of promise for usage as drilling fluid enhancers in order to solve difficult drilling issues. Nevertheless, in order to fully utilize the potential of these particles, there are still difficulties that must be defeated.

Rafati et al. [16] specified that improved drilling and recovery methods are required for nontraditional hydrocarbon resources such as shale gas, shale oil, deep water, and arctic reservoirs. Moreover, it is important to reduce the ecological impact related to oil recovery procedures. Nanotechnology has proved to be a viable answer to these problems in the oil and gas sector. Several researchers have been performed to investigate the use of nanotechnology to improve drilling fluids. Improvement of rheological, filtration, and heat transport characteristics, as well as friction minimization in drilling fluids, were studied in such research. Researchers further revealed that nanoparticles may enhance fluid's thermal stability, lubricity, hole cleaning, and wellbore stability, as well as reduce the development of hydrates in the fluid circulation system.

Mehdi et al. [17] studied that with the rising need for oil products, new hydrocarbon sources must be explored. This would need digging wells in unusual formations and under challenging circumstances. Drilling fluids are determined to account for 5 to 15% of total capital investment and frequently lead to the collapse of drilling operations. As a result, it is critical to adjust drilling fluid characteristics to the wellbore environment. As a result, extremely efficient and cost-effective drilling fluids are required. Drilling fluids of the future must have improved rheological characteristics, as well as greater temperature and filtration control characteristics. Durability of additives, severe fluid loss, and breakdown of polymers are just a couple of minor challenges that a drilling fluid may face, all of which can contribute to drooping of weighting forces and rock cutting.

There are several research articles available that show the improvement in the drilling fluids by application on nanofluids and particles in it. Aluminum oxide, magnesium oxide, titanium dioxide, and copper oxide have been introduced at 2 distinct percentages to a 7% bentonite water-based mud: 0.5 vol% and 1.5 vol% by Alsaba et al. [18]. The rheological characteristics of the drilling fluid, involving plastic viscosity, yield point, and gel strength, were measured utilizing a standardized viscometer and compared to a source drilling fluid containing 7% bentonite to account for the effect of nanoparticle additions. Furthermore, quantitative research was carried out to help comprehend the effect of various parameters on hole cleaning efficiency, such as rheological characteristics, hole size, and flow rate. Aluminum oxide, magnesium oxide, titanium dioxide, and copper oxide have been introduced at 2 distinct percentages to a 7% bentonite water-based mud: 0.5 vol% and 1.5 vol%. The rheological characteristics of the drilling fluid, involving plastic viscosity, yield point, and gel strength, were measured utilizing a standardized viscometer and compared to a reference drilling fluid containing 7% bentonite to account for the effect of nanoparticle additions. Furthermore, quantitative research was carried out to help comprehend the effect of various parameters on hole cleaning efficiency, such as rheological characteristics, hole size, and flow rate. When rheological properties seem to be high, the effect of changing the flow rate seems to be minor, according to this research work. Furthermore, as compared to the base example having just 7% bentonite, the effect of nanoparticles inclusion on hole cleaning was much more evident for bigger hole diameters with greater cutting sizes, demonstrating the potential of utilizing nanoparticles to improve hole cleaning.

Anoop et al. [19] investigated the rheological properties of natural oil-based nanofluids under HPHT. Mechanically dispersed commonly available SiO_2 nanoparticles in a specially formulated paraffinic mineral oil (Therm Z-32) yielded nanofluids for this study. This research looks at mineral oil and nanofluids at 1 and 2 vol%. An HPHT viscometer is used to determine the rheological properties of the base fluid and nanofluids. The viscosity of the nanofluids is determined at pressures ranging from 100 kPa to 42 MPa, and temperatures ranging from 25 to 140 °C, and at different shear rates during the performance of experiment. The study revealed that when the pressure was rose, the viscosity values of both nanofluids and the base fluid rose. Furthermore, at HTHP nanofluids exhibited non-Newtonian behavior.

The particle size distribution and morphology of silica nanoparticles were specified by Ghanbari et al. [20] used DLS analysis and FE-SEM after they were synthesized by using solgel technique inside an acidic environment comprising TEOS and HCl. The substance is extremely monodispersed and made up of amorphous SiO_2 nanoparticles, according to the findings. Following that, a simple method for nanoparticle's dispersion in bentonite suspensions, low-salinity, and high-salinity muds was described, and the stability of the dispersions was examined under various experimental circumstances. Lastly, the API filter press test was used to examine the influence of silica nanoparticles on rheological characteristics and fluid's filtration behavior. Under this investigation, the provided dispersion approach outperformed the prior dispersion approaches, and this method of dispersion must be used when adding nanoparticles in drilling muds.

Abdo et al. [21] produced and checked sepiolite in drilling muds in its nanoform to enhance the rheological characteristics and fluid loss of the drilling fluids under usual and high-pressure and high-temperature conditions. The introduction of 4% by weight nanosepiolite of 30–60 nm to a base drilling mud enhanced its rheological characteristics and stabilized it under high-pressure and high-temperature conditions, according to the findings. When compared to base drilling fluids lacking nanosepiolite, fluid loss was considerably reduced. The fluid loss was not affected by raising the temperature and pressure of the base drilling fluids containing nanosepiolite.

Thermal decomposition of biopolymers is among the most expensive drilling hazards, because it leads to additional maintenance issues including barite sag, fluid loss, pipe adhesion, drilling stoppage, and so forth. As a result, developing a drilling fluid capable of preserving biopolymer characteristics under high-pressure and high-temperature conditions is a major ongoing issue for the drilling and petroleum industries. The study by Halali et al. [22] proposed CNTs as the required addition to meet this demand. The suitable surfactants were Tween 80, PMMA, and ACUMER, all of which exhibited excellent tolerance with the CNT. The level of reliability of these kinds of fluids determines their efficiency. As a result, "rheological characteristics, filtration, and zeta potential" were used to investigate fluid stabilization from several perspectives. The findings show that CNT can increase drilling fluid's viscosity, particularly at lower shear rates, that is consistent to fluid shear thinning in the presence of CNT. It also increases the exact value of "zeta potential," which was previously under − 20 mV across all nanofluids. It may minimize filtering through over 93.3% under high-pressure and high-temperature settings, improved fluid thermal conductivity by 12%, and increased shale recovery by 10.5%, adding to the CNT benefits.

The utilization of CuO and ZnO nanofluids made utilizing different base fluids like xanthan gum, PEG, and PVP to enhance the thermal, electrical, and fluid-loss characteristics of water-based mud which were studied by Ponmani et al. [23] The thermal and electrical characteristics of NWBM were improved with the addition of nanofluids, making them more suitable for sophisticated drilling operations. Through exploiting the development of composites and aggregates induced by the presence of nano-, micro-, and macroparticles in the mud system, nanofluid-based drilling fluids can play an essential role in preventing lost circulation. The introduction of tiny quantities of nanofluids improves fluid loss and some other mud characteristics, demonstrating nanofluid-enhanced water-based drilling mud's (NWBM's) advantages in complicated settings. Microfluid-enhanced water-based drilling mud's (MWBM's) different characteristics were also examined and compared to those of NWBM. Compared to MWBM and WBM, NWBM regularly outperformed. Additional study concerning different aspects of nanofluid-based drilling fluids is required in order to better learn and improve their ability to perform in filtration control and pore plugging in porous medium.

Aftab et al. [24] used ZnO nanoparticles with water as a base fluid. Experimentation was performed on low-pressure and low-temperature settings; then, same experiment was performed on high pressure and high temperature. Quantity of nanozinc oxide particles used for this purpose was 1 g in water-based drilling fluids. This addition helped in increasing the rheological properties of DFs, reducing the loss of filtrate, and also decrease in friction coefficient occurred at high pressure and high temperature scenario.

According to Taraghikhah et al. [25], in comparison to typical shale inhibitors, the nanodrilling fluid with lower than 1% wt/v nanoadditive has an effective shale recovering. Pore plugging as a physical shale inhibitory method is validated by SEM pictures of obtained shales, following shale recovery tests. Regardless of the reality that pore plugging is the main method for shale inhibition in the presence of nanoadditives, the adhesive nature of nanosilica and the deposition of nanoparticles on the surface of shales define another mechanism known as physisorption, in which nanosilica forms a hydrophobic layer on the shale's surface to prevent water invasion. SEM scans also confirmed this feature. Lubricity tests revealed that this nanoadditive is an effective lubricant in addition to inhibiting shale. This nanoadditive improved other mud characteristics, including rheological characteristics. It does, though, have a small impact on fluid loss management. As the concentration utilized in this experiment is just 1 wt%, so it was assumed to be cost-effective.

