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ENTROPY GENERATION AND THERMAL EFFICIENCY OPTIMIZATION OF HYBRID NANOFLUID-BASED DRILLING MUDS UNDER HIGH-PRESSURE AND HIGH-TEMPERATURE WELLBORE CONDITIONS: A COMPREHENSIVE REVIEW

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ABSTRACT

Drilling in high-pressure and high-temperature (HPHT) formations places the circulating drilling fluid at the centre of a severe thermal and hydraulic problem. Bottomhole temperatures above 150 °C and pressures above 69 MPa degrade polymeric additives, alter mud density and rheology, accelerate bit and tool wear, and shorten the life of downhole electronics. Hybrid nanofluids, in which two or more dissimilar nanoparticles are dispersed in a base fluid, have emerged as a promising route to drilling muds with enhanced thermal conductivity, improved rheological stability, reduced fluid loss and better lubricity. However, the same nanoparticles that strengthen heat transfer also raise viscosity and frictional pressure losses, so any thermal gain must be weighed against the hydraulic penalty. The second law of thermodynamics, through the concept of entropy generation, provides a single and physically consistent metric for this trade-off. Using an integrative narrative review methodology with structured thematic synthesis of 293 sources published from the earliest records to date, this paper consolidates the current understanding of (i) the HPHT wellbore thermal environment, (ii) the formulation, stability and thermophysical properties of hybrid nanofluid-based drilling

muds, (iii) the theoretical framework for entropy generation in non-Newtonian, temperature- and pressure-dependent mud flows in drill pipes and annuli, (iv) first-law and second-law measures of thermal efficiency, and (v) optimization strategies ranging from classical entropy generation minimization to multi-objective evolutionary algorithms and machine-learning surrogates. The synthesis shows that an optimal total nanoparticle loading, usually at low volume fractions, generally exists where the reduction in heat-transfer irreversibility is balanced by the rise in frictional irreversibility, and that this optimum shifts with flow rate, temperature, pressure, particle mixing ratio and rheological model. Building on this evidence, a six-layer conceptual model is proposed that links HPHT property characterization, coupled wellbore thermo-hydraulics, second-law assessment, constrained optimization and field feedback, moderated by stability, equipment integrity, occupational safety, environmental and supply chain factors. The discussion identifies key gaps, including scarce property data above 200 °C and 100 MPa, the near absence of validated wellbore-scale entropy analyses, uncertain long-term colloidal stability, and limited treatment of health, environmental and economic constraints. Implications for researchers, drilling engineers, HSE practitioners and policy makers are outlined, the limitations of the review are acknowledged, and a research agenda is proposed.

KEYWORDS: Hybrid Nanofluids; Drilling Fluids; Entropy Generation; Bejan Number; Hpht Wells; Thermal Efficiency; Non-Newtonian Rheology; Optimization.

Nomenclature

Symbol	Description	Symbol	Description
Be	Bejan number (-)	T	Temperature (K)
Br	Brinkman number (-)	T_0	Reference / ambient temperature (K)
c_p	Specific heat capacity (J kg^{-1} K^{-1})	U	Overall heat transfer coefficient (W m^{-2} K^{-1})
ECD	Equivalent circulating density (kg m^{-3})	u	Axial velocity (m s^{-1})
f	Darcy friction factor (-)	$\dot{W}$	Pumping power (W)
K	Consistency index (Pa s^n)	z	Measured depth coordinate (m)
k	Thermal conductivity (W m^{-1} K^{-1})		Greek symbols
n	Flow behaviour index	$\dot{\gamma}$	Shear rate (s^{-1})

Symbol	Description	Symbol	Description
	(-)		
N_s	Entropy generation number (-)	η	Efficiency or performance index (-)
Nu	Nusselt number (-)	μ	Dynamic viscosity (Pa s)
P	Pressure (Pa)	ρ	Density (kg m^{-3})
PEC	Performance evaluation criterion (-)	σ	Electrical conductivity (S m^{-1})
q	Volumetric flow rate (m^3 s^{-1})	τ, τ_y	Shear stress, yield stress (Pa)
Re	Reynolds number (-)	φ	Nanoparticle volume fraction (-)
S'''_{gen}	Volumetric entropy generation rate (W m^{-3} K^{-1})		Subscripts: bf base fluid; nf nanofluid; hnf hybrid nanofluid; p1, p2 nanoparticle types; a annulus; p drill pipe; f formation

1. INTRODUCTION

1.1 Background

Drilling fluids, commonly called drilling muds, perform a set of interdependent functions: they transport cuttings to the surface, maintain hydrostatic control of formation pressure, stabilize the borehole wall, cool and lubricate the bit and drill string, transmit hydraulic power to downhole motors, and convey measurement-while-drilling signals (Bourgoyne et al., 1986; Caenn et al., 2011). As exploration has moved toward deeper reservoirs, deepwater sub-salt plays and geothermal resources, an increasing share of wells is drilled under high-pressure and high-temperature (HPHT) conditions. Industry practice commonly labels a well as HPHT when the static bottomhole temperature exceeds about 150 °C (300 °F) and the pore pressure exceeds about 69 MPa (10,000 psi), with ultra-HPHT and extreme categories reaching beyond 205 °C and 138 MPa, and beyond 260 °C and 241 MPa respectively.

Under these conditions the drilling fluid becomes the primary thermal management agent of the well. Its ability to remove heat from the bit and the near-wellbore formation, and to deliver that heat to the surface where it is rejected, controls downhole tool temperatures, the thermal stresses imposed on the wellbore wall and the thermal degradation of the mud itself. At the same time, temperature and pressure change mud density and rheology in opposite directions, which complicates the prediction of equivalent circulating density (ECD) in narrow margin wells (Kårstad and Aadnøy, 1998). Conventional water-based and oil-based muds rely on polymers, clays and weighting agents whose performance deteriorates sharply

as temperature rises, through polymer chain scission, clay flocculation and dehydration, and barite sag.

Nanotechnology has been proposed as a means of extending the operating window of drilling fluids (Amanullah and Al-Tahini, 2009; Abdo and Haneef, 2012). Since the term nanofluid was introduced to describe suspensions of nanometre-sized particles with anomalously high thermal conductivity (Choi and Eastman, 1995), a large literature has examined their heat transfer behaviour (Xuan and Li, 2000; Keblinski et al., 2002; Buongiorno, 2006). In the drilling context, nanoparticles of silica, alumina, copper oxide, zinc oxide, iron oxide, titania, graphene derivatives and carbon nanotubes have been shown to modify rheology, reduce filtrate loss, strengthen filter cakes, improve thermal stability and enhance thermal conductivity (Vryzas and Kelessidis, 2017; Aftab et al., 2017). Hybrid nanofluids, which combine two or more nanoparticle species, extend this concept by exploiting synergy between particles with complementary properties, for example a highly conductive metal or carbon phase paired with a chemically stable oxide phase (Sarkar et al., 2015; Babu et al., 2017; Huminic and Huminic, 2018). Recent modelling work has extended this concept further to hybrid and ternary hybrid nanofluids under magnetic fields, Hall currents, slip and dissipative heating (Panda et al., 2025a, 2025b; Oluwaseun and Agbaje, 2025; Oluwaseun et al., 2025).

Beyond hydrocarbons, HPHT drilling know-how is increasingly transferred to geothermal development, where remote-sensing interpretation of hydrothermal alteration helps locate high-temperature resources (Dagodzo, 2018). This work sits within a broader energy transition in which smart grids, renewable yield and load forecasting, and wind power prediction are reshaping energy systems (Adenuga, 2022; Ezeugwa et al., 2023; Komi, 2021; Komi, 2023), while just-transition, diversification and energy-poverty analyses frame the social dimension of resource-dependent regions (Komi and Adamolekun, 2024; Komi and Adamolekun, 2026; Komi and Ganiu, 2025; Komi, 2025). Community trust, social licence and inclusive financing increasingly determine whether energy projects proceed and endure (Komi and Adeniji, 2024a; Komi and Adeniji, 2024b; Komi, 2024), and logistics efficiency, hydrogen, renewable propane and biofuel blends are being examined as lower-carbon options for field energy supply (Bello et al., 2023; Monye et al., 2025a; Monye et al., 2025b; Opara et al., 2024; Shittu et al., 2019). Improving the thermodynamic efficiency of drilling operations is therefore aligned with the wider decarbonization agenda of the energy industry.

1.2 Why entropy generation?

The first law of thermodynamics measures how much heat a mud can carry, but not the quality of the energy conversion involved. Adding nanoparticles almost always raises the effective viscosity of the fluid, and drilling muds are already shear-thinning, yield-stress fluids whose frictional losses dominate the pump pressure budget. A mud that removes slightly more heat but requires substantially more pumping power, or raises ECD beyond the fracture gradient, is not an improvement. Second-law analysis resolves this ambiguity by expressing both heat-transfer and frictional losses as entropy generation, which is related through the Gouy-Stodola theorem to the useful work destroyed in the process (Bejan, 1982, 1996). Minimizing entropy generation therefore provides a rational, single-objective basis for selecting nanoparticle type, mixing ratio, loading and operating conditions, while constraint handling or multi-objective formulations can bring in the drilling-specific requirements on density, rheology and fluid loss.

Entropy generation in nanofluid flows has been reviewed extensively for heat exchangers, channels and enclosures (Mahian et al., 2013; Mahian et al., 2019), and more recently for magnetohydrodynamic nanofluid flows with velocity slip and viscous dissipation (Oluwaseun et al., 2023) and for shear-thinning Carreau fluids in porous media (Folarin et al., 2026a). Separately, nano-enhanced drilling fluids have been reviewed from the viewpoint of rheology, filtration and wellbore stability (Vryzas and Kelessidis, 2017; Aftab et al., 2017). The intersection of these two bodies of work, namely the second-law performance of hybrid nanofluid-based muds circulating through the drill string and annulus of an HPHT well, has received far less systematic attention. This review addresses that gap.

1.3 Aim, research questions and structure

The aim of this review is to establish a second-law basis for the design and operation of hybrid nanofluid-based drilling muds in HPHT wells. Four research questions guide the work. RQ1: How do HPHT wellbore conditions and hybrid nanoparticle additives jointly shape the thermophysical and rheological behaviour of drilling muds? RQ2: How can entropy generation be formulated and interpreted for non-Newtonian, temperature- and pressure-dependent mud circulation? RQ3: Which first-law and second-law metrics and optimization approaches are most suitable for identifying thermodynamically efficient formulations and operating conditions? RQ4: What engineering, safety, environmental and economic factors condition the field deployment of such fluids, and where are the main research gaps? The remainder of the paper is organized as follows. Section 2 describes the research method. Section 3 presents the results and discussion: the synthesis of the literature on the HPHT

environment, hybrid nanofluid muds, property models, the entropy generation framework, thermal efficiency, optimization and the evidence base (Sections 3.1 to 3.7); a proposed conceptual model (Section 3.8); discussion of the principal findings and knowledge gaps (Sections 3.9 and 3.10); considerations for field deployment (Section 3.11); implications (Section 3.12); limitations of the review (Section 3.13); and future research directions (Section 3.14). Section 4 concludes. Related analytical and numerical studies of nanofluid transport under comparable thermal, magnetic and slip conditions provide relevant precedent (Folarin et al., 2026a; Oluwaseun et al., 2023; Oluwaseun et al., 2025).

