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Non-Newtonian Drilling Fluid Flow and Heat Transfer in Horizontal and Inclined Wellbores: A Review of Mathematical Models, Numerical Methods, and Engineering Applications

Henry Chukwuemeka Olisakwe [1]*, Oghenekaro Ekelemu [2], Obinna Joshua Ochulor [3], Oludayo Olatoye Sofoluwe [4], Joshua Maduegbulam Umejuru [5]

[1] Department of Mechanical Engineering, Nnamdi Azikiwe University, Awka, Anambra State, Nigeria
[2] Nigeria LNG Limited, Bonny Island, Rivers State, Nigeria
[3] H-PTP Energy Services Ltd, Nigeria
[4] TotalEnergies EP Headquarters, Paris, France
[5] TotalEnergies EP Nigeria Limited, Port Harcourt, Nigeria

* Corresponding Author: **Henry Chukwuemeka Olisakwe**

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Abstract

Horizontal and highly inclined wells dominate modern oil, gas and geothermal development, yet they remain among the most difficult to drill. Their drilling fluids are shear-thinning and viscoplastic, flow through eccentric annuli around a rotating drillstring, carry cuttings that settle into beds on the low side of the hole, and exchange heat with the drillstring and formation while their rheology changes with temperature and pressure. These coupled processes govern equivalent circulating density (ECD), hole cleaning, tool life and wellbore stability. This paper presents an integrative review of the mathematical models, numerical methods and engineering applications for non-Newtonian drilling fluid flow and heat transfer in horizontal and inclined wellbores. Using a structured search of petroleum engineering, fluid mechanics and heat transfer databases, extended by citation tracking into adjacent fields, a corpus of 273 sources published from the earliest records to date was assembled and synthesised thematically. The synthesis covers rheological constitutive models, eccentric and rotating annular flow, mechanistic cuttings transport, transient wellbore heat transfer, and numerical approaches ranging from one-dimensional simulators to CFD, CFD-DEM, spectral methods and machine learning, together with applications in hydraulics design, managed pressure drilling, HPHT and geothermal drilling, equipment integrity, process safety, environmental management and supply chain delivery. From this synthesis an integrated conceptual model is proposed that links four coupled physics modules (rheology, hydraulics, cuttings transport and heat transfer) to tiered solution methods, predicted well states, operational decision layers and digital twin feedback. The discussion identifies points of consensus and contradiction, notably the effect of drillstring rotation in eccentric annuli and the sensitivity of predictions to yield-stress regularisation. Implications for researchers, drilling engineers, operators and regulators are outlined, the limitations of the review are stated, and a research agenda is proposed centred on fully coupled thermo-hydraulic-cuttings models, thixotropy, drillstring dynamics, open benchmark data sets and physics-informed surrogates.

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1. Introduction

The shift from vertical wells to directional, horizontal and extended-reach wells has transformed hydrocarbon recovery, unlocked unconventional shale plays, and made deep geothermal and carbon storage projects technically possible. A horizontal lateral can expose thousands of metres of reservoir to the wellbore, but drilling it places severe demands on the circulating