According to Akhtarmanesh et al. [26], Wellbore's instability creates plenty of issues, such as the need for an expensive drilling operation. Sloughing or swelling shales, as well as abnormally pressurized shale deposits, cause several wellbore abnormalities. Pore pressure propagation and chemical evaporation are the major processes in shale disruptions, with various degrees of effect, in terms of physical and chemical characteristics of shale and thermodynamics conditions. This article looks at these processes to see how important they are in terms of wellbore stabilization. Pore throat physical blocking is a sensible method to minimize pressure rise around the wellbore for wellbore stability management. For this purpose, nanoparticles were utilized. Membrane Efficiency Screening Equipment (MESE) was utilized to test the behavior of various water-based drilling fluids (WBDFs) on pressure of pore. Three separate drilling fluids, each with its own set of additives, were tested in contact with the Gurpi formation, with and without the inclusion of nanoparticles. The Gurpi formation may be found in Iran's western and southern sedimentary basins. The introduction of nanoparticles resulted in much superior physical plugging, resulting in a drop in porosity and an increase in pressure. One of the nanoparticle-based mud compositions decreased "pressure increase" around the wellbore by up to 97%.

To reduce wellbore instability concerns in problematic shale deposits, specific formulations of drilling fluids with high shale inhibitory properties are required according to Jain and Mahto [27]. In this work, polyacrylamide/clay nanocomposite (PANC) was employed as a drilling fluid additive after prepared. PANC outperformed partly hydrolyzed polyacrylamide in terms of shale encapsulation, according to the results of the experiments. As a result, it was recommended that synthesized nanocomposite can be utilized as a drilling fluid addition in a WBDF system that is inhibitive.

3 Different types of nano-based drilling fluids

Drilling fluids are important and crucial for drilling process and used as lubricant, for wellbore cleaning and for shale inhibition. Properties of drilling fluids were important for efficient drilling fluids application. Drilling fluids were used to lubricate and cool the drilling bit. Under high temperature and pressure, drilling fluids were unable to function properly. This problem allows the researchers to come up with the better ideas. Now, the research was being conducted to use such fluid along with drilling fluids that enhance the rheological properties of the fluid. So, nanofluids were used along with the drilling fluids. Different drilling fluids that were used for drilling of petroleum was carbon nanotubes, graphenes, and nanocellulose as shown in Fig. 2.

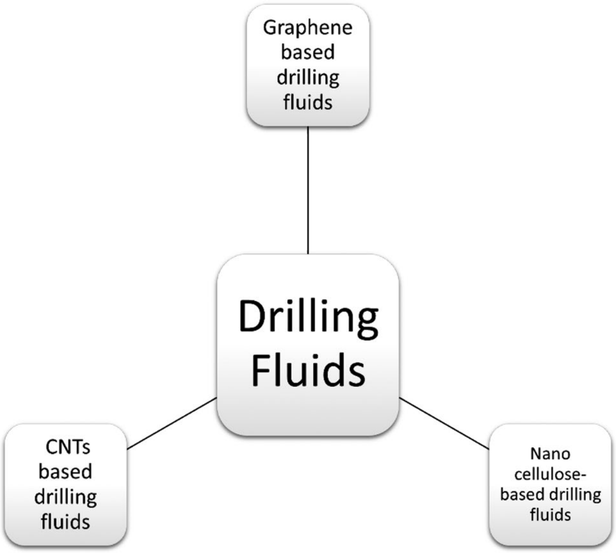


Fig. 2 Various types of nano-based drilling fluids

3.1 Graphene-based drilling fluids

Graphene-based drilling fluids are widely used in petroleum industry and proved to be efficient in terms of performance. Naseer et al. [28] experimentally investigated the performance of drilling fluids using nanoparticles. They observed that by the addition of nanoparticles, the rheological properties of drilling mud were modified under high temperature and pressure. Xuan et al. [29] carried out a study on the graphite oxide–based nanoparticles for fluid loss control. They studied the thermal stability of graphene oxide under high temperature and pressure. They observed that graphene oxide was thermal stable at 150 °C. Taha et al. [30] studied the application of nanographenes in enhancing the performance of drilling fluids. They concluded that various laboratory tests show that nanographene has the ability of torque reduction round about 50%. Chai et al. [31] experimentally investigated the properties of carbon nanotube/graphene. They observed that by the adding nanomaterials, the thermophysical properties of drilling fluids were enhanced. Also, nanoparticles do not affect the quality of drilling fluid such as shear stress and viscosity.

Ho et al. [32] performed experimental investigation to study the rheological properties of drilling fluid (oil based) using graphene's nanosheets. They concluded that the viscosity of oil-based drilling fluids using graphene was higher as compared to hydrogenated oil-based drilling fluids. Chai et al. [33] studied thermophysical properties of drilling fluids using graphene nanosheets. They observed that by increasing the concentration of nanoparticles to a temperature of 50 °C, 14.4% enhancement in thermal conductivity was recorded. Paul et al. [34] reviewed the tribological performance of drilling fluids using nanolubricants as well as its derivative. Also, nanolubricants provide greater stability while comparing it with micro-sized particles. Yuxiu et al. [35] performed experimental investigation on high performance plunging agent using modified graphene. They used the ethylene-diamine modified with graphene (EDA-G). They observed that ethylene-diamine exhibits high performance at volumetric concentration of 0.2% by weight. Rana et al. [36] studied the properties of glucopyranose grafted with graphene (Glu-Gr) as shale inhibitor. They observed that glucopyranose modified with graphene gives high-inhibition durability and dispersion recovery while comparing it with traditional drilling mud. The mechanism of shale inhibition is shown in Fig. 3.

Zubaidi et al. [37] carried out experimental investigation to improve to improve the properties of drilling fluids using commercial bentonites and local clay. They mixed different nanomaterials like magnesium oxide, titanium oxide, and graphene in commercial bentonites. Different volumetric concentrations were used 0.4%, 0.2%, 0.1%, 0.05%, 0.01%, and 0.05% respectively. They concluded that magnesium oxide gives better results as compared to other nanomaterials.

Aftab et al. [38] investigated enhancement of rheological properties of water-based mud (WBM). They have used different nanoparticles like graphene nanoplatelet, carbon nanotube, and nanosilica. They concluded that graphene nanoplatelets performed better enhancement in water-based mud as compared to other particles. Ridha et al. [39] investigated the performance filtration of water-based drilling fluid using graphene nanoplatelets (GNPs). Three different samples of water-based drilling fluids were prepared including nanosilica (NS), potassium chloride (KCL), and GNPs. They concluded that at high temperature and every concentration, graphene nanoplatelets indicate effective filtration for water-based drilling fluids.

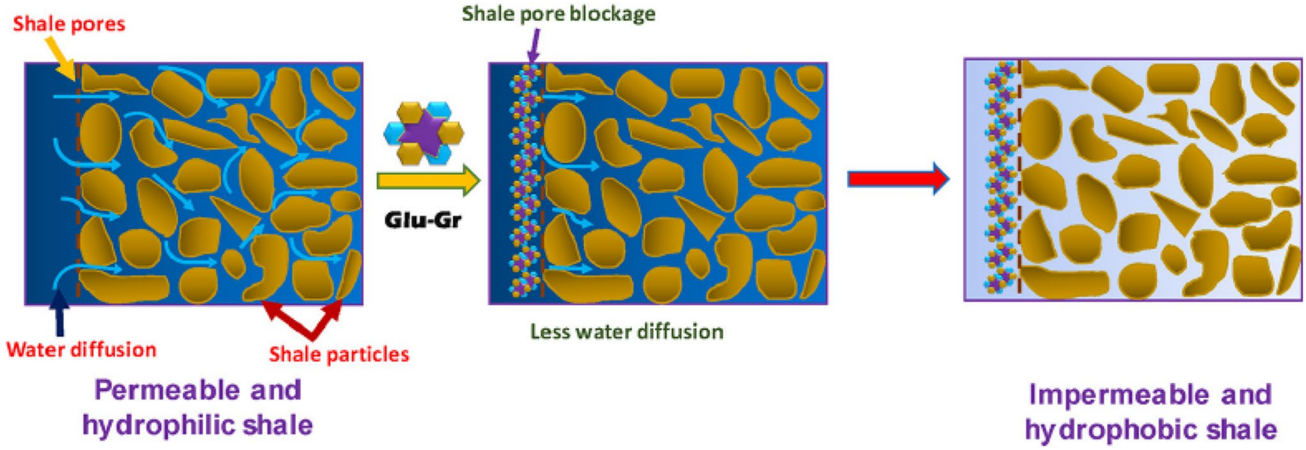


Fig. 3 Schematic representation for shale inhibition mechanism [36]

Rana et al. [40] studied the effect of surfactant addition modified with graphene to improve the rheological. They concluded that by using sodium dodecyl sulfate (SDS) as surfactant modified with graphene (SDS-Gr), there was control in fluid loss and rheology of drilling mud was modified. Applications of drilling fluids using graphenes and its derivatives are shown in Table 1.

3.2 Carbon nanotubes and its derivative-based drilling fluids

Carbon nanotube–based various drilling fluids are also investigated in oil sector. Ibrahim et al. [41] investigated the rheological behavior of drilling fluids. They used the graphene nanoplatelets to improve the dispersion rate in the aqueous solution. They observed high dispersion of graphene nanoplatelets at higher shear rate. Halali et al. [22] perform experimental investigation on stability of the polymeric fluids using carbon nanotubes (CNTs). They concluded that by using carbon nanotubes under high temperature and high pressure, the filtration was reduced to 93.3%. Also, 12% enhancement in thermal conductivity was recorded and shale recovery was increased to 10.5%.