2. RESEARCH METHOD

2.1 Review design

This study adopts an integrative narrative review design with structured thematic synthesis. An integrative design was chosen because the topic lies at the intersection of several disciplines, namely drilling engineering, nanofluid heat transfer, non-Newtonian fluid mechanics and thermodynamics, and because the evidence base mixes experimental, numerical, analytical and conceptual studies that cannot be pooled statistically. The review therefore aims to integrate, critique and synthesize these strands into a coherent framework rather than to estimate pooled effect sizes, as a meta-analysis would. The four research questions stated in Section 1.3 structured the identification, classification and synthesis of the literature.

2.2 Literature identification

Literature was identified through three complementary routes. First, foundational and seminal works were drawn from the established canon of heat transfer, nanofluid science, entropy generation and drilling engineering, including classical models of suspension properties, wellbore heat transmission and circulating mud temperature. Second, keyword-guided searching of scholarly indexes and publisher platforms was combined with backward citation tracking from key reviews of nanofluids, hybrid nanofluids, entropy generation and nano-based drilling fluids. Representative search strings combined terms such as “hybrid nanofluid”, “nanofluid”, “drilling fluid” or “drilling mud”, “HPHT” or “high temperature”, “entropy generation”, “Bejan number”, “non-Newtonian”, “Herschel-Bulkley”, “wellbore heat transfer” and “optimization”. Third, curated seed lists of recent publications were screened to capture current modelling studies on hybrid and non-Newtonian nanofluids and transferable cross-disciplinary work on safety, asset integrity, energy systems, digital technologies, environmental management and supply chains that bears on field deployment.

2.3 Inclusion and exclusion criteria

Sources were included if they (i) were peer-reviewed journal articles, conference papers, book chapters or authoritative textbooks; (ii) were published in English up to and including 2026; and (iii) were either directly related to the topic (drilling fluids, HPHT wellbores, nanofluids and hybrid nanofluids, entropy generation, thermal efficiency, optimization) or semi-related, meaning they contributed transferable methods (for example computational, data-driven or reliability methods) or deployment context (for example process safety, environmental management, energy systems or supply chains). Sources were excluded if they had no identifiable methodological or contextual link to the research questions, were non-scholarly, were duplicates, or carried a publication date later than 2026. Applying these criteria yielded a final corpus of 293 sources spanning 1881 to 2026, with most published from 2018 onward, reflecting the recent growth of hybrid nanofluid and data-driven engineering research.

2.4 Classification and thematic synthesis

Each included source was read for its objectives, methods, principal findings and relevance, and was coded into one of nine themes aligned with the research questions (Table 1). Themes T1 to T3 form the technical core of the review and inform the literature synthesis in Sections 3.1 to 3.7. Themes T4 and T5 supply methods for modelling and optimization. Themes T6 to T9 provide the deployment context that moderates the conceptual model in Section 3.8 and the discussion in Sections 3.9 to 3.14. Synthesis proceeded in three steps: descriptive mapping of each theme, cross-theme integration around the thermal-hydraulic trade-off, and abstraction of the integrated findings into the conceptual model and research propositions.

Table 1. Thematic classification of the reviewed literature (N = 293).

Code	Theme	Scope	Sources
T1	Drilling fluids, HPHT wells and wellbore heat transfer	Drilling fluid functions, HPHT conditions, circulating temperature, density and rheology at depth, nano-enhanced muds	19
T2	Nanofluid and hybrid nanofluid fundamentals and modelling	Property models, hybrid synergy, two-phase transport, non-Newtonian and magnetohydrodynamic nanofluid flows	24
T3	Entropy generation and second-law analysis	Local entropy generation, entropy generation minimization, nanofluid entropy studies	7
T4	Computational, materials and thermal engineering methods	CFD, thermofluid and filtration simulation, multi-objective design, materials processing and selection	23

Code	Theme	Scope	Sources
T5	AI, digital twins, predictive maintenance and data governance	Neural-network surrogates, digital twins, condition monitoring, model and data governance, OT security	44
T6	Energy systems and energy transition	Rig and grid power efficiency, microgrids and storage, forecasting, alternative fuels, just transition	33
T7	Process safety, occupational safety and asset integrity	Drilling and process safety, human factors, contractor governance, corrosion, NDT and integrity management	76
T8	Environmental management, emissions and health	Produced water, flaring and methane, carbon accounting, contaminant transport, environmental health risk	36
T9	Supply chain, economics and project delivery	Procurement and supply resilience, capital decisions, project governance and schedule risk	31
	Total		293

2.5 Quality appraisal and weighting of evidence

Evidence was weighted according to its proximity to HPHT drilling conditions. Experimental measurements on drilling muds under elevated temperature and pressure were given the greatest weight, followed by laboratory measurements on nanofluids at near-ambient conditions, validated numerical and analytical studies, and finally conceptual frameworks and reviews from adjacent fields. Theoretical results obtained for idealized geometries, constant properties or Newtonian fluids were interpreted as indicative of trends rather than as quantitative predictions for drilling muds. Conceptual and cross-disciplinary sources were used to inform deployment considerations and were not treated as evidence of thermal or hydraulic performance.

3. RESULTS AND DISCUSSION

This section presents the results of the review and discusses them. The results are first reported as a thematic synthesis in seven parts that move from the physical setting to design and evidence: the HPHT wellbore environment (3.1), hybrid nanofluid-based drilling muds (3.2), thermophysical and rheological property models (3.3), the entropy generation framework (3.4), thermal efficiency measures (3.5), optimization strategies (3.6) and the experimental and numerical evidence base (3.7). These results are then integrated into a

conceptual model (3.8) and discussed in terms of principal findings, knowledge gaps, deployment considerations, implications, limitations and future research (3.9 to 3.14).

3.1 The HPHT Wellbore Thermal and Hydraulic Environment

3.1.1 Classification and operating envelope

Table 2 summarizes a widely used industry tiering of HPHT conditions. The thresholds are approximate and operator-specific, but they are useful because they align with practical limits of elastomers, downhole electronics and conventional mud additives.

Table 2. Commonly used tiers of HPHT well conditions.

Tier	Bottomhole temperature	Pressure	Typical implications for mud design
HPHT	150 to 205 °C (300 to 400 °F)	69 to 138 MPa (10,000 to 20,000 psi)	Polymer degradation begins; temperature-stable additives required
Ultra-HPHT	205 to 260 °C (400 to 500 °F)	138 to 241 MPa (20,000 to 35,000 psi)	Most organic polymers fail; oil-based or specialty fluids dominate
Extreme HPHT (HPHT-hc)	Above 260 °C (500 °F)	Above 241 MPa (35,000 psi)	Inorganic or high-performance formulations; very limited field data

3.1.2 Circulating temperature profile

During circulation, cool mud travels down the drill pipe, is heated by convection through the pipe wall from the warmer annular fluid, absorbs frictional and bit-generated heat at the bottom, and then gains heat from the formation as it returns up the annulus. The classical analytical models of Raymond (1969) and Holmes and Swift (1970), together with the transient formation heat conduction treatment of Ramey (1962) and the generalized models of Kabir et al. (1996), show that the maximum circulating temperature typically occurs in the annulus somewhat above the bit, and that the bottomhole circulating temperature can be tens of degrees below the static formation temperature. The steady, one-dimensional energy balances for the pipe and annular streams can be written as:

$$(\rho c_p)_{hnf}\, q\, \frac{dT_p}{dz} = 2\pi r_p U_p (T_a - T_p) + Q_{f,p} \quad (1)$$

$$-(\rho c_p)_{hnf}\, q\, \frac{dT_a}{dz} = 2\pi r_w U_a (T_f - T_a) - 2\pi r_p U_p (T_a - T_p) + Q_{f,a} \quad (2)$$

where $Q_{f,p}$ and $Q_{f,a}$ are frictional heat sources per unit length, U_p and U_a are overall heat transfer coefficients across the pipe wall and the wellbore wall, and T_f is the formation

temperature at the wellbore radius, obtained from a transient conduction solution. In both equations the mud properties enter through the heat capacity rate $(\rho c_p)q$ and through the convective film coefficients embedded in U. Nanoparticles therefore influence the circulating temperature profile in two ways: by altering the heat capacity of the stream and by altering the convective resistances, which depend on thermal conductivity and on the rheology-dependent flow regime.

3.1.3 Pressure and temperature effects on mud properties

Mud density increases with pressure through compressibility and decreases with temperature through thermal expansion. For oil-based fluids in particular these effects are significant enough that surface density measurements can misrepresent downhole hydrostatic pressure (Kårstad and Aadnøy, 1998). A commonly used empirical form is:

$$\rho(P,T) = \rho_0 \exp[c_p(P - P_0) - \alpha_T(T - T_0)] \quad (3)$$

where c_P is the isothermal compressibility and α_T the volumetric thermal expansion coefficient. Rheological parameters show stronger sensitivity. Viscosity and consistency generally fall with temperature, following an Arrhenius-type dependence, and rise with pressure. Yield stress may increase or decrease with temperature depending on clay chemistry, polymer type and the presence of nanoparticles, which can act as bridging or crosslinking sites. These coupled dependencies matter for second-law analysis because frictional entropy generation scales with the product of shear stress and shear rate divided by local temperature.

3.1.4 Thermal problems in HPHT drilling

- **Thermal degradation of additives.** Common viscosifiers and fluid-loss polymers such as xanthan gum, carboxymethyl cellulose and starch derivatives lose performance at elevated temperature, leading to loss of suspension capacity and increased filtrate.
- **Downhole tool limits.** Measurement-while-drilling and logging-while-drilling electronics, batteries and elastomeric seals have rated temperature limits; improved mud cooling directly extends tool life.
- **Wellbore stability.** Cooling of the near-wellbore rock by circulating mud reduces hoop stress and can either stabilize or destabilize the borehole depending on stress regime; heating on connection or trip can induce thermally driven ballooning and losses.
- **Narrow pressure windows.** In HPHT wells the margin between pore and fracture pressure is often small, so any increase in annular friction from nano-additives must be explicitly accounted for in ECD.

• **Bit thermal damage.** Polycrystalline diamond compact cutters are sensitive to thermal degradation at the cutter-rock interface; improved convective cooling at the bit face is a direct benefit of higher conductivity fluids.

Thermal management in HPHT drilling is inseparable from operational and process safety. Conceptual frameworks for operational integrity in high-risk drilling emphasize balancing productivity with safety compliance (Nwangwu et al., 2018), while heat stress models for crews working in extreme environments highlight the human cost of elevated surface and rig-floor temperatures (Arumosoye and Obriki, 2018; Obriki, 2026). Risk-based process engineering, the integration of HAZOP with reliability analysis, process safety and management of change, and emergency response readiness provide the governance context in which new fluid systems must be introduced (Arumosoye and Obriki, 2023; Asibor and Isong, 2019; Asibor et al., 2023; Makut et al., 2022b), and AI-based detection of process failures offers a route to earlier intervention (Asibor, 2025). Risk-based front-end engineering and systems-engineering approaches developed for offshore and deepwater production facilities, together with human-factors process safety models, are directly transferable to HPHT rig design and mud system layout (Makut et al., 2021a; Makut et al., 2021c; Makut et al., 2022a; Oduro, 2023).