Madkour et al. [42] investigated the performance of polymeric nanocomposites in oil-based drilling fluids. They used graphene nanoplatelets and multiwall carbon nanotubes (MWCNTs) and made nanocomposites using casting techniques. They concluded that polymeric nanocomposites show superior advantages in oil drilling and for lubricating purposes. Ismail et al. [43] investigated novel approach for enhancing the properties of water-based drilling fluids. They used glass bends, nanosilica, and multi-walled carbon nanotubes (MWCNTs) to improve the rheological behavior. They concluded that for water-based drilling fluid, MWCNT proved to be better rheological modifier.

Ahmad et al. [44] investigated the polymer-based nanocomposites using carbon nanotubes (CNT) under high temperature. They concluded that by using 2% volumetric concentration of nanocomposites, shale reduction was reduced to 90%. Also, under high temperature, nanocomposites enhance the borehole stability, filtration characteristics, and rheological properties of water-based drilling fluids. Rana et al. [45] investigated the modification in water-based mud using polyvinylpyrrolidone (PVP) and single-walled carbon nanotubes (SWCNTs) under low temperature and low pressure. They concluded that by using (PVP/SWCNTs) composites, 89.5% dispersion recovery was achieved. Applications of the drilling fluids using carbon nanotubes and its derivatives are listed in Table 2.

3.3 Nanocellulose-based drilling fluids

Nanocellulose-based drilling was studied by different authors. Li et al. [46] measured the performance of water-based fluid using cellulose nanoparticles. They concluded that by using cellulose nanocrystals, reduction

Table 1 Various drilling fluids using graphenes and its derivatives

Concentration	Type of nanoparticle	Base fluid	Experimental conditions	Modified properties	References
3% by weight	Nanographite	Water-based mud	High temp, high pressure	Control in fluid loss and rheological properties of the fluid	[28]
0.6% by weight	Nanographite oxide	Water-based mud	High temp, high pressure	Control in fluid loss	[29]
3% by weight	Nanographite modified with surfactant	Water-Based Mud	High temp, high pressure	Control in fluid loss, rheological properties of the fluid and swelling inhibition	[30]
100 ppm	Nanographene	Vegetable oil	Low temp, low pressure	Shear stress and viscosity	[31]
100 ppm	Graphene nanosheets	Vegetable	Low temp, low pressure	Thermal conductivity	[33]
0.4% by weight	EDA-G	Water-based mud	Low temp, low pressure	Control in fluid loss and swelling inhibition	[35]
0.85% by weight	Glu-Gr	Water-based mud	Low temp, low pressure	Swelling inhibition and rheological properties of the fluid	[36]
0.4% by weight	MgO, TiO_2, and graphene	Water-based mud	Low temp, low pressure	Control in fluid loss and rheological properties of the fluid	[37]
0.1 ppb	GNP	Water-based mud	High temp, high pressure	Control in fluid loss, rheological properties of the fluid and swelling inhibition	[38]
0.3 ppb	GNP	Water-based mud	High temp, high pressure	Control in fluid loss	[39]
0.85% by weight	SDS-Gr	Water-based mud	Low temp, low pressure	Control in fluid loss, rheological properties of the fluid, and swelling inhibition	[40]
100–500 ppm	GNPs	Water-based mud	Low temp, low pressure	Rheological properties of the fluid	[41]

Table 2 Carbon nanotubes and its derivatives used as drilling fluids

Concentration	Type of nanoparticle	Base fluid	Experimental conditions	Modified properties	References
0.6% by weight	CNTs	Water-based mud	High temp and high pressure	Control in fluid loss and thermal conductivity	[22]
____	MWCNTs/polylactic acid	Oil-based mud	High temp and high pressure	Mechanical, electrical, and thermal stability with enhancement in rheological properties of the fluid	[42]
0.00285% by weight	Nanocomposites (MWCNTs/SiO_2)	____	Low temp and low pressure	Control in fluid loss and viscosity	[43]
2% by weight/vol	Nanocomposites (CNT/polymer)	Water- and oil-based mud	High temp and high pressure	Stability of bore hole, improvement in filtration, and rheological characteristics	[44]
0.85% by weight	Nanocomposites (SWCNT/PVP)	Water-based mud	Low temp and low pressure	Control in fluid loss and shale inhibition	[45]

in fluid loss and enhancement in rheological properties of fluid were observed. Li et al. [47] also investigated the performance of water-based fluid using polyanionic cellulose (PAC) and cellulose nanocrystals (CNCs). They concluded that these nanoparticles produce the synergetic effect and enhance the performance of drilling mud. Song et al. [48] investigated the performance of bentonite-based drilling fluid using cellulose nanoparticles (CNCs) and cellulose nanofibers (CNFs). They observed improvement in the rheological properties of the drilling fluid using cellulose-based nanoparticles. Liu et al. [49] investigated the cellulose nanofibers (CNFs) and its application in filtration and rheological properties of fluid. They concluded that cellulose nanofibers (CNFs) have good rheological behavior and having better filtration properties.

Hall et al. [50] investigated performance of the water-based fluid using nanocellulose. They concluded that by using nanocellulose along with its derivatives, reduction in fluid loss and enhancement in rheological properties of fluid were observed. Saboori et al. [51] investigated the filtration properties of drilling fluid using polystyrene core and nano carboxymethyl cellulose (CMC). They concluded that by using these nanoparticles, the filtration properties of drilling fluid were enhanced. Li et al. [52] performed an investigation on the performance of drilling fluid using cellulose nanocrystals. They concluded that filtration properties and rheological behavior of drilling fluid were improved. Liu et al. [53] investigated the drilling fluid using poly-AMPS-DMA (PAD) composite. They concluded that because of Fe^{3+} linkage reaction, the stability of nanocomposites was improved.

Hall et al. [54] investigated the performance of drilling fluid using biopolymer bends and nanocellulose. They concluded that by using such nanoparticles, rheological behavior and loss of fluid control were improved. Li et al. [55] investigated the performance of drilling fluid polyanionic cellulose (PAC) and cellulose nanofibers. They concluded that by these nanoparticles, novel rheological behavior as well as filtration properties were also improved. Villada et al. [56] investigated the performance of water-based mud by replacing xanthan gum with cellulose nanofibers. They concluded that by using such nanoparticles, better thermal stability and good rheological behavior of drilling mud were observed. Heggset et al. [57] investigated the temperature stability using nanocellulose dispersion. They concluded that better temperature stability was recoded for cellulose nanocrystals at 140 °C. Zoveidavianpoor and Samsuri [58] investigated the filtration control of water-based mud using nanostarch. They concluded that 64.2% improvement in fluid loss was exhibited using nanostarch. The applications of drilling fluids using carbon nanocellulose and its derivatives are listed in Table 3.

3.4 Other different types of nanoparticles used in drilling fluids

The various other types of drilling fluids have been investigated by different researchers which are summarized in Table 4.

4 Thermophysical properties of nano-based drilling fluids

In a variety of heat exchange processes, heat transfer fluids (HTFs) serve as the energy carrier [75–77]. Since it is readily available, inexpensive, and compatible with a wide range of materials and procedures, water or steam

Table 3 Drilling fluid based on carbon nanocellulose and its derivatives

Concentration	Type of nanoparticle	Base fluid	Experimental conditions	Modified properties	References
1% by weight	CNCs	Water-based fluid	Low temp and low pressure	Control in fluid loss and improvement rheological properties of the fluid	[46]
0.5% by weight	CNCs	Water-based fluid	Low temp and low pressure	Improvement in rheological properties of the fluid	[47]
0.4% by weight	CNCs, CNFs	Water-based mud	Low temp and low pressure	Control in fluid loss and improvement in rheological properties of the fluid	[48]
0.5% by weight	CNFs	Water-based mud	Low temp and low pressure	Control in fluid loss, shear thinning, and improvement in rheological properties of the fluid	[49]
0.5% by weight	CNFs and its derivatives	Water-based mud	Low temp and low pressure	Control in fluid loss and improvement rheological properties of the fluid	[50]
3% by weight	CMC and polystyrene core	Water-based mud	Low temp and low pressure	Control in fluid loss and improvement rheological properties of the fluid	[51]
2% by weight	CNCs	Water-based mud	Low temp and low pressure	Control in fluid loss and improvement rheological properties of the fluid	[52]
2% by weight	PAD Fe^{3+}	Water-based mud	High temp and high pressure	Control in fluid loss and improvement rheological properties of the fluid	[53]
0.5% by weight	CNFs	Water-based mud	Low temp and low pressure	Control in fluid loss and improvement rheological properties of the fluid	[54]
3% by weight	CNFs/PAC	Water-based mud	Low temp and low pressure	Control in fluid loss and improvement rheological properties of the fluid	[55]
0.35% by weight	CNFs	Water-based mud	Low temp and low pressure	Control in fluid loss and improvement rheological properties of the fluid	[56]
0.8% by weight	CNP	Water-based mud	110 − 140 °C	Improvement in temperature stability	[57]
2.5% by weight	Nanostarch	Water-based mud	High temp and high pressure	Control in fluid loss and improvement rheological properties of the fluid	[58]

is the most commonly used HTF [78–80]. Other HTFs, such as ethylene glycol (EG) and its water mixtures, as well as other oils, are used in specialized applications to extend the temperature range beyond that of water [81, 82]. The most important considerations for evaluating the function and performance of HTFs are their thermophysical parameters, such as thermal conductivity, density, heat capacity, and viscosity [83]. The improved thermophysical features of HTF enable a highly efficient heat transfer technique more specifically for waste heat recovery applications as part of an expanding industrial energy efficiency endeavor [78, 84–86]. Heat transfer in any heat transfer medium is limited by finite values of thermophysical parameters. These characteristics are crucial in determining the degree of heat transmission. To modify the heat transfer performance, active and passive strategies are applied. Mechanical processes are examples of active approaches. Altering the fluid characteristics and modifying shape and surface area are examples of passive approaches. Passive approaches are less expensive, more beneficial, and more effective than active techniques. The passive category includes increasing heat transfer by suspending nanoparticles in a base liquid [87]. The system's performance should improve as a result of nanoparticles addition. The various thermophysical properties of nano-based drilling fluids are given in Fig. 4.

Table 5 enlists the thermophysical properties of frequently used nanoparticles which show specific heat, density, and thermal conductivity values of nanoparticles that are independent from their particle sizes.

Multiple mathematical models have been investigated that depict the rheology of drilling fluids that include

Table 4 Different types of nanoparticle used in drilling fluids

Authors	Types of nanoparticles	Fluid loss volume (ml)	Initial gel strength (Pa)	10 min gel strength (Pa)
Gbadamosi et al. [59]	Silica	5.1	7	8
Perween et al. [60]	$BiFeO_3$	7.8	13	20
Cheraghian [61]	Silica	10	13	32
Zhang et al. [62]	$CaCO_3$	5.7	—	—
Smith et al. [63]	Al_2O_3	6	11	40
Lucky and Johnson [64]	Yttrium oxide	—	15	16
Ghasemi et al. [65]	Al_2O_3	—	15	39
Jain et al. [66]	Silica	7.2	3.5	6.5
Aftab et al. [67]	ZnO	4.7	6	9
Mao et al. [68]	Silica	4.8	—	—
Dejtaradon et al. [69]	ZnO	14	15	37
Abdo and haneef [70]	Montmorillonite	7	—	21.5
Abdo et al. [21]	Sepiolite	8	—	—
Kumar [71]	MWCNT	5	—	7
Ismail [72]	Nanosilica	7	—	6
Jain et al. [73]	MWCNT	9	4.5	7
Husin et al. [74]	Silver	2	—	—

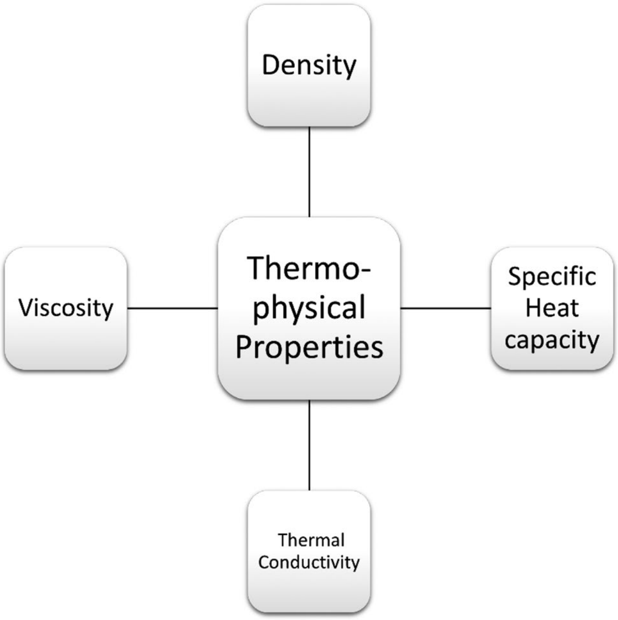


Fig. 4 Different vital thermophysical properties

power law model, Bingham plastic model, Hershel-Buckley model, and Casson model. The model that shows the shear stress-shear rate analysis is sine qua non for pressure drops and hydraulic calculation is best rheological model [89]. The two most vital rheological properties of drilling muds are thixotropic and yield stress [90] and model that predict yield stresses are viscoplastic models or yield stress models. The yield power law also known as Herschel-Buckley rheological model accurately predicts mud rheology and offers many advantages over the Bingham plastic and power law rheological models because it more accurately characterizes mud behavior across the entire shear rate [91].

4.1 Thermal conductivity

The thermal conductivity of fluids plays an important role in measuring thermal performance. The rate of heat transport in a fluid is substantially determined by the thermal conductivity of the fluid [92–94]. The thermal conductivity of drilling fluids increases as the fraction of nanoparticles in working fluids increases. Furthermore, due to Brownian motion at higher temperatures, the thermal conductivity value of a nanofluid is reported to be greater [95]. The thermal conductivity of working fluid is also improving as the surface area of nanoparticles increases. Smaller grain size nanoparticles will have a larger total surface area than nanoparticles with larger grain sizes in this situation. As a result, the area of contact between the nanoparticle surface and the base fluid will grow. Similarly, utilizing particle morphologies that increase the conducting area would result in increased thermal conductivity for the same type of nanoparticles [96]. Table 6 shows thermal conductivity variation of several nanoparticles under different operating conditions.

It fits well with the Maxwell model in the low particle volume fraction because the particle volume fraction is unlimited [105–107]. The Wasp model, on the other

Table 5 Thermophysical properties of various nanoparticles [88]

Nanoparticle	Purity (%)	Size of Particle (nm)	Density (kg/m^3)	Thermal conductivity (W/m K)	Specific heat (J/kg K)
Al_2O_3	99.99	4	3900	40	880
	99.5	78			
	95	48			
	99.95	136			
TiO_2	99.99	28	3900	8.4	692
	99.99	45			
	99.5	200			
CuO	99.5	77	6320	32.9	550.5
SiO_2	98.5	55–75	2220	1.4	745
ZnO	99.5	30–50	5630	27.2	494
Fe_2O_3	99.6	28	5240	8.4	628
ZrO_2	99.95	30	5560	1.85	456
MgO	99.5	18	3580	61.9	921
HBN	99.85	65–75	2100	400–751	795
	99.7	790			

Table 6 Thermal conductivity variations under different operating conditions

Authors	Size of nanoparticle (nm)	Temperature (°C)	Particle fraction	Findings
Kedzierski et al. [97]	20–40	15–45	0.1–0.4 (vol. %)	The thermal conductivity was reported to be 0.2 W/m K
Ohunakin et al. [98]	13	29–32	0.2 (g/L)	Thermal conductivity values increased by 2.75% and 0.45% in TiO_2-MO and SiO_2 nanolubricants, respectively
Zawawi et al.[99]	13–30	30–80	0.02–0.1 (vol. %)	At 30 °C, the thermal conductivity of the 0.1% fraction improved by 2.41%
Sanukrishn a and Prakash [93]	13	20–90	0.07–0.6 (vol. %)	At a concentration of 0.6% at 20 °C, the greatest thermal conductivity value was 1.48 W/m K
Zawawi et al. [100]	13–100	30–80	0.02–0.1 (vol. %)	At 30 °C, the thermal conductivity of a 0.1% Al_2O_3-TiO_2/PAG nanolubricant rose by 2.41%
Sanukrishna and Prakash [101]	21	20–90	0.07–0.8 (vol. %)	The thermal conductivity of 0.6% SiO_2-PAG nanolubricant is 1.31 times than pure lubricant
Gill et al. [102]	5–15	32	0.2–0.6 (g/L)	In varied percentages of TiO_2-MO nanolubricant, the thermal conductivity gain varies between 14.37 and 41.25%
Narayanasarma and Kuzhiveli [103]	5–20	25–100	0.01–0.2 (vol. %)	At 85 °C, the thermal conductivity of 0.2% SiO_2-POE nanolubricant was calculated to be 1.109 W/m K
Alawi et al. [104]	15	10–35	1–4 (vol. %)	Thermal conductivity increased by 28.88% at 4% fraction on 35 °C

hand, is identical to the Maxwell model, albeit it does not specify a particle shape [106]. Thermal conductivity models are also described in the literature [108].