3.2 Hybrid Nanofluid-Based Drilling Muds

3.2.1 From mono nanofluids to hybrid nanofluids

A mono nanofluid contains a single nanoparticle species. Experimental work on drilling fluids has shown that such particles can improve several properties at very low concentrations, often below 1 wt%. William et al. (2014) reported that CuO and ZnO nanoparticles in a xanthan-gum water-based mud enhanced thermal conductivity and electrical conductivity and improved high-pressure rheological behaviour, with CuO showing the stronger thermal effect. Smith et al. (2018) found that alumina nanoparticles improved rheological and filtration properties of water-based muds under HPHT testing. Ismail et al. (2016) showed that multi-walled carbon nanotubes and nanosilica could enhance rheology and lubricity relative to conventional additives. Mao et al. (2015) demonstrated that a hydrophobically associated polymer-silica core-shell composite could act as a filtrate reducer at ultra-high temperature.

A hybrid nanofluid combines two or more particle species, either as a physical mixture or as a composite in which one phase is grown on or coated by another. The rationale is synergy:

one component may provide high thermal conductivity (copper, silver, graphene, carbon nanotubes), another may provide chemical and thermal stability or favourable surface charge (alumina, silica, titania), and a third may contribute specific drilling functions such as magnetic responsiveness (Fe_3O_4) or shale inhibition. Suresh et al. (2011) prepared Al_2O_3-Cu/water hybrid nanofluids and measured thermal conductivity and viscosity enhancements, establishing a template subsequently followed by many studies. Reviews by Sarkar et al. (2015), Babu et al. (2017) and Huminic and Huminic (2018) summarize the general finding that hybrid nanofluids can deliver larger heat transfer gains than mono nanofluids at the same total loading, although viscosity also tends to rise and the advantage is not universal.

3.2.2 Candidate hybrid combinations for drilling muds

Table 3 lists hybrid pairings that have been investigated in drilling fluid or general nanofluid research and that are relevant to HPHT mud design. The listed functions are those most frequently reported; quantitative performance depends strongly on base mud chemistry, particle size, surface treatment and mixing ratio.

Table 3. Representative hybrid nanoparticle combinations and their principal functions in drilling muds.

Hybrid system	Expected thermal role	Expected drilling-fluid role
Al_2O_3-Cu, Al_2O_3-CuO	High conductivity metal or metal oxide with stable oxide carrier; enhanced k_{hnf}	Rheology modification, filtration control, thermal stability of suspension
SiO_2-graphene oxide (GO), SiO_2-MWCNT	Carbon phase provides very high intrinsic conductivity and percolation paths	Nanosilica plugs shale pore throats; GO forms thin, low-permeability filter cakes; improved lubricity
Fe_3O_4-based hybrids (with SiO_2, clay or carbon)	Moderate conductivity gain; field-responsive heat transfer	Magnetically tunable rheology; potential for recovery and recycling of particles
ZnO-CuO, TiO_2-CuO	Combined oxide conductivity enhancement	Thermal and electrical property tuning; some antibacterial and anti-corrosion benefits
Nanoclay-polymer-metal oxide composites	Limited conductivity gain	Temperature-resistant viscosity and fluid-loss control at ultra-high temperature

3.2.3 Preparation and stability

Nanofluids are prepared by one-step methods, in which particles are synthesized directly in the base fluid, or by the far more common two-step method, in which dry nanoparticles are

dispersed using mechanical stirring, ultrasonication and surfactants (Suresh et al., 2011; Babu et al., 2017). In drilling fluids the dispersion medium is itself complex, containing clays, polymers, salts, weighting agents and, in oil-based muds, an emulsified brine phase. Colloidal stability is therefore governed not only by particle surface charge (often characterized by zeta potential) and steric stabilization, but also by interactions with bentonite platelets and polymer chains, by electrolyte concentration that compresses the electric double layer, and by temperature, which increases Brownian motion and can desorb stabilizing surfactants.

HPHT conditions are especially demanding. Thermal degradation of dispersants can trigger agglomeration; agglomerates have different conductivity and viscosity behaviour than well-dispersed particles and can settle with barite. Long-duration stability tests under combined temperature, pressure, shear and salinity are rarely reported, which introduces significant uncertainty into thermal and second-law performance predictions based on short-term laboratory property data. Two-phase formulations based on the Buongiorno (2006) model, which account for Brownian diffusion and thermophoresis, offer a route to predicting particle migration and deposition in temperature gradients (Oluwaseun and Agbaje, 2025). Thermophoretic particle deposition, analysed by Baithalu et al. (2025), is directly relevant to drilling because steep radial temperature gradients near the wellbore wall and drill pipe may drive nanoparticles toward cooler surfaces, depleting the bulk fluid and altering filter cake composition.

Lessons from advanced materials processing are relevant to the design of hybrid and core-shell particles for HPHT muds. Studies of nanowire heterojunction stability, spray pyrolysis film formation and charge transport in thin-film architectures illustrate how processing conditions control interface quality and defect populations at the nanoscale (Atta et al., 2024; Atta, 2026a; Atta, 2026b). Sputter deposition and closed-loop plasma control demonstrate scalable routes to uniform functional coatings (Olodo et al., 2025; Olodo et al., 2026a; Olodo et al., 2026d), and work on advanced materials for integrated devices and on damage mechanisms in semiconductors shows how microstructure governs thermal and radiation tolerance (Erhimefe and Gideon, 2025; Gideon and Erhimefe, 2025). Predictive models of microstructural evolution under directed energy deposition, and dynamic mechanical analysis for high-performance material selection, offer analogous tools for selecting particle and coating materials that must survive prolonged exposure to high temperature and shear (Adewoyin et al., 2020a; Ogunnowo et al., 2021b; Ogunnowo et al., 2022a; Ogunnowo et al., 2022b).

3.2.4 Effects on rheology, filtration and lubricity

Across the drilling literature, low concentrations of nanoparticles typically increase plastic viscosity and yield point, reduce API and HPHT filtrate volume, produce thinner filter cakes and reduce the coefficient of friction (Vryzas and Kelessidis, 2017; Aftab et al., 2017). These effects are favourable for hole cleaning and wellbore stability, but the rise in effective viscosity directly increases frictional entropy generation and pump pressure. Minakov et al. (2018) showed that nanoparticle additives can measurably change pressure losses and cuttings transport efficiency in vertical boreholes, underscoring that thermal and hydraulic performance must be evaluated together.

3.3 Thermophysical Property and Rheological Models

3.3.1 Density and heat capacity

For a hybrid nanofluid with particle volume fractions φ_1 and φ_2 and total fraction $\varphi = \varphi_1 + \varphi_2$, mixture rules based on mass and energy conservation are well supported by experiments (Pak and Cho, 1998; Takabi and Salehi, 2014):

$$\rho_{hnf} = (1-\varphi)\rho_{bf} + \varphi_1\rho_{p1} + \varphi_2\rho_{p2} \quad (4)$$

$$(\rho c_p)_{hnf} = (1-\varphi)(\rho c_p)_{bf} + \varphi_1(\rho c_p)_{p1} + \varphi_2(\rho c_p)_{p2} \quad (5)$$

In a drilling mud the base fluid properties ρ_{bf} and $c_{p,bf}$ refer to the complete unloaded mud, including weighting material. Because metal oxide nanoparticles are dense, their contribution to mud weight is small at typical loadings but must be included in ECD calculations, while their lower specific heat slightly reduces the volumetric heat capacity.

3.3.2 Thermal conductivity

The classical Maxwell (1881) model for dilute spherical suspensions and its extension by Hamilton and Crosser (1962) for non-spherical particles remain the reference models:

$$\frac{k_{nf}}{k_{bf}} = \frac{k_p + (m-1)k_{bf} - (m-1)\varphi(k_{bf} - k_p)}{k_p + (m-1)k_{bf} + \varphi(k_{bf} - k_p)} \quad (6)$$

where $m = 3/\psi$ is the empirical shape factor and ψ the particle sphericity, so that $m = 3$ recovers the Maxwell model. Particle shape matters in practice: comparative analyses of hybrid nanofluids with spherical, cylindrical, platelet and blade-shaped particles show that shape factor can change predicted heat transfer appreciably (Ratha et al., 2026), which is relevant for platelet-like graphene and nanoclay additives in muds. For hybrid nanofluids, Takabi and Salehi (2014) proposed replacing the particle conductivity by a volume-weighted mean:

$$\frac{k_{hnf}}{k_{bf}} = \frac{\frac{\varphi_1 k_{p1} + \varphi_2 k_{p2}}{\varphi} + 2k_{bf} + 2(\varphi_1 k_{p1} + \varphi_2 k_{p2}) - 2\varphi k_{bf}}{\frac{\varphi_1 k_{p1} + \varphi_2 k_{p2}}{\varphi} + 2k_{bf} - (\varphi_1 k_{p1} + \varphi_2 k_{p2}) + \varphi k_{bf}} \quad (7)$$

Static mixture models do not capture mechanisms such as Brownian motion, liquid layering at the particle interface, clustering and percolation (Keblinski et al., 2002), nor the temperature dependence observed in many experiments. Empirical correlations of the form $k_{hnf}/k_{bf} = f(\varphi, T, d_p,$ mixing ratio) fitted to measured data are therefore common, but almost all such correlations have been developed at or near atmospheric pressure and below 100 °C. Their extrapolation to HPHT mud conditions is one of the most important unresolved uncertainties in the field.

3.3.3 Viscosity of the suspension

The Brinkman (1952) relation is widely used in theoretical studies of hybrid nanofluids:

$$\mu_{hnf} = \frac{\mu_{bf}}{(1-\varphi_1-\varphi_2)^{2.5}} \quad (8)$$

Experimental viscosities of nanofluids frequently exceed Brinkman predictions, especially for high aspect ratio particles such as carbon nanotubes and graphene sheets, and for agglomerated suspensions. For drilling muds, the Newtonian viscosity model is in any case insufficient, and nanoparticle effects should be expressed through the parameters of a non-Newtonian constitutive law.

3.3.4 Non-Newtonian rheology under HPHT conditions

Drilling muds are viscoplastic and shear-thinning. The Herschel-Bulkley model (Herschel and Bulkley, 1926) is usually preferred because it reduces to the Bingham plastic and power-law models as special cases:

$$\tau = \tau_y + K\dot{\gamma}^n \quad \text{for } |\tau| > \tau_y \quad (9)$$

Temperature and pressure dependence can be embedded through the parameters. A practical form that has been applied to HPHT mud data is:

$$K(T,P) = K_0 \exp\left[\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right) + \beta_P(P-P_0)\right] \quad (10)$$

with similar empirical relations for $\tau_y(T, P)$ and $n(T, P)$. Nanoparticle loading is then introduced through multiplicative factors, for example $K_{hnf} = K_{bf}\, g(\varphi_1, \varphi_2, T)$, fitted to rheometer data. Because frictional entropy generation depends on the full shear stress field, the choice of rheological model has a first-order influence on predicted optimal loadings.