4.2 Viscosity

The most significant thermophysical variables determining system pressure drop is viscosity [87]. Nanoparticles are dispersed in base fluids; the viscosity value increases in all circumstances. A high viscosity rating, on the other hand, is not appropriate for fluid systems. The viscosity change of drilling fluids has been the subject of several investigations [109]. Mahbubul et al. [110]conducted a thermophysical investigation of the Al_2O_3-R141b nanorefrigerant. The studies were carried out in fractions of 0.1–0.4% at temperatures ranging from 5 to 20 °C. At a fraction of 0.4%, the greatest viscosity

Table 7 Viscosity variation under various conditions for different nanoparticles

Authors	Size of nanoparticle (nm)	Temperature (°C)	Particle Fraction	Findings
Kedzierski et al. [97]	20–40	15–45	0.1–0.4 (vol. %)	The viscosity of ZnO-POE dropped as the temperature increases
Ohunakin et al. [98]	13	29–32	0.2 (g/L)	In SiO_2 and TiO_2, viscosity values increased by 0.99% and 6.09%, respectively
Zawawi et al [99]	13–30	30–80	0.02–0.1 (vol. %)	At 60 °C, viscosity augmented 9.71% for 0.1% particle fraction
Kumar et al [111]	20	10–60	0.2–1 (wt. %)	At 60 °C, the viscosity value enhanced by 17% for 1% particle fraction
Zawawi et al [100]	13–100	30–80	0.02–0.1 (vol. %)	20.50% increase in viscosity value observed
Sanukrishna and Prakash [101]	21	20–90	0.07–0.8 (vol. %)	Nanolubricant has a viscosity that is ten times higher than pure lubricant
Gill et al [102]	5–15	32	0.2–0.6 (g/L)	The viscosity surged in the 0.2% particle fraction and continued to rise as the particle fraction was raised
Narayanasarma and Kuzhiveli [103]	5–20	25–100	0.01–0.2 (vol. %)	The nanolubricant's viscosity has direct relation with particle fraction and inverse with temperature
Alawi et al [104]	15	10–35	1–4 (vol. %)	At 35 °C, the viscosity raised 12.63% for 4% particle fraction

value was attained [95]. Several studies by various authors on viscosity presented in Table 7.

TiO_2 and Al_2O_3 had viscosities about 3 and 200 times higher than the base liquid at higher concentrations (10%) [112]. The most commonly used viscosity models are also discussed in the literature [108] for viscosity calculations.

4.3 Density

The heat transfer capabilities of drilling fluids are influenced by density [113]. In general, introducing nanoparticles to a base liquid lowers the specific heat and raises the density. The density variation has been the subject of several studies as presented in Table 8.

4.4 Specific heat capacity

The amount of energy required to raise the temperature of a unit mass of matter by 1 °C is known as the specific heat capacity, represented in metric units as J/g K. Unfortunately, the addition of NPs to BF reduces the specific heat capacity of the resulting NF [96]. The specific heat capacity of various fluids is presented in Table 9.

5 Mechanical properties

The mechanical properties of NP-based drilling fluids should be considered during its operation, and it includes rheological properties and thermal and wellbore stabilities. Boyou et al. [115] used various concentrations of NPs of silica for drilling system to enhance the lift forces. They investigated different NPs and different concentrations of silica NPs. The study concluded that NPs enhanced the performance of drilling system and cutting operations as well. Wang et al. [116] mixed magnesium, aluminum, and silicate NPs in drilling fluid to measure the performance. The rheological as well as thermal stabilities were checked. The results concluded that

Table 8 Density variation of drilling fluids at different conditions

Authors	Concentration	Temperature	Nanoparticle size (nm)	Remarks
Alawi and Sidik [114]	1–5 (vol. %)	27–52	20	The density dropped as the temperature rose. The maximum density was found at 5%
Mahbubul et al. [110]	5 (vol. %)	10–35	15	Density augmented by 11%
Kedzierski et al. [97]	0.1–0.4 (vol. %)	15–45	20–40	The density dropped as the temperature was increased
Alawi et al. [104]	1–4 (vol. %)	10–35	15	At 35 °C, density increased by 11.54% at 4% fraction

Table 9 Specific heat capacity of various fluids and particles

	Specific heat, kJ/kg K
Common base fluids	
Distilled water (DI)	4.18
Ethylene glycol (EG)	2.35
Engine oil (EO)	1.88
Silicon oil (SO)	1.51
Ethylene glycol–water (1:1 vol.)	3.28
Common nanoparticles	
Magnesia MgO	0.955
Aluminum Al	0.877
Copper	0.385
Silver	0.234
Alumina	0.775
Copper oxide	0.525
Graphene	0.643–2.100
Silica SiO_2	0.680–0.745
Titania TiO_2	0.692–0.711

NP-based drilling fluids decreased use of traditional one. Pourkhalil et al. [117] investigated ZnO NPs in drilling fluid. The effect of ZnO on a shale core was checked by SEM as depicted in Fig. 5. They concluded that NP additives lead to blocking pore spaces in shale samples.

6 Challenges

The benefits of NP-based drilling fluids have a great impact on enhancing the performance of drilling systems. However, there are also many issues related to it which should be kept in mind during its application. Some of the major issues are [118][118][118]:

- NP cost should be kept in mind while using it which have a great influence on the project execution.
- The preparation and production of NPs are also very costly, and this factor should be considered while making it.
- The various conditions that affect the properties of NPs are also kept in mind during field operation.
- The chemical composition can be changed during operation, and stability or changing of structure may occur which should be considered during operation.
- Very less studies have been found related to the analysis of NPs in filed operation, so safety hazards must be considered before using it.

7 Conclusions and future recommendations

The major concluding remarks of this review are:

- Drilling fluids or muds were introduced that performed various tasks together with cooling. In petroleum engineering, drilling technology is linked to issues including significant loss of fluid, inadequate cleanup of hole, and pipe clogging.
- Various types of nanoparticles used in literature like CNTs, graphene nanoplates, cellulose type, and other hybrid particles are used in drilling fluids to improve the performance of drilling fluids. The concentration of NPs used in the literature was approximately 3–5 %.
- Drilling fluids of different types are proved to be efficient in drilling industry as these fluids travel through the system using pumps known as mud pumps.
- The different thermophysical properties like thermal conductivity, viscosity, and specific heat capacity of drilling fluids are also discussed in this review to conclude the performance of drilling fluids.
- The enhancement in value of thermal conductivity was observed to be increased by 10–15 %. The increment in viscosity was measured to 8–12 %. The mechanical properties of NP-based drilling fluids also improve the performance.
- More various types of drilling fluids should be investigated in the future for better performance of drilling

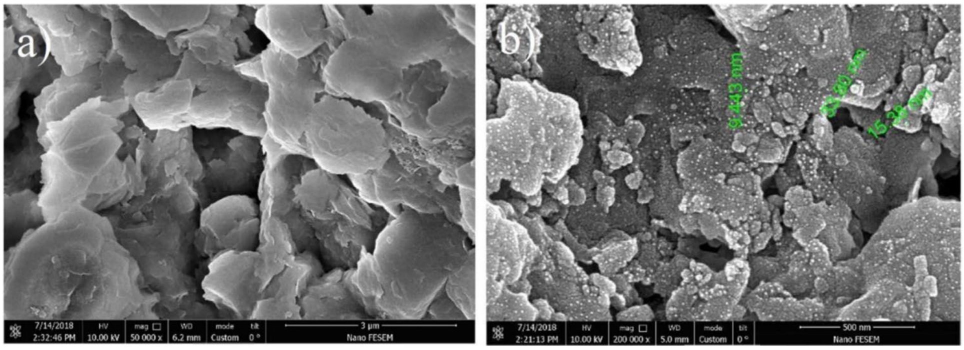


Fig. 5 SEM of shale cores **a** before NP additive and **b** after adding ZnO NPs [117]

fluids. Hybrid combination could be proved to be more efficient than the used one.

- The production and manufacturing costs are also too high so low-cost nanoparticle-based drilling fluids should be explored by future researchers which will bring a significant cost reduction and uptake the importance of drilling fluids.

Data availability There is no data available for this work.

Declarations

Conflict of interest The authors declare no competing interests.