A broad family of non-Newtonian constitutive models has been coupled with nanofluid and hybrid nanofluid transport in recent studies, and several are relevant to drilling muds. The Carreau model captures the transition from a zero-shear to a power-law regime and has been used for entropy analysis in porous media with slip (Folarin et al., 2026a). Viscoelastic Oldroyd-B (Folarin et al., 2026b) and Maxwell (Panda et al., 2025c) models describe the memory effects of polymer-rich muds. The Casson model, a yield-stress model widely used

for suspensions, has been combined with two-phase nanofluid transport and Cattaneo-Christov heat flux (Panda et al., 2026). Williamson (Ratha et al., 2026) and third-grade (Agbaje et al., 2025) models represent alternative shear-thinning and higher-order behaviour, while micropolar formulations with Darcy-Forchheimer drag (Shamshuddin et al., 2025) account for particle microrotation and inertial resistance in porous media. Such models offer useful alternatives to the Herschel-Bulkley law when muds display viscoelasticity or strong microstructural effects at HPHT.

3.4 Entropy Generation Framework for Mud Circulation

3.4.1 Local entropy generation rate

Following Bejan (1979, 1982), the local volumetric entropy generation rate in a flowing, heat-conducting fluid is the sum of contributions from heat conduction across finite temperature gradients, viscous dissipation and, where electromagnetic fields are present, Joule heating:

$$S'''_{gen} = \frac{k_{hnf}}{T^2}(\nabla T \cdot \nabla T) + \frac{1}{T}(\boldsymbol{\tau}:\nabla \mathbf{u}) + \frac{\sigma_{hnf} B^2 u^2}{T} \quad (11)$$

The first term is the heat-transfer irreversibility, S'''_{HT}; the second is the fluid-friction irreversibility, S'''_{FF}; the third, S'''_{MF}, applies to magnetically assisted or magnetically responsive (for example Fe_3O_4-containing) muds. For fully developed axial flow of a generalized Newtonian fluid in a drill pipe or concentric annulus, with the radial coordinate r and axial coordinate z, the expression reduces to:

$$S'''_{gen} = \frac{k_{hnf}}{T^2}\left[\left(\frac{\partial T}{\partial r}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right] + \frac{\tau_{rz}}{T}\left(\frac{\partial u}{\partial r}\right) \quad (12)$$

For a Herschel-Bulkley mud, the frictional term outside the unsheared plug becomes $(\tau_y + K|\partial u/\partial r|^n)|\partial u/\partial r|/T$, and is zero within the plug where the velocity gradient vanishes. The plug region therefore contributes heat-transfer irreversibility only, which is one reason why yield stress, a property strongly influenced by nanoparticles, has a distinctive effect on the second-law performance of drilling muds compared with Newtonian nanofluids.

Further contributions may be added depending on the physics retained. Radiative heat flux becomes more significant at very high temperatures and has been incorporated into nanofluid heat transfer analyses with radiation and heat sources (Agbaje et al., 2025; Panda et al., 2025c). Hall current effects modify the magnetic irreversibility in strongly magnetized hybrid nanofluids (Panda et al., 2025a, 2025b; Oluwaseun and Agbaje, 2025). Porous-medium drag terms, of Darcy or Darcy-Forchheimer form, contribute frictional irreversibility when mud filtrate flows through the filter cake and near-wellbore rock (Shamshuddin et al., 2025; Folarin et al., 2026a). Finally, under rapid thermal transients, Fourier conduction may be

replaced by the Cattaneo-Christov non-Fourier model, which introduces a thermal relaxation time and alters the heat-transfer component of entropy generation (Folarin et al., 2026b; Panda et al., 2026).

3.4.2 Integrated entropy generation and dimensionless measures

Integrating over a control volume, for example a unit length of annulus or the full circulating system, yields the total entropy generation rate $S_{gen} = \int S'''_{gen}\, dV$. Several dimensionless measures are used to interpret it:

$$\mathrm{Be} = \frac{S_{HT}}{S_{HT}+S_{FF}+S_{MF}} \quad (13)$$

$$\mathrm{Ns} = \frac{S_{gen}T_0^2}{k_{bf}(\Delta T)^2}, \qquad N_{s,a} = \frac{S_{gen,hnf}}{S_{gen,bf}} \quad (14)$$

The Bejan number Be ranges from 0 to 1: values near 1 indicate that heat-transfer irreversibility dominates, values near 0 that friction dominates. The augmentation entropy generation number $N_{s,a}$ directly compares a hybrid nanofluid mud with its unloaded base mud under the same duty; values below unity indicate a thermodynamic improvement. The Gouy-Stodola theorem relates entropy generation to destroyed work, $\dot{W}_{lost} = T_0 S_{gen}$, so that entropy generation can be translated into an equivalent pumping power penalty or energy cost.

3.4.3 Dimensionless groups governing the trade-off

Non-dimensionalizing the governing equations for mud flow in a wellbore shows that the entropy generation number depends on the Reynolds number (generalized for non-Newtonian fluids), the Prandtl number, the Brinkman number $\mathrm{Br} = \mu U^2/(k\Delta T)$, the Bingham or Hedstrom number for yield-stress effects, the flow behaviour index n, the annular diameter ratio and eccentricity, and the volume fractions and property ratios of the nanoparticles. The ratio Br/Ω, where $\Omega = \Delta T/T_0$ is a dimensionless temperature difference, is particularly useful because it measures the relative weight of frictional to thermal irreversibility. HPHT wells have large ΔT between the mud and the formation, which tends to raise thermal irreversibility, while high pump rates and viscous nano-enhanced muds raise the frictional share.

3.4.4 The optimal nanoparticle loading

The central result of second-law analysis of nanofluid flows (Mahian et al., 2013) carries over to drilling muds. Increasing the total nanoparticle fraction raises k_{hnf}, reduces temperature gradients for a given heat flux and lowers S_{HT}. It also raises the effective consistency and yield stress, increasing S_{FF}. When thermal irreversibility initially dominates, the total entropy generation falls with loading until frictional effects overtake it, producing a minimum at an optimal volume fraction φ_{opt}. Figure 1 illustrates this trade-off conceptually.

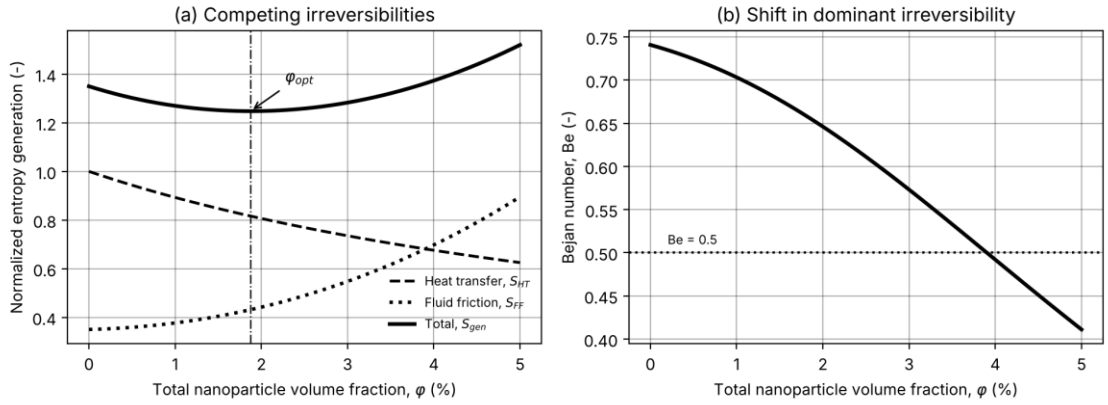


Figure 1. Conceptual illustration (normalized, not drawn from a specific data set) of (a) the competing heat-transfer and fluid-friction contributions to entropy generation as total hybrid nanoparticle loading increases, showing an interior optimum φ_{opt}, and (b) the corresponding decline in Bejan number as friction becomes the dominant irreversibility.

The position of the optimum depends on the operating point. At high flow rates or in narrow annuli, frictional irreversibility is already large and φ_{opt} shifts toward very low loadings, possibly to zero, implying that nanoparticles are thermodynamically unfavourable for heat removal alone and can only be justified by their other functions. At low flow rates with large thermal driving forces, as during reduced-rate circulation to cool a hot well, the optimum shifts to higher loadings. The mixing ratio φ_1/φ_2 is a second design variable: a small fraction of a high-conductivity carbon or metal phase may deliver most of the conductivity gain, while the oxide phase provides stability with less viscosity penalty per unit volume than high aspect ratio particles.

3.4.5 Wellbore-specific features

- **Counter-current coupling.** Pipe and annular streams exchange heat across the drill string, so entropy generation in one stream depends on the temperature field of the other; a system-level analysis must integrate over both streams and the bit.
- **Axial variation of properties.** Temperature and pressure vary by more than 150 °C and 100 MPa between surface and bottomhole, so k_{hnf}, K, τ_y and n vary along the well. Local optima differ from global optima.
- **Eccentricity and rotation.** Drill pipe eccentricity and rotation alter velocity and shear fields, changing S_{FF} distribution and creating low-shear zones where yield-stress plugs and particle settling may occur. Studies of nanofluid flow over rotating and squeezing disks, including oil-based (kerosene) nanofluids, give insight into rotation-driven heat transfer that

is analogous to flow near a rotating bit face or drill string (Oluwaseun et al., 2024; Oluwaseun and Agbaje, 2025).

- **Bit and nozzle losses.** A large part of the frictional pressure drop occurs at the bit nozzles, where dissipation is intense and local heating occurs; nanoparticle effects on nozzle losses are rarely included in second-law models.
- **Transient operations.** Connections, trips and kicks create transient thermal states in which entropy generation differs markedly from steady circulation. Unsteady and oscillatory nanofluid flow analyses (Oluwaseun et al., 2023, 2025) provide methods applicable to these transient states.

3.5 Thermal Efficiency of Nano-Enhanced Mud Systems

3.5.1 First-law measures

First-law performance is commonly expressed through the Nusselt number, the convective heat transfer coefficient, the bottomhole circulating temperature reduction, or the heat removal rate $Q = (\rho c_p)_{hnf} q (T_{out} - T_{in})$. For non-Newtonian fluids in pipes and annuli, Nusselt correlations based on generalized Reynolds and Prandtl numbers are applied, although validated correlations for hybrid nanofluid muds under HPHT conditions are lacking. Because conductivity enhancement increases Nu only modestly in turbulent flow while raising friction, first-law gains alone can be misleading.

3.5.2 Performance evaluation criterion

A widely used combined metric compares heat transfer enhancement with friction penalty at equal pumping power:

$$\mathrm{PEC} = \frac{Nu_{hnf}/Nu_{bf}}{\left(f_{hnf}/f_{bf}\right)^{1/3}} \quad (15)$$

Values of PEC greater than unity indicate that the nano-enhanced fluid improves heat transfer more than it increases pumping cost. The exponent 1/3 follows from the equal pumping power constraint in turbulent pipe flow; for laminar annular flow of yield-stress fluids, the appropriate exponent differs and should be derived for the specific flow regime.