References

1. Gerali F (2020) An historical overview over the development of the drilling fluids technology in the 19th century. History of Petroleum Exploration and Production View project. The ICOHTEC Newsletter View project. Re Met 33:75–86
2. Hoelscher KP, De Stefano G, Riley M, Young S (2012) Application of nanotechnology in drilling fluids. Soc Pet Eng - SPE Int Oilf Nanotechnol Conf 2012:297–303. https://doi.org/10.2118/157031-ms
3. Mansoor HHA, Devarapu SR, Samuel R et al (2021) Experimental investigation of aloe-vera-based CuO nanofluid as a novel additive in improving the rheological and filtration properties of water-based drilling fluid. SPE Drill Complet 36:542–551. https://doi.org/10.2118/205004-PA
4. Farahbod F (2021) Experimental investigation of thermo-physical properties of drilling fl uid integrated with nanoparticles: improvement of drilling operation performance. Powder Technol 384:125–131. https://doi.org/10.1016/j.powtec.2021.02.002
5. Keshavarz M, Gha A, Agin F et al (2020) Application of amorphous silica nanoparticles in improving the rheological properties, filtration and shale stability of glycol-based drilling fl uids. Int Commun Heat Mass Transf 115:104625. https://doi.org/10.1016/j.icheatmasstransfer.2020.104625
6. Perween S, Beg M, Shankar R et al (2018) Journal of Petroleum Science and Engineering. Effect of zinc titanate nanoparticles on rheological and filtration properties of water based drilling fluids 170:844–857. https://doi.org/10.1016/j.petrol.2018.07.006
7. Zamora-Ledezma C, Narváez-Muñoz C, Guerrero VH et al (2022) Nanofluid formulations based on two-dimensional nanoparticles, their performance, and potential application as water-based drilling fluids. ACS Omega 7:20457–20476
8. Mansoor HHA, Devarapu SR, Samuel R et al (2022) Investigation of chia based copper oxide nanofluid for water based drilling fluid: an experimental approach. J Nat Gas Sci Eng 107:104775
9. Arain AH, Ridha S, Mohyaldinn ME, Suppiah RR (2022) Improving the performance of invert emulsion drilling fluid using boron nitride and graphene nanoplatelets for drilling of unconventional high-temperature shale formations. J Mol Liq 363:119806
10. Dutta D, Bharadwaj S, Kumar D, Das BM (2022) Development of a nano-based drilling fluid using copper nanoparticles for Upper Assam formations: rheological interpretation. Pet Sci Technol 40(22):2685–2709
11. Naderi ME, Khavarpour M, Fazaeli R, Ghadi A (2022) Improving the fluid loss and rheological characteristics of oil-based drilling fluid by using copper oxide nanoparticles. Int J Nano Dimens 13:205–213
12. Lei M, Huang W, Sun J et al (2022) The utilization of self-crosslinkable nanoparticles as high-temperature plugging agent in water-based drilling fluid. SPE J 27:2628–2641
13. Dora TK, Krishna KV, Iqbal MI, Ranjan A (2022) An experimental analysis on nanoparticles role in drilling fluids. Mater Today Proc 68:717–721
14. Zhao X, Li D, Zhu H et al (2022) Advanced developments in environmentally friendly lubricants for water-based drilling fluid: a review. RSC Adv 12:22853–22868
15. Vryzas Z, Kelessidis VC (2017) Nano-based drilling fluids: a review. Energies 10:540. https://doi.org/10.3390/en10040540
16. Rafati R, Smith SR, Sharifi Haddad A et al (2018) Effect of nanoparticles on the modifications of drilling fluids properties: a review of recent advances. J Pet Sci Eng 161:61–76. https://doi.org/10.1016/j.petrol.2017.11.067
17. Medhi S, Chowdhury S, Dk G, Mehrotra U (2019) Nanotechnology: an emerging drilling fluid solution. Oil Gas Res 5:163. https://doi.org/10.4172/2472-0518.1000163
18. Alsaba MT, Al Dushaishi MF, Abbas AK (2020) Application of nano water-based drilling fluid in improving hole cleaning. SN Appl Sci 2:1–7. https://doi.org/10.1007/s42452-020-2723-2
19. Anoop K, Sadr R, Al-Jubouri M, Amani M (2014) Rheology of mineral oil-SiO2 nanofluids at high pressure and high temperatures. Int J Therm Sci 77:108–115. https://doi.org/10.1016/j.ijthermalsci.2013.10.016
20. Ghanbari S, Kazemzadeh E, Soleymani M, Naderifar A (2016) A facile method for synthesis and dispersion of silica nanoparticles in water-based drilling fluid. Colloid Polym Sci 294:381–388. https://doi.org/10.1007/s00396-015-3794-2
21. Abdo J, AL-Sharji H, Hassan E (2016) Effects of nano-sepiolite on rheological properties and filtration loss of water-based drilling fluids. Surf Interface Anal 48:522–526. https://doi.org/10.1002/sia.5997
22. Halali MA, Ghotbi C, Tahmasbi K, Ghazanfari MH (2016) The role of carbon nanotubes in improving thermal stability of polymeric fluids: experimental and modeling. Ind Eng Chem Res 55:7514–7534. https://doi.org/10.1021/acs.iecr.6b00784
23. Ponmani S, Nagarajan R, Sangwai JS (2016) Effect of nanofluids of cuo and zno in polyethylene glycol and polyvinylpyrrolidone on the thermal, electrical, and filtration-loss properties of water-based drilling fluids. SPE J 21:405–415. https://doi.org/10.2118/178919-PA
24. Aftab A, Ali M, Sahito MF et al (2020) Environmental friendliness and high performance of multifunctional Tween 80/ZnO-nanoparticles-added water-based drilling fluid: an experimental approach. ACS Sustain Chem Eng 8:11224–11243. https://doi.org/10.1021/acssuschemeng.0c02661
25. Taraghikhah S, Kalhor Mohammadi M, Tahmasbi Nowtaraki K (2015) Multifunctional nanoadditive in water based drilling fluid for improving shale stability. 1–17. https://doi.org/10.2523/iptc-18323-ms
26. Akhtarmanesh S, Shahrabi MJA, Atashnezhad A (2013) Improvement of wellbore stability in shale using nanoparticles. J Pet Sci Eng 112:290–295. https://doi.org/10.1016/j.petrol.2013.11.017
27. Jain R, Mahto V (2015) Evaluation of polyacrylamide/clay composite as a potential drilling fluid additive in inhibitive water based drilling fluid system. J Pet Sci Eng 133:612–621. https://doi.org/10.1016/j.petrol.2015.07.009
28. Nasser J, Jesil A, Mohiuddin T et al (2013) Experimental investigation of drilling fluid performance as nanoparticles. World

J Nano Sci Eng 03:57–61. https://doi.org/10.4236/wjnse.2013.33008

29. Xuan Y, Jiang G, Li Y (2014) Nanographite oxide as ultrastrong fluid-loss-control additive in water-based drilling fluids. J Dispers Sci Technol 35:1386–1392. https://doi.org/10.1080/01932691.2013.858350
30. Taha NM, Lee S (2015) Nano graphene application improving drilling fluids performance. InInternational petroleum technology conference 2015 Dec 6. OnePetro. https://doi.org/10.2523/IPTC-18539-MS
31. Chai YH, Yusup S, Chok VS et al (2017) Comparison of rheological properties of graphene/carbon nanotube hydrogenated oil based biodegradable drilling fluid. IOP Conf Ser Mater Sci Eng 206:012042. https://doi.org/10.1088/1757-899X/206/1/012042
32. Ho CY, Yusup S, Soon CV, Arpin MT (2016) Rheological behaviour of graphene nano-sheets in hydrogenated oil-based drilling fluid. Procedia Eng 148:49–56. https://doi.org/10.1016/j.proeng.2016.06.490
33. Chai YH, Yusup S, Chok VS et al (2017) Thermophysical properties of graphene nanosheets – hydrogenated oil based nanofluid for drilling fluid improvements. Appl Therm Eng 122:794–805. https://doi.org/10.1016/j.applthermaleng.2017.05.012
34. Paul G, Hirani H, Kuila T, Murmu NC (2019) Nanolubricants dispersed with graphene and its derivatives: an assessment and review of the tribological performance. Nanoscale 11:3458–3483. https://doi.org/10.1039/c8nr08240e
35. Yuxiu A, Guancheng J, Yourong Q et al (2016) High-performance shale plugging agent based on chemically modified graphene. J Nat Gas Sci Eng 32:347–355. https://doi.org/10.1016/j.jngse.2016.04.048
36. Rana A, Arfaj MK, Saleh TA (2020) Graphene grafted with glucopyranose as a shale swelling inhibitor in water-based drilling mud. Appl Clay Sci 199:105806. https://doi.org/10.1016/j.clay.2020.105806
37. Al-Zubaidi NS, Alwasiti AA, Mahmood D (2017) A comparison of nano bentonite and some nano chemical additives to improve drilling fluid using local clay and commercial bentonites. Egypt J Pet 26:811–818. https://doi.org/10.1016/j.ejpe.2016.10.015
38. Aftab A, Ismail AR, Ibupoto ZH (2017) Enhancing the rheological properties and shale inhibition behavior of water-based mud using nanosilica, multi-walled carbon nanotube, and graphene nanoplatelet. Egypt J Pet 26:291–299. https://doi.org/10.1016/j.ejpe.2016.05.004
39. Ridha S, Ibrahim A, Shahari R, Fonna S (2018) Graphene nanoplatelets as high-performance filtration control material in water-based drilling fluids. IOP Conf Ser Mater Sci Eng 352:012025. https://doi.org/10.1088/1757-899X/352/1/012025
40. Rana A, Saleh TA, Arfaj MK (2019) Improvement in rheological features, fluid loss and swelling inhibition of water-based drilling mud by using surfactant-modified graphene. Soc Pet Eng - Abu Dhabi Int Pet Exhib Conf 2019. ADIP 2019:1–10. https://doi.org/10.2118/197774-ms
41. Ibrahim A, Ridha S, Amer A, et al (2019) Influence of degree of dispersion of noncovalent functionalized graphene nanoplatelets on rheological behaviour of aqueous drilling fluids. Int J Chem Eng 2019:. https://doi.org/10.1155/2019/8107168
42. Madkour TM, Fadl S, Dardir MM, Mekewi MA (2016) High performance nature of biodegradable polymeric nanocomposites for oil-well drilling fluids. Egypt J Pet 25:281–291. https://doi.org/10.1016/j.ejpe.2015.09.004
43. Ismail AR, Aftab A, Ibupoto ZH, Zolkifile N (2016) The novel approach for the enhancement of rheological properties of water-based drilling fluids by using multi-walled carbon nanotube, nanosilica and glass beads. J Pet Sci Eng 139:264–275. https://doi.org/10.1016/j.petrol.2016.01.036
44. Mudaser Ahmad H, Shahzad Kamal M, Al-Harthi MA, et al (2018) Synthesis and experimental investigation of novel CNT-polymer nanocomposite to enhance borehole stability at high temperature drilling applications. Soc Pet Eng - SPE Kingdom Saudi Arab Annu Tech Symp Exhib 2018, SATS 2018. https://doi.org/10.2118/192352-ms
45. Rana A, Khan I, Ali S et al (2020) Controlling shale swelling and fluid loss properties of water-based drilling mud via ultrasonic impregnated SWCNTs/PVP nanocomposites. Energy Fuels 34(8):9515–9523. https://doi.org/10.1021/acs.energyfuels.0c01718
46. Li MC, Wu Q, Song K et al (2015) Cellulose nanoparticles as modifiers for rheology and fluid loss in bentonite water-based fluids. ACS Appl Mater Interfaces 7(8):5006–5016. https://doi.org/10.1021/acsami.5b00498
47. Li M, Wu Q, Song K et al (2015) Cellulose nanocrystals and polyanionic cellulose as additives in bentonite water-based drilling fluids: rheological modelling and filtration mechanisms. Ind Eng Chem Res 55(1):133–143. https://doi.org/10.1021/acs.iecr.5b03510
48. Song K, Wu Q, Li M et al (2016) Performance of low solid bentonite drilling fluids modified by cellulose nanoparticles. J Nat Gas Sci Eng. https://doi.org/10.1016/j.jngse.2016.08.036
49. Liu C, Li M, Mei C et al (2020) Cellulose nanofibers from rapidly microwave-delignified energy cane bagasse and their application in drilling fluids as rheology and filtration modifiers. Ind Crop Prod 150:112378. https://doi.org/10.1016/j.indcrop.2020.112378
50. Hall LJ, Deville JP, Araujo CS, Li S, Rojas OJ, Carolina N (2017) Nanocellulose and its derivatives for high-performance water-based fluids. Paper presented at the SPE International Conference on Oilfield Chemistry, Montgomery. https://doi.org/10.2118/184576-MS
51. Saboori R, Sabbaghi S, Kalantariasl A, Mowla D (2018) Improvement in filtration properties of water-based drilling fluid by nanocarboxymethyl cellulose/polystyrene core–shell nanocomposite. J Pet Explor Prod Technol. https://doi.org/10.1007/s13202-018-0432-9
52. Li M, Ren S, Zhang X et al (2018) Surface-chemistry-tuned cellulose nanocrystals in bentonite suspension for water-based drilling fluids. ACS Appl Nano Mater 1(12):7039–7051. https://doi.org/10.1021/acsanm.8b01830
53. Liu AX, Qu J, Wang A et al (2019) Hydrogels prepared from cellulose nanofibrils via ferric ion-mediated crosslinking reaction for protecting drilling fluid. Carbohydr Polym 212:67–74. https://doi.org/10.1016/j.carbpol.2019.02.036
54. Hall LJ, Deville JP, Santos CM, Rojas OJ, Araujo CS (2018) Nanocellulose and biopolymer blends for high-performance water-based drilling fluids. Paper presented at the IADC/SPE Drilling Conference and Exhibition, Fort Worth, Texas. https://doi.org/10.2118/189577-MS
55. Li MC, Tang Z, Liu C et al (2020) water-redispersible cellulose nanofiber and polyanionic cellulose hybrids for high-performance water-based drilling fluids. Ind Eng Chem Res 59(32):14352–14363. https://doi.org/10.1021/acs.iecr.0c02644
56. Natalia I, Eleonora C, Marı YV (2018) Cellulose nanofibrils as a replacement for xanthan gum (XGD) in water based muds (WBMs) to be used in shale formations. 0123456789:7091–7112. https://doi.org/10.1007/s10570-018-2081-z
57. Heggset EB, Chinga-carrasco G, Syverud K (2017) Temperature stability of nanocellulose dispersions. Carbohydr Polym 157:114–121. https://doi.org/10.1016/j.carbpol.2016.09.077
58. Zoveidavianpoor M (2016) The use of nano-sized tapioca starch as a natural water-soluble polymer for fi ltration control in water-based drilling muds. J Nat Gas Sci Eng 34:832–840. https://doi.org/10.1016/j.jngse.2016.07.048

59. Gbadamosi AO, Junin R, Abdalla Y et al (2018) Experimental investigation of the effects of silica nanoparticle on hole cleaning efficiency of water-based drilling mud. J Pet Sci Eng. https://doi.org/10.1016/j.petrol.2018.09.097
60. Perween S, Thakur NK, Beg M, Sharma S, Ranjan A (2019) Enhancing the properties of water based drilling fluid using bismuth ferrite nanoparticles. Colloids Surfaces A Physicochem Eng Asp 561:165–177. https://doi.org/10.1016/j.colsurfa.2018.10.060
61. Cheraghian G (2019) Nanokomposit stabilisiert Bohrflüssigkeiten. Keramische Zeitschrift 71(1–2):25. https://doi.org/10.1007/s42410-019-0006-6
62. Zhang H, Zhong Y, She J, Kuang J (2019) Experimental study of nano-drilling fluid based on nano temporary plugging technology and its application mechanism in shale drilling. Appl Nanosci. https://doi.org/10.1007/s13204-019-01046-w
63. Smith SR, Rafati R, Haddad AS, Hamidi H (n.d.) School of Engineering, University of Aberdeen, Aberdeen, United Kingdom, AB24 3UE Baroid Drilling Fluid Laboratory, Halliburton, Dyce, Aberdeen, United Kingdom, AB21 0GN
64. Anawe PAL, Folayan AJ (2018) Investigation of the effect of yttrium oxide (Y2O3) nanoparticle on the rheological properties of water based mud under high pressure high temperature (HPHT) environment. Int J Mech Eng Technol 9(7):545–559
65. Ghasemi N, Mirzaee M, Aghayari R, Maddah H (2018) Investigating created properties of nanoparticles based drilling mud. Heat Mass Transf. 54:1381–1393. https://doi.org/10.1007/s00231-017-2229-7
66. Jain R, Mahto V, Sharma VP (2015) Journal of Natural Gas Science and Engineering Evaluation of polyacrylamide-grafted-polyethylene glycol / silica nanocomposite as potential additive in water based drilling mud for reactive shale formation. J Nat Gas Sci Eng 26:526–537. https://doi.org/10.1016/j.jngse.2015.06.051
67. Aftab A, Ismail AR, Khokhar S, Ibupoto ZH (2016) Novel zinc oxide nanoparticles deposited acrylamide composite used for enhancing the performance of water-based drilling fluids at elevated temperature conditions. J Pet Sci Eng 146:1142–1157.https://doi.org/10.1016/j.petrol.2016.08.014
68. Mao H, Qiu Z, Shen Z, Huang W (2015) Hydrophobic associated polymer based silica nanoparticles composite with core–shell structure as a filtrate reducer for drilling fluid at ultra-high temperature. J. Pet. Sci. Eng. 129:1–14. https://doi.org/10.1016/j.petrol.2015.03.003
69. Dejtaradon AP, Hamidi H (2019) Graphical abstract PT SC. Colloids Surfaces A Physicochem Eng Asp. https://doi.org/10.1016/j.colsurfa.2019.03.050
70. Abdo J, Haneef MD (2013) Clay nanoparticles modified drilling fluids for drilling of deep hydrocarbon wells. Appl Clay Sci 86:76–82. https://doi.org/10.1016/j.clay.2013.10.017
71. Kumar A, Parveen S, Husain S et al (2014) Applied Surface Science. A comparative study of nitrogen plasma effect on field emission characteristics of single wall carbon nanotubes synthesized by plasma enhanced chemical vapor deposition. Appl Surf Sci 322:236–241. https://doi.org/10.1016/j.apsusc.2014.10.116
72. Ismail AR, Rosli W, Sulaiman W et al (2016) Nanoparticles performance as fluid loss additives in water based drilling fluids 864:189–193. https://doi.org/10.4028/www.scientific.net/MSF.864.189
73. Jain R, Mahto TK, Mahto V (2016) Rheological investigations of water based drilling fluid system developed using synthesized nanocomposite. Korea-Australia Rheol J 28:55–65. https://doi.org/10.1007/s13367-016-0006-7
74. Husin H, Elraies KA, Choi HJ, Aman Z (2018) Influence of graphene nanoplatelet and silver nanoparticle on the rheological properties of water-based mud. Appl Sci 8(8):1386. https://doi.org/10.3390/app8081386
75. Jouhara H, Chauhan A, Nannou T et al (2017) Heat pipe based systems-advances and applications. Energy 128:729–754
76. Jouhara H, Khordehgah N, Almahmoud S et al (2018) Waste heat recovery technologies and applications. Therm Sci Eng Prog 6:268–289
77. Delpech B, Milani M, Montorsi L et al (2018) Energy efficiency enhancement and waste heat recovery in industrial processes by means of the heat pipe technology: case of the ceramic industry. Energy 158:656–665
78. Brough D, Mezquita A, Ferrer S et al (2020) An experimental study and computational validation of waste heat recovery from a lab scale ceramic kiln using a vertical multi-pass heat pipe heat exchanger. Energy 208:118325
79. Jouhara H, Olabi AG (2018) Industrial waste heat recovery. Elsevier. https://doi.org/10.1016/j.energy.2018.07.013
80. Olabi AG, Elsaid K, Sayed ET et al (2021) Application of nanofluids for enhanced waste heat recovery: a review. Nano Energy 84:105871
81. Rafiq M, Shafique M, Azam A, Ateeq M (2021) Transformer oil-based nanofluid: The application of nanomaterials on thermal, electrical and physicochemical properties of liquid insulation-a review. Ain Shams Eng J 12:555–576
82. Sekrani G, Poncet S (2018) Ethylene- and propylene-glycol based nanofluids: a litterature review on their thermophysical properties and thermal performances. Appl Sci 8:2311
83. Wang Y, Al-Saaidi HAI, Kong M, Alvarado JL (2018) Thermophysical performance of graphene based aqueous nanofluids. Int J Heat Mass Transf 119:408–417
84. Fierro JJ, Escudero-Atehortua A, Nieto-Londoño C et al (2020) Evaluation of waste heat recovery technologies for the cement industry. Int J Thermofluids 7:100040
85. Jouhara H, Żabnieńska-Góra A, Khordehgah N et al (2020) Latent thermal energy storage technologies and applications: a review. Int J Thermofluids 5–6:100039. https://doi.org/10.1016/j.ijft.2020.100039
86. Agathokleous R, Bianchi G, Panayiotou G et al (2019) Waste heat recovery in the EU industry and proposed new technologies. Energy Procedia 161:489–496
87. Patil MS, Kim SC, Seo J-H, Lee M-Y (2016) Review of the thermo-physical properties and performance characteristics of a refrigeration system using refrigerant-based nanofluids. Energies 9:22
88. Sujith SV, Kim H, Lee J (2022) A review on thermophysical property assessment of metal oxide-based nanofluids: industrial perspectives. Metals (Basel) 12:165
89. Adewale FJ, Lucky AP, Oluwabunmi AP, Boluwaji EF (2017) Selecting the most appropriate model for rheological characterization of synthetic based drilling mud. Int J Appl Eng Res 12:7614–7629
90. Usman B, Bilal S, Shuwa SM (2019) Modelling the rheology and determination of fluid loss of drilling mud formulated from organophyllic clay developed from locally sourced Nigerian bentonitic clay. FUDMA J Sci 2616–1370(3):177–182
91. Barnes HA, Walters K (1985) The yield stress myth? Rheol acta 24:323–326
92. Nair V, Tailor PR, Parekh AD (2016) Nanorefrigerants: a comprehensive review on its past, present and future. Int J Refrig 67:290–307
93. Sanukrishna SS, Prakash MJ (2018) Thermal and rheological characteristics of refrigerant compressor oil with alumina nanoparticles—an experimental investigation. Powder Technol 339:119–129
94. Asadi A, Pourfattah F, Szilágyi IM et al (2019) Effect of sonication characteristics on stability, thermophysical properties, and heat transfer of nanofluids: a comprehensive review. Ultrason Sonochem 58:104701