3.5.3 Second-law efficiency

Second-law, or exergetic, efficiency compares the useful exergy effect with the exergy supplied. For a mud system whose purpose is to remove heat from a hot environment at temperature T_h and reject it at the surface, a suitable definition is:

$$\eta_{II} = 1 - \frac{T_0 S_{gen}}{\dot{W}_{pump} + \dot{Q}\left(1 - \frac{T_0}{T_h}\right)} \quad (16)$$

This expression accounts both for the pumping work input and the thermal exergy content of the heat removed. A hybrid nanofluid mud improves the system thermodynamically only if it raises η_{II} under the same operational constraints. In practice, the ECD constraint, the rheological specification for hole cleaning and the API or HPHT filtrate limits must also be met, which converts the problem into a constrained or multi-objective optimization.

3.5.4 Thermal efficiency indices relevant to drilling

Beyond generic thermodynamic metrics, drilling applications benefit from operation-specific indices, including: (i) the reduction in maximum circulating temperature at the bottomhole assembly per unit increase in pump pressure; (ii) the time to cool a well to a target temperature before running temperature-sensitive tools; (iii) the bit cooling effectiveness, defined as the ratio of heat removed at the bit to frictional heat generated there; and (iv) the energy cost per unit depth drilled. Expressing these indices alongside S_{gen} and η_{II} helps translate laboratory nanofluid research into field-relevant decisions.

Because frictional entropy generation is ultimately paid for as pumping work, the efficiency of the rig power system determines the fuel and emissions cost of each unit of destroyed exergy. Power electronics and converter efficiency, harmonic mitigation in distribution networks, grounding design and voltage control with distributed generation all influence the losses between the generator and the mud pump (Adeniji et al., 2020; Adeniji et al., 2025; Adenuga, 2023; Oshevire et al., 2017; Shittu et al., 2025b), and automation strategies for grid operation and multilevel inverter design improve conversion efficiency further (Shittu et al., 2025c; Tackie et al., 2023). Hybrid solar-diesel microgrids, battery storage in hot climates, IoT-enabled microgrid and storage integration, and portfolio optimization of solar, wind and storage assets are increasingly relevant to rig and camp power (Ijiga et al., 2023b; Ilesanmi et al., 2024; Komi and Ganiu, 2022; Shittu et al., 2025a), as are decentralized control architectures, edge intelligence for microgrid control and community-oriented solar microgrid co-optimization (Komi and Adamolekun, 2022; Komi and Adeniji, 2020; Komi and Ganiu, 2023). Solar integration and load distribution studies in developing economies, and blockchain-based peer-to-peer energy trading, indicate how drilling sites might share and balance power locally (Shittu et al., 2021; Sunday and Omoegun, 2018; Sunday and Omoegun, 2019). A second-law view of mud circulation therefore connects naturally to the energy management of the whole drilling facility.

3.6 Optimization Strategies

3.6.1 Problem formulation

The general optimization problem for a hybrid nanofluid mud can be stated as follows. Design variables include total loading φ, mixing ratio φ_1/φ_2, particle size and shape, surface functionalization, base mud type, flow rate and inlet temperature. The primary objective is to minimize S_{gen} or maximize η_{II}, possibly together with secondary objectives such as minimizing cost or maximizing heat removal. Constraints include:

$$\text{ECD} = \rho_{hnf} + \frac{\Delta P_a}{g\, h_{TVD}} \leq \rho_{frac} - \Delta\rho_{margin} \qquad (17)$$

- Pore pressure and wellbore stability: ECD and static density above the pore and collapse gradients.
- Hole cleaning: minimum annular velocity and low-shear yield stress requirements for cuttings transport.
- Filtration: API and HPHT filtrate volumes below specification.
- Stability: no significant sedimentation or agglomeration over the expected circulation and static periods at bottomhole conditions.
- Environmental and cost limits on particle type and concentration.

3.6.2 Methods

Whichever optimization strategy is adopted, an efficient and accurate solver for the governing nonlinear equations is required. Spectral quasilinearization methods, including overlapping-grid variants, have proved highly accurate for coupled momentum, energy and concentration equations of non-Newtonian and hybrid nanofluids (Agbaje et al., 2025; Panda et al., 2025a; Ratha et al., 2026; Folarin et al., 2026b), and the bivariate simple iteration method on overlapping grids has been applied to unsteady ternary hybrid nanofluid flows (Oluwaseun et al., 2025). Such solvers are attractive for generating the large numbers of evaluations required by optimization loops.

The computational toolkit for thermofluid design in other engineering sectors is also directly applicable. Advances in thermofluid simulation for heat-transfer optimization in compact devices, CFD-driven design of fluid-particle separation and cake filtration systems, and AI-based optimization of multiphysics fluid dynamics provide methods for resolving coupled heat transfer, particle transport and filtration in the wellbore and filter cake (Adewoyin et al., 2020b; Adewoyin et al., 2021; Adewoyin et al., 2024; Ogunnowo et al., 2023b). Simulation-based HVAC optimization using heat-flow analytics and thermodynamic efficiency analysis

of air-conditioning systems show how first-law and second-law metrics can be embedded in practical design loops (Ogunnowo et al., 2021a; Sunday et al., 2019). Topology optimization and reliability-centred design combining finite element analysis with design failure mode and effects analysis offer structured ways to co-optimize thermal performance and mechanical reliability of downhole hardware (Ogunnowo et al., 2023a; Ogunnowo et al., 2024c), and multi-algorithm treatment of loss and weight objective functions for induction motors illustrates multi-objective formulations of the kind needed to balance thermal gains against hydraulic penalties (Amayo and Popoola, 2017; Amayo et al., 2015; Amayo, 2017).

Table 4 compares the main optimization approaches that have been applied to nanofluid entropy problems and that are transferable to drilling muds.

Table 4. Optimization approaches for second-law design of hybrid nanofluid muds.

Approach	Description	Strengths	Limitations
Analytical entropy generation minimization (EGM)	Closed-form $S_{gen}(\varphi, Re, Br, ...)$ for idealized geometries; differentiate to find optimum (Bejan, 1996)	Physical insight; identifies scaling laws	Requires simplifying assumptions (fully developed flow, constant properties)
Parametric numerical studies	Solve coupled flow and energy equations (finite difference, finite volume, CFD) over a parameter grid	Handles real geometry, variable properties, non-Newtonian rheology	Computationally expensive; optimum only as good as grid resolution
Response surface methodology (RSM) and design of experiments	Fit polynomial surrogate to experimental or numerical results; locate optimum statistically	Efficient use of experiments; quantifies interactions	Limited accuracy for strongly nonlinear responses
Evolutionary multi-objective optimization (e.g. genetic algorithms, NSGA-II, particle swarm)	Search for Pareto front of S_{gen} versus heat removal, cost, ECD	Handles conflicting objectives and constraints	Many function evaluations; needs surrogate for CFD
Spectral quasilinearization and overlapping-grid solvers	High-order spectral discretization of the nonlinear boundary-value problems for velocity, temperature and entropy (Agbaje et al., 2025; Oluwaseun et	High accuracy with few grid points; fast parametric sweeps	Best suited to simplified geometries; complex wellbore domains need extension

Approach	Description	Strengths	Limitations
	al., 2025)		
Machine-learning surrogates (artificial neural networks, Gaussian processes, gradient boosting)	Learn property or performance maps from data; coupled to optimizers (Folarin et al., 2026a; Panda et al., 2026; Mondal et al., 2026)	Fast evaluation; can capture complex property behaviour	Requires large, high-quality HPHT data sets; poor extrapolation
Physics-informed and hybrid data-physics models	Embed conservation laws and entropy constraints in learned models	Better extrapolation; thermodynamic consistency	Emerging methods; limited validation in drilling

Artificial intelligence is increasingly used alongside physics-based nanofluid models. Artificial neural networks have been trained on numerical solutions to predict entropy generation, shear stress and heat transfer rates in non-Newtonian nanofluid flows (Folarin et al., 2026a; Panda et al., 2026), and AI-assisted spectral solvers have been reported for viscoelastic hybrid nanofluids (Folarin et al., 2026b). Mondal et al. (2026) review the wider influence of AI on advanced nanofluid models. Experience from other data-intensive fields reinforces the importance of well-designed data pipelines that link measurement, curation and prediction (Aladegba and Ayinde, 2024) and of rigorous validation practices for machine-learning predictors (Aladegba and Ayinde, 2026c). For drilling muds, these lessons point to the need for curated HPHT property databases before data-driven optimization can be trusted.

Digital twins and predictive maintenance provide the operational layer needed to apply second-law optimization in real time. AI-powered digital twins for renewable energy systems, smart substations, maritime electrical infrastructure, tiered twins for resource-constrained sites, and twins for real-time monitoring of mechanical systems and offshore static equipment demonstrate the architecture required to couple live sensor data with physics models (Komi and Adeniji, 2023; Obetta et al., 2026; Ogunnowo et al., 2024a; Shittu and Shittu, 2024; Shittu et al., 2023; Shittu et al., 2026). Predictive maintenance and condition monitoring in critical power infrastructure, vibration-based monitoring of rotating machinery, sensor-based fault detection, and the transition from reactive to predictive maintenance are directly applicable to mud pumps, centrifuges and heat exchangers (Adaramola et al., 2018; Omoegun et al., 2023; Sunday and Omoegun, 2022; Sunday et al., 2020; Yeboah et al., 2024). Related work on reliability-centred maintenance, lean predictive maintenance and Industry 4.0 reliability methods in high-technology manufacturing, maintenance metrics for

minimizing non-routine flaring from rotating machinery failure, and interpretable machine learning for early failure prediction broadens the available methods (Ekelemu et al., 2026; Komi and Adamolekun, 2021; Olodo et al., 2026b; Olodo et al., 2026c; Oyeleke et al., 2026). Reliability engineering and failure analysis in complex systems, lifecycle reliability assessment, AI-predictive maintenance on cloud analytics, lifecycle performance models and predictive forecasting for resource allocation support the data-driven decision layer (Adelanwa et al., 2023; Adelanwa et al., 2024; Gideon et al., 2019; Makut et al., 2024; Mayo et al., 2021; Unamma et al., 2018; Unamma et al., 2021), while advanced RF MEMS devices point toward improved wireless sensing and telemetry (Gideon, 2025b).

Trustworthy data-driven optimization also requires disciplined data and model governance. Human-in-the-loop decision systems, automated model governance, AI-assisted risk and incident analysis and context-aware data curation help ensure that surrogate models used for mud design remain reliable and auditable (Ashore-Onisemo et al., 2025; Nwakamma et al., 2024; Oyesiji et al., 2024; Unamma et al., 2025). Machine-learning approaches to data wrangling and curation, leakage-proof benchmarking protocols and predictive validation pipelines provide transferable practices for building HPHT property databases (Ajala et al., 2026; Ndupu et al., 2026b; Nwakamma et al., 2026), while continuous-integration and hardware-in-the-loop validation of embedded systems, on-device model compression and privacy-preserving edge intelligence are relevant to deploying models on rig-site and downhole hardware (Ndupu et al., 2026a; Nwakamma et al., 2025; Oyesiji et al., 2025; Oyesiji et al., 2026). As drilling control systems become more automated, the security of operational technology also matters: physics-informed detection and digital twins for cyber-physical ransomware defence, threat modelling of AI-enabled OT, and machine-learning detection of anomalies in SCADA and industrial control networks are prerequisites for safely closing the loop between models and rig equipment (Adebayo et al., 2022; Adebayo et al., 2023; Adegbite et al., 2023; Amadi et al., 2025a; Amadi et al., 2025b; Ojukwu et al., 2023).

3.7 Synthesis of Experimental and Numerical Evidence

Table 5 summarizes representative studies that underpin the current understanding. They fall into three groups: nano-enhanced drilling fluid experiments, hybrid nanofluid property studies, and theoretical and review work on entropy generation and wellbore heat transfer.

Table 5. Representative studies relevant to second-law design of hybrid nanofluid drilling muds.

Study	Focus	Principal relevance to this review
Raymond (1969); Holmes and Swift (1970); Kabir et al. (1996)	Circulating mud temperature models	Provide the wellbore energy balance framework into which nanofluid properties and entropy terms can be inserted
Ramey (1962)	Transient wellbore heat transmission	Formation time function for transient heat exchange between mud and rock
Bejan (1979, 1982, 1996)	Entropy generation in convective heat transfer; EGM	Theoretical foundation for local and integrated entropy generation and the thermal-friction trade-off
Mahian et al. (2013, 2019)	Reviews of entropy generation and modelling in nanofluid flows	Establish the existence of optimal loadings and the influence of property models on second-law predictions
Suresh et al. (2011); Takabi and Salehi (2014)	Hybrid nanofluid preparation and property modelling	Experimental property data for Al_2O_3-Cu and widely used hybrid conductivity model
Sarkar et al. (2015); Babu et al. (2017); Huminic and Huminic (2018)	Reviews of hybrid nanofluids	Summarize synergy, stability challenges and viscosity penalties
Abdo and Haneef (2012); Amanullah and Al-Tahini (2009)	Early nano-enhanced drilling fluids	Demonstrate potential of nanomaterials for difficult drilling conditions
William et al. (2014)	CuO and ZnO in xanthan gum water-based mud	Improved thermal conductivity and high-pressure rheology; direct thermal evidence for nano-muds
Ismail et al. (2016)	MWCNT and nanosilica in water-based mud	Rheology and lubricity improvements with carbon and oxide nanomaterials, the building blocks of hybrids
Smith et al. (2018)	Al_2O_3 nanoparticles at HPHT	Rheology and filtration benefits retained under HPHT test conditions
Mao et al. (2015)	Polymer-silica core-shell filtrate reducer	Composite nanostructures for ultra-high temperature fluid loss control
Minakov et al. (2018)	Nanoparticle effects on pressure loss and cuttings transport	Quantifies the hydraulic side of the trade-off in borehole geometry
Oluwaseun et al. (2023); Folarin et al. (2026a)	Entropy generation in MHD nanofluid and Carreau fluid flows	Second-law analysis with slip, viscous dissipation, porous media and ANN prediction

Study	Focus	Principal relevance to this review
Panda et al. (2025a, 2025b); Oluwaseun and Agbaje (2025); Oluwaseun et al. (2025)	Hybrid and ternary hybrid nanofluid modelling	Hall current, slip, magnetic dipole and Buongiorno two-phase effects on hybrid nanofluid heat transfer
Folarin et al. (2026b); Panda et al. (2026); Mondal et al. (2026)	AI-assisted nanofluid modelling	Neural-network and AI-assisted prediction of heat transfer and shear stress in non-Newtonian nanofluids
Vryzas and Kelessidis (2017); Aftab et al. (2017)	Reviews of nano-based drilling fluids	Comprehensive overview of formulation and performance; note scarcity of thermal and second-law studies

Several consistent conclusions emerge. First, nanoparticles at low loading reliably improve conductivity, rheological stability and filtration of drilling muds, and hybrid formulations can enhance these benefits. Second, the rise in viscosity and yield stress is significant and, in second-law terms, frequently decisive. Third, theoretical studies of nanofluid flows show that total entropy generation can be reduced only within a bounded window of loadings and operating conditions. Fourth, and most importantly, very few studies have combined measured HPHT properties of a real hybrid nanofluid mud with a coupled wellbore thermal-hydraulic model and a full entropy analysis. Most second-law studies use idealized Newtonian or power-law fluids, constant properties and simplified geometries, while most drilling studies report rheology and filtration without any thermodynamic analysis.

3.7.1 Influence of key parameters

- **Total loading.** Entropy generation typically shows a minimum at low volume fractions, often in the range of a few tenths of a percent to a few percent in theoretical studies; the optimum is narrower for high aspect ratio particles that raise viscosity sharply.
- **Mixing ratio.** A small fraction of a high-conductivity phase combined with a lower-viscosity oxide phase often yields a better second-law outcome than either mono nanofluid at the same total loading.
- **Flow rate.** Higher circulation rates lower thermal irreversibility per unit heat removed but raise friction steeply; there is an optimal Reynolds number for a given heat duty.
- **Temperature.** Higher temperature reduces mud viscosity and, for many nanofluids, increases relative conductivity enhancement, both of which favour higher optimal loadings at depth than at the surface.

- **Pressure.** Pressure increases viscosity and density; its effect on nanofluid conductivity is poorly characterized, which is a major source of uncertainty in HPHT predictions.
- **Rheological model.** Yield stress introduces plug regions with no frictional entropy generation, and the flow behaviour index governs the distribution of shear; Newtonian approximations can misplace the optimum substantially.
- **Magnetic fields.** For Fe_3O_4-based hybrids, Lorentz forces can tune velocity profiles and heat transfer but add Joule irreversibility; such concepts remain largely theoretical for drilling.

3.8 Conceptual Model

3.8.1 Overview

The literature synthesis shows that the thermal benefit of hybrid nanoparticles cannot be judged in isolation from their hydraulic, stability, safety, environmental and economic consequences. To integrate these strands, this review proposes a six-layer conceptual model for the second-law design of hybrid nanofluid-based drilling muds in HPHT wells (Figure 2). The model translates the physical relationships reviewed in Sections 3.3 to 3.6 into a structured decision pathway, and it embeds the deployment considerations drawn from themes T4 to T9 as moderating factors and as a feedback loop.

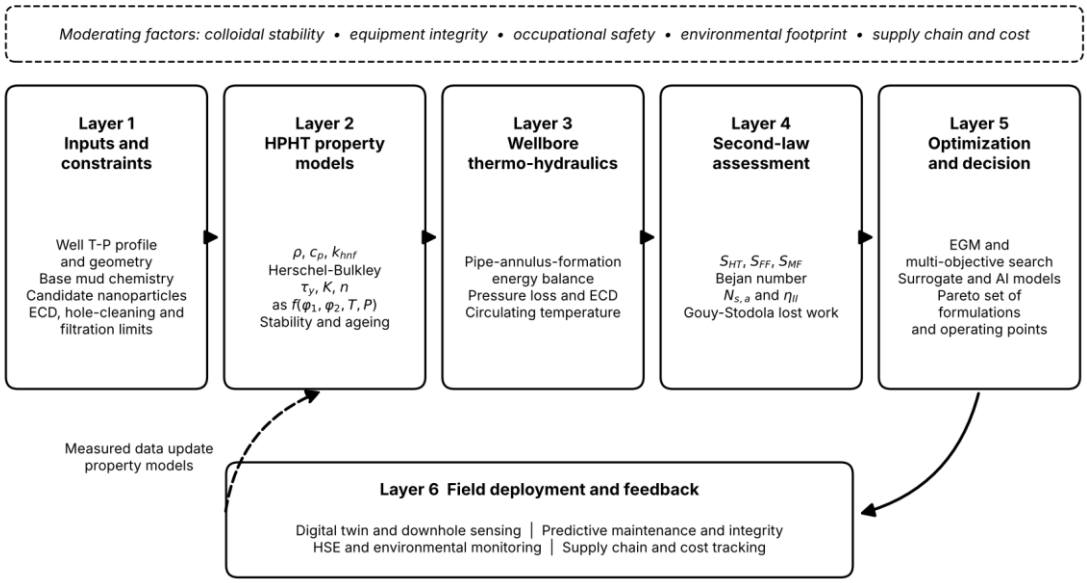


Figure 2. Proposed six-layer conceptual model for second-law design of hybrid nanofluid-based drilling muds under HPHT conditions. Solid arrows show the design pathway; the dashed arrow shows feedback of field data into property models; the dashed frame lists moderating factors.

3.8.2 Model layers

Table 6 summarizes the content of each layer and the literature on which it draws.

Table 6. Layers of the conceptual model, their content and supporting literature.

Layer	Content	Principal supporting literature
1. Inputs and constraints	Well temperature and pressure profile, geometry, base mud chemistry, candidate nanoparticles and mixing ratios; ECD window, hole-cleaning, filtration and stability requirements	Bourgoyne et al. (1986); Caenn et al. (2011); Kårstad and Aadnøy (1998); Vryzas and Kelessidis (2017)
2. HPHT property models	ρ_{hnf}, $(\rho c_p)_{hnf}$, k_{hnf} and Herschel-Bulkley parameters as functions of φ_1, φ_2, T and P; stability and ageing effects	Hamilton and Crosser (1962); Takabi and Salehi (2014); Suresh et al. (2011); William et al. (2014); Smith et al. (2018)
3. Wellbore thermo-hydraulics	Coupled pipe-annulus-formation energy balance, pressure losses, circulating temperature and ECD along the well	Raymond (1969); Holmes and Swift (1970); Ramey (1962); Kabir et al. (1996); Minakov et al. (2018)
4. Second-law assessment	Local and integrated entropy generation (S_{HT}, S_{FF}, S_{MF}), Bejan number, $N_{s,a}$, η_{II} and Gouy-Stodola lost work	Bejan (1979, 1982, 1996); Mahian et al. (2013, 2019); Oluwaseun et al. (2023); Folarin et al. (2026a)
5. Optimization and decision	Entropy generation minimization, constrained multi-objective search, spectral and CFD solvers, AI surrogates; Pareto set of formulations and operating points	Agbaje et al. (2025); Oluwaseun et al. (2025); Mondal et al. (2026); Panda et al. (2026)
6. Field deployment and feedback	Digital twins, downhole sensing, predictive maintenance, integrity, HSE and environmental monitoring, supply chain and cost tracking; measured data update Layer 2	Shittu and Shittu (2024); Obetta et al. (2026); Obriki and Arumosoye (2023); Falegan and Aniebonam (2026)

The moderating factors at the top of Figure 2 act on every layer. Colloidal stability determines whether laboratory property values persist downhole; equipment integrity constrains particle hardness and loading; occupational safety governs powder handling and mixing; environmental considerations shape particle choice and waste management; and supply chain and cost determine whether an optimized formulation can be sourced at field scale.