95. Mahbubul IM, Saidur R, Amalina MA (2013) Thermal conductivity, viscosity and density of R141b refrigerant based nanofluid. Procedia Eng 56:310–315
96. Elsaid K, Abdelkareem MA, Maghrabie HM et al (2021) Thermophysical properties of graphene-based nanofluids. Int J Thermofluids 10:100073
97. Kedzierski MA, Brignoli R, Quine KT, Brown JS (2017) Viscosity, density, and thermal conductivity of aluminum oxide and zinc oxide nanolubricants. Int J Refrig 74:3–11
98. Ohunakin OS, Adelekan DS, Babarinde TO et al (2017) Experimental investigation of TiO2-, SiO2- and Al2O3-lubricants for a domestic refrigerator system using LPG as working fluid. Appl Therm Eng 127:1469–1477
99. Zawawi NNM, Azmi WH, Redhwan AAM et al (2017) Thermophysical properties of Al2O3-SiO2/PAG composite nanolubricant for refrigeration system. Int J Refrig 80:1–10
100. Zawawi NNM, Azmi WH, Redhwan AAM et al (2018) Experimental investigation on thermo-physical properties of metal oxide composite nanolubricants. Int J Refrig 89:11–21
101. Sanukrishna SS, Prakash MJ (2018) Experimental studies on thermal and rheological behaviour of TiO2-PAG nanolubricant for refrigeration system. Int J Refrig 86:356–372
102. Jatinder G, Ohunakin OS, Adelekan DS et al (2019) Performance of a domestic refrigerator using selected hydrocarbon working fluids and TiO2–MO nanolubricant. Appl Therm Eng 160:114004
103. Narayanasarma S, Kuzhiveli BT (2019) Evaluation of the properties of POE/SiO2 nanolubricant for an energy-efficient refrigeration system–an experimental assessment. Powder Technol 356:1029–1044
104. Alawi OA, Salih JM, Mallah AR (2019) Thermo-physical properties effectiveness on the coefficient of performance of Al2O3/R141b nano-refrigerant. Int Commun Heat Mass Transf 103:54–61
105. Kumar PM, Kumar J, Tamilarasan R et al (2015) Review on nanofluids theoretical thermal conductivity models. Eng J 19:67–83
106. Murshed SMS, Leong KC, Yang C (2008) Thermophysical and electrokinetic properties of nanofluids–a critical review. Appl Therm Eng 28:2109–2125
107. Lee J-H, Lee S-H, Choi C, Jang S, Choi S (2011) A review of thermal conductivity data, mechanisms and models for nanofluids. Int J Micro-Nano Scale Transp. https://doi.org/10.1260/1759-3093.1.4.269
108. Yıldız G, Ağbulut Ü, Gürel AE (2021) A review of stability, thermophysical properties and impact of using nanofluids on the performance of refrigeration systems. Int J Refrig 129:342–364
109. Saidur R, Kazi SN, Hossain MS et al (2011) A review on the performance of nanoparticles suspended with refrigerants and lubricating oils in refrigeration systems. Renew Sustain Energy Rev 15:310–323
110. Mahbubul IM, Saadah A, Saidur R et al (2015) Thermal performance analysis of Al2O3/R-134a nanorefrigerant. Int J Heat Mass Transf 85:1034–1040
111. Kumar R, Singh J, Kundal P (2018) Effect of CuO nanolubricant on compressor characteristics and performance of LPG based refrigeration cycle: experimental investigation. Heat Mass Transf 54:1405–1413
112. Alawi OA, Sidik NAC, Xian HW et al (2018) Thermal conductivity and viscosity models of metallic oxides nanofluids. Int J Heat Mass Transf 116:1314–1325
113. Bhattad A, Sarkar J, Ghosh P (2018) Improving the performance of refrigeration systems by using nanofluids: a comprehensive review. Renew Sustain Energy Rev 82:3656–3669
114. Alawi OA, Sidik NAC (2014) Influence of particle concentration and temperature on the thermophysical properties of CuO/R134a nanorefrigerant. Int Commun Heat Mass Transf 58:79–84
115. Boyou NV, Ismail I, Sulaiman WRW et al (2019) Experimental investigation of hole cleaning in directional drilling by using nano-enhanced water-based drilling fluids. J Pet Sci Eng 176:220–231
116. Wang K, Jiang G, Liu F et al (2018) Magnesium aluminum silicate nanoparticles as a high-performance rheological modifier in water-based drilling fluids. Appl Clay Sci 161:427–435
117. Pourkhalil H, Nakhaee A (2019) Effect of nano ZnO on wellbore stability in shale: an experimental investigation. J Pet Sci Eng 173:880–888
118. Cheraghian G (2021) Nanoparticles in drilling fluid: a review of the state-of-the-art. J Mater Res Technol 13:737–753
119. Bianchi MG, Bussolati O, Chiu M et al (2019) Evaluation of potential engineered nanomaterials impacts on human health: from risk for workers to impact on consumers. In: Exposure to Engineered Nanomaterials in the Environment. Elsevier, pp 263–287
120. Hoet PHM, Brüske-Hohlfeld I, Salata OV (2004) Nanoparticles–known and unknown health risks. J Nanobiotechnology 2:1–15