3.8.3 Research propositions

The model gives rise to the following propositions, which are intended to be tested in future experimental, numerical and field studies:

- **P1.** For a given well and operating point, total entropy generation in mud circulation exhibits a minimum at an interior total nanoparticle loading φ_{opt} whenever heat-transfer irreversibility dominates in the unloaded base mud (Be > 0.5).
- **P2.** At equal total loading, an appropriately chosen hybrid mixing ratio yields lower total entropy generation than either constituent mono nanofluid, because conductivity gains and viscosity penalties scale differently with each particle type.
- **P3.** The optimal loading φ_{opt} increases with depth and temperature and decreases with flow rate and annular confinement, so system-level optima differ systematically from optima computed at surface or bottomhole conditions alone.
- **P4.** Second-law optima obtained with Newtonian or power-law approximations differ materially from those obtained with yield-stress (Herschel-Bulkley) rheology, because plug regions suppress frictional irreversibility.
- **P5.** Formulations selected on second-law grounds will deliver their predicted benefit in the field only when colloidal stability, equipment integrity and HSE constraints are satisfied; these moderating factors can eliminate otherwise optimal designs.
- **P6.** Closing the loop between field measurements and property models through digital twins and data-driven surrogates progressively reduces the gap between predicted and realized thermal efficiency.

3.8.4 Operational workflow

The conceptual model can be operationalized through the following six-step workflow for HPHT mud design:

- **Step 1. HPHT property characterization.** Measure density, thermal conductivity, specific heat and Herschel-Bulkley parameters of candidate hybrid muds over the expected temperature and pressure range, including aged samples.
- **Step 2. Property model fitting.** Fit temperature-, pressure- and loading-dependent correlations, with uncertainty bounds; prefer physically constrained forms.
- **Step 3. Coupled wellbore model.** Solve the pipe-annulus-formation heat transfer and hydraulics problem along the well, and compute local and integrated entropy generation, Be and ECD.

- **Step 4. Surrogate construction.** Build a reduced-order or machine-learning surrogate of the wellbore model for rapid evaluation.
- **Step 5. Constrained multi-objective optimization.** Generate the Pareto set between S_{gen} (or η_{II}), bottomhole temperature reduction and cost, subject to ECD, hole-cleaning and filtration constraints.
- **Step 6. Validation.** Verify optimized formulations in flow loop tests and, where possible, against downhole temperature and pressure data.

3.9 Discussion of Principal Findings

The review set out to answer four research questions. With respect to RQ1, the synthesis shows that HPHT conditions and hybrid nanoparticles act on mud properties in coupled and sometimes opposing ways. Temperature lowers consistency but can raise or lower yield stress; pressure raises viscosity and density; and nanoparticles at low loading generally increase thermal conductivity, yield stress and plastic viscosity while improving filtration and thermal stability. The net thermal-hydraulic effect therefore depends on where along the well, and at what operating point, the mud is evaluated.

With respect to RQ2, the Bejan formulation of local entropy generation, extended to Herschel-Bulkley rheology and coupled to wellbore energy balances, provides a consistent basis for comparing formulations. Its distinctive feature in drilling applications is the role of yield stress, which creates plug regions free of frictional irreversibility. With respect to RQ3, combined metrics such as the augmentation entropy generation number and second-law efficiency are better suited to mud design than first-law indicators alone, and constrained multi-objective optimization supported by fast solvers and surrogate models is the most promising route to practical design. With respect to RQ4, the review finds that deployment is conditioned as much by stability, integrity, safety, environmental and supply chain factors as by thermodynamic performance, which motivates the moderating layer of the conceptual model.

Two broader observations follow. First, the literatures on nano-enhanced drilling fluids and on nanofluid entropy generation have developed largely in parallel: drilling studies seldom report thermodynamic analysis, while entropy studies seldom use realistic mud rheology, geometry or HPHT properties. Second, most hybrid nanofluid entropy studies are theoretical, so the existence of an optimal loading is well supported in principle but has rarely been verified for real muds. These observations frame the gaps below.

3.10 Knowledge Gaps in the Literature

- **HPHT property data.** Measurements of thermal conductivity, heat capacity and rheology for hybrid nanofluid muds above about 200 °C and 100 MPa are scarce. Existing property correlations are largely derived at ambient pressure.
- **Long-term stability.** Few studies assess colloidal stability under prolonged exposure to HPHT, high salinity, contaminants such as CO_2 and H_2S, and cyclic shear in the circulating system.
- **Coupled system-level analysis.** Entropy generation analyses rarely consider the full circulating system, including surface equipment, drill pipe, bit nozzles, annulus and formation heat exchange, together with transient operations.
- **Validation.** Second-law predictions for drilling muds have not been systematically validated against flow loop measurements or downhole temperature and pressure data.
- **Interaction with weighting agents and solids.** The influence of barite, drilled solids and clays on nanoparticle dispersion and effective properties is poorly understood.
- **Oil-based and synthetic muds.** Most nano-mud studies use water-based fluids, whereas HPHT wells frequently use oil-based or synthetic-based muds; hybrid nanofluid behaviour in invert emulsions is underexplored.
- **Health, safety and environment.** Toxicity, disposal, cuttings contamination and occupational exposure to nanoparticles are rarely integrated into design optimization. Studies of persistent contaminants at waste-handling and recycling sites show how pollutants accumulate in soils and translate into measurable human health risk (Aladegba and Ayinde, 2026b, 2026d), and oxidative stress and DNA damage are recognized pathways linking pollutant exposure to harm (Aladegba and Ayinde, 2026a). Similar exposure and risk-assessment frameworks are needed for nano-enhanced drilling waste.
- **Economics and scale-up.** The cost of nanomaterials, their recovery through solids control equipment and the logistics of large-volume preparation are seldom quantified.
- **Standardization.** There is no standard test protocol for thermal properties of drilling muds at HPHT, which hinders comparison between studies.

3.11 Considerations for Field Deployment

Beyond the thermal-hydraulic trade-off, four groups of practical considerations condition whether second-law optimized hybrid nanofluid muds can be adopted in the field.

3.11.1 Equipment integrity, erosion and corrosion

Nanoparticle-laden muds also raise questions of erosion, corrosion and equipment integrity. Hard oxide particles can accelerate abrasive wear of pumps, valves, nozzles and tubulars,

while changes in fluid chemistry can alter corrosion behaviour. Green corrosion inhibitors, AI-augmented corrosion modelling, corrosion prediction from non-destructive testing data, and studies of long-term environmental degradation of materials provide relevant methods (Adewoyin et al., 2023; Atta et al., 2018; Atta et al., 2025; Ogunnowo et al., 2024d). Non-destructive testing for weld integrity, NDT-based integrity management of refinery equipment, welding inspection standards and NDT for predictive and preventive failure analysis support the inspection of surface mud-handling equipment (Atta et al., 2020; Atta et al., 2021; Atta et al., 2022; Ogunnowo et al., 2020; Ogunnowo et al., 2024b). Risk-based inspection and fitness-for-service of ageing pressure vessels, integrity management of fired heaters and boilers, reliability-centred and CMMS-based maintenance of static equipment, cause-tree failure analysis, IoT-enabled condition monitoring, non-intrusive inspection and spare-parts standardization from the offshore sector offer mature frameworks that could be extended to HPHT mud systems (Obetta et al., 2021; Obetta et al., 2023; Obetta et al., 2024; Obetta et al., 2025a; Obetta, 2018; Obetta, 2019; Obetta, 2020; Olisakwe et al., 2026). Integrity assurance of turret moorings, buoy bearings and offloading hoses, corrosion management for marine export equipment and optimization of offloading operations further illustrate condition-based approaches for equipment exposed to aggressive fluids (Obetta and Ninduwezuor-Ehiobu, 2018; Obetta and Ninduwezuor-Ehiobu, 2019; Obetta et al., 2020; Obetta et al., 2022; Obetta et al., 2025b).

3.11.2 Environmental management and emissions

The environmental footprint of drilling fluids extends from mud formulation to waste handling. Produced water risk assessment, treatment, decentralized systems, beneficial reuse and data-driven optimization of treatment infrastructure offer models for managing nanoparticle-bearing aqueous waste streams (Falegan and Aniebonam, 2022; Falegan and Aniebonam, 2023; Falegan and Aniebonam, 2024; Falegan and Aniebonam, 2025; Falegan and Aniebonam, 2026). Flare-gas recovery, methane emission reduction, conversion of flared gas into products, decarbonization of liquefaction facilities, gas gathering and vapour recovery, flare loss detection and transition management across operating cycles show how energy efficiency and emissions control are pursued across oil and gas operations (Amarahobu et al., 2025b; Asibor and Isong, 2020; Asibor and Olisakwe, 2022; Asibor et al., 2026; Ekelemu and Adikwu, 2026b; Ekelemu and Akano, 2025b; Makut and Olisakwe, 2022), and CO_2 utilization in mature oil fields and direct air capture represent complementary carbon-management pathways (Ijiga et al., 2023a; Liadi et al., 2024). Data integration for greenhouse gas inventories, carbon accounting, predictive frameworks for subsurface

contamination pathways, vapour intrusion and spatially explicit contaminant migration, and remote-sensing early warning provide tools for tracking the environmental fate of drilling discharges (Azeez and Badmus, 2018; Azeez and Badmus, 2024a; Azeez and Badmus, 2024b; Badmus, 2025; Lamidi and Olamide, 2018; Lamidi, 2023), and UAV-based pipeline and corridor monitoring extends this surveillance to field infrastructure (Dagodzo and Ahiaeke Patrick, 2020). Evidence on environmental pollution and community health in resource-extraction regions underlines the stakes (Osinem et al., 2025). Waste-handling discipline, sustainable environmental practices within safety management systems, environmental compliance frameworks, predictive safety analytics with ESG implications, digital-twin environmental compliance in oil, gas and utilities, automated ESG reporting and ESG-integrated procurement indicate how nano-mud programmes can be governed responsibly (Abioye et al., 2023; Arumosoye et al., 2025; Arumosoye et al., 2026; Ike et al., 2025; Obogo et al., 2024a; Obogo et al., 2024b; Okojie et al., 2020).

3.11.3 Occupational safety, human factors and contractor governance

Introducing nano-enhanced fluids also changes the occupational hazard profile at the rig site, through powder handling, mixing and exposure during mud conditioning. Mature literature on safety management offers relevant guidance. Critical reviews of occupational safety management systems in oil and gas maintenance, internal QHSE audit systems and data-driven safety risk control in energy infrastructure projects define the management context (Obogo et al., 2020a; Obogo et al., 2020c; Obriki and Arumosoye, 2018). Hazard identification and near-miss reporting, continuous hazard monitoring, digital safety data streams and predictive safety analytics support earlier detection of unsafe conditions (Arumosoye and Obriki, 2019; Obogo et al., 2019c; Obogo et al., 2021a; Obogo et al., 2025a; Obogo et al., 2026; Obriki and Arumosoye, 2023; Obriki et al., 2023a). Studies of human error causation, recurrence of unsafe behaviours, behavioural safety programmes and workforce training address the human dimension of handling novel materials (Obriki and Arumosoye, 2020; Obriki and Arumosoye, 2022; Obriki et al., 2022a; Obriki et al., 2023b), and safety theory developed for semiconductor manufacturing, where nanoscale materials are routinely handled, offers a close analogue (Ogunnowo et al., 2025).

Safety governance across contractors and project organizations is equally relevant because mud services are typically provided by specialist contractors. Contractor and subcontractor safety performance, safety governance for multi-contractor projects, compliance systems and integrated safety management models address these interfaces (Arumosoye and Obriki, 2020; Obogo et al., 2019b; Obogo et al., 2021c; Obogo et al., 2022; Obogo et al., 2025b; Obriki and

Arumosoye, 2024a), while safety leadership, leadership-driven culture change, management walkthroughs and organizational learning maturity models shape the culture in which new practices are adopted (Arumosoye and Obriki, 2021; Arumosoye and Obriki, 2024; Obogo et al., 2019a; Obogo et al., 2023; Obriki and Arumosoye, 2019). Incident prevention in maintenance environments, incident investigation and learning, institutionalization of life-preserving practices, leading safety signals, emergency preparedness and risk pathways for lifting, rigging and crane operations complete the picture of rig-site risk management (Arumosoye and Obriki, 2022; Obogo et al., 2020b; Obogo et al., 2021b; Obriki and Arumosoye, 2021; Obriki and Arumosoye, 2024b; Obriki et al., 2022b; Obriki et al., 2025). Process-industry research on control-room alarm management, logbook handover standardization, proactive panel operations, permit-to-work and isolation control, decision-making in process upsets, the shift supervisor as a human barrier, gas testing for hot work, mentorship of technicians and cross-departmental alignment during expansion projects offers transferable lessons for drilling crews managing complex fluid systems (Amarahobu et al., 2025a; Ekelemu and Adikwu, 2026a; Ekelemu and Akano, 2025a; Ekelemu et al., 2025a; Ekelemu et al., 2025b; Ekelemu et al., 2025c; Ekelemu, 2025a; Ekelemu, 2025b; Ekelemu, 2025c).

3.11.4 Supply chain, economics and project delivery

Economic viability depends on supply chains and project delivery as well as on technical performance. Strategic procurement optimization in oil and gas, inventory availability and uptime, contract negotiation and vendor governance, supply chain risk management for EPC and gas processing projects, and strategic sourcing for fuel and equipment supply describe how specialty additives are acquired and managed (Agbabiaka et al., 2019; Asibor et al., 2019; Okonkwo et al., 2018a; Okonkwo et al., 2018b; Okonkwo et al., 2019). Dual sourcing under price volatility, procurement resilience during disruptions, resilience frameworks for critical infrastructure, regulatory-compliant procurement in high-risk environments, materials readiness and asset lifecycle and inventory visibility address the continuity risks that a new nanomaterial supply would introduce (Asibor et al., 2021; Babayemi et al., 2020; Ogunwole et al., 2021; Okonkwo et al., 2021a; Okonkwo et al., 2021b; Okonkwo et al., 2023a). Digital supply chain governance, secure supply chain systems, predictive procurement planning, ERP adoption, cost control models, IT-integrated national supply chain optimization and systems-engineering integration of IT with supply chain operations provide the digital backbone (Okonkwo et al., 2023b; Okonkwo et al., 2024a; Okonkwo et al., 2024b; Okonkwo et al., 2024c; Okonkwo et al., 2024d; Okonkwo et al., 2024e; Okonkwo et al., 2025), and

supply chain lessons from nanomaterials in healthcare and semiconductor risk mitigation are informative for sourcing engineered nanoparticles (Gideon, 2025a; Ike et al., 2024). At project level, capital budgeting for field development, technical due diligence in energy M&A, longitudinal subsurface data trends and multimodal reservoir forecasting determine whether improved drilling performance translates into asset value (Nwangwu et al., 2020; Nwangwu et al., 2021; Nwangwu et al., 2022; Nwangwu et al., 2023). Project governance in multinational infrastructure, solar deployment management in emerging markets, sustainability-linked contracting, critical path and resource optimization, predictive schedule-risk methods and change-programme evaluation offer frameworks for managing the field trials needed to qualify new fluid systems (Abdulhadi and Hamdan, 2026; Amayo et al., 2023; Amayo et al., 2024a; Amayo et al., 2024b; Amayo et al., 2025; Makut et al., 2021b; Obukadata et al., 2022; Zhou et al., 2024; Zhou et al., 2025).

3.12 Implications

3.12.1 Theoretical and research implications

The review implies that second-law analysis should become a standard companion to rheology and filtration testing in nano-enhanced drilling fluid research. Entropy generation studies of hybrid nanofluids should adopt yield-stress rheology, temperature- and pressure-dependent properties and wellbore geometries if their results are to be transferable to drilling. The six propositions in Section 3.8.3 provide testable hypotheses that can organize experimental programmes and modelling studies, and the conceptual model offers a common framework for comparing results across studies.

3.12.2 Practical implications for drilling and mud engineers

For practitioners, the main implication is that more nanoparticles are not necessarily better. Mud engineers should evaluate candidate hybrid formulations at representative HPHT conditions and operating points, track ECD and pump pressure alongside thermal performance, and treat the optimal loading as a function of depth, flow rate and well geometry rather than a fixed recipe. Second-law metrics can be embedded in hydraulics software and real-time drilling advisory systems, so that flow rate and mud properties are adjusted to minimize destroyed work while maintaining hole cleaning and well control. Digital twins and condition monitoring of pumps and solids-control equipment can verify that predicted benefits are realized and that abrasive or corrosive effects remain acceptable.

3.12.3 Implications for HSE, environmental governance and policy

The introduction of engineered nanoparticles into drilling operations has occupational and environmental consequences that current mud qualification practices do not fully address. Operators and service companies should extend hazard identification, exposure control and waste-handling procedures to nanomaterials, and regulators should consider guidance on discharge, cuttings disposal and monitoring of nanoparticle-bearing waste. Policy makers interested in energy efficiency and emissions reduction can view second-law optimization of drilling fluids as one of many incremental measures that reduce fuel use and emissions in upstream operations, particularly in geothermal and deep hydrocarbon drilling.

3.12.4 Economic and managerial implications

Managers should weigh the cost of nanomaterials, preparation and recovery against savings in pumping energy, tool life, non-productive time and wellbore problems. Because supply of specialty nanomaterials may be concentrated among few suppliers, procurement resilience and qualification of alternative sources are important. Field trials should be managed as structured programmes with clear performance indicators, including second-law metrics, so that investment decisions rest on measured rather than assumed benefits.

3.13 Limitations of the Review

Several limitations of this review should be acknowledged.

- **Review design.** The study is an integrative narrative review rather than a systematic review or meta-analysis. Although structured criteria guided inclusion and synthesis, selection bias cannot be excluded, and no pooled quantitative estimates of effect sizes are reported.
- **Scope of the corpus.** The corpus is limited to English-language sources published up to 2026. Relevant industry reports, proprietary field data and non-English literature may have been missed.
- **Nature of the evidence.** Much of the second-law evidence comes from theoretical and numerical studies of idealized geometries and Newtonian or simplified non-Newtonian fluids. Conclusions about optimal loadings in real HPHT muds are therefore indicative and require experimental and field confirmation.
- **Semi-related literature.** Cross-disciplinary sources on safety, asset integrity, energy systems, digital technologies, environmental management and supply chains were included for their transferable methods and deployment context. Their findings were not generated for drilling fluids and are used as analogies and frameworks rather than as direct evidence.

- **Conceptual model and figures.** The conceptual model and the research propositions are derived from the synthesis and have not yet been empirically validated. Figure 1 is a conceptual illustration and is not drawn from a specific data set.
- **Rapidly evolving field.** Hybrid nanofluid and AI-assisted modelling research is growing quickly, so some recent developments may not be captured.

3.14 Future Research Directions

The following priorities would advance the field toward practical, thermodynamically optimized HPHT drilling fluids:

- Develop HPHT-capable apparatus and standard protocols for measuring thermal conductivity and specific heat of muds under combined temperature and pressure, and create open databases of hybrid mud properties.
- Formulate physically consistent property models that include temperature, pressure, particle interactions with clays and polymers, and agglomeration kinetics, with quantified uncertainty.
- Couple entropy generation analysis with full transient wellbore thermal-hydraulic simulators that include eccentric annuli, pipe rotation, cuttings beds and bit nozzles.
- Use entropy generation minimization and multi-objective optimization jointly with drilling constraints, producing Pareto sets that engineers can apply in mud programme design.
- Exploit physics-informed machine learning and AI-assisted spectral solvers (Mondal et al., 2026; Folarin et al., 2026b) to extrapolate limited HPHT data while respecting conservation laws and the second law.
- Explore functionalized and core-shell hybrid nanostructures, and ternary hybrid formulations (Oluwaseun et al., 2025), designed specifically for high-temperature stability in saline and oil-based systems.
- Investigate stimuli-responsive hybrids, including magnetic and thermally responsive particles, that allow real-time tuning of rheology and heat transfer.
- Extend the framework to geothermal drilling, where very high temperatures and long circulation periods make thermal efficiency especially valuable.
- Integrate life-cycle assessment and techno-economic analysis so that second-law gains are weighed against environmental and financial costs, and adapt AI-enabled exposure monitoring and early-warning concepts from environmental health (Aladegba et al., 2021, 2025) to the handling and disposal of nanoparticle-laden muds and cuttings.

4. CONCLUSION

This review has examined the entropy generation and thermal efficiency optimization of hybrid nanofluid-based drilling muds for HPHT wellbores. The principal conclusions are as follows.

- HPHT drilling makes the circulating mud the main thermal management system of the well, and its thermal and hydraulic performance are tightly coupled through temperature- and pressure-dependent properties.
- Hybrid nanofluids offer a credible route to muds with higher thermal conductivity, improved rheological and filtration performance, and enhanced thermal stability, often at lower total loading than mono nanofluids.
- Because nanoparticles also increase viscosity and yield stress, first-law improvements alone are an unreliable design criterion. Entropy generation analysis provides a unified measure that captures both heat transfer and frictional penalties.
- A consistent framework for drilling applications combines the Bejan local entropy generation formulation with Herschel-Bulkley rheology, hybrid nanofluid property models and wellbore energy balances, and is interpreted through the Bejan number, augmentation entropy generation number and second-law efficiency.
- An optimal total loading and mixing ratio generally exist, but their values depend on flow rate, temperature, pressure, geometry and rheological model, so optimization must be performed at system level and under drilling constraints such as ECD, hole cleaning and filtration.
- Progress now depends on reliable HPHT property data, long-term stability studies, coupled and validated wellbore models, and multi-objective, data-informed optimization that includes environmental and economic factors.

Addressing these needs would allow the drilling industry to design hybrid nanofluid muds not only for what they can do in the laboratory, but for how efficiently they convert pumping energy into useful cooling, wellbore control and drilling performance in the most demanding wells.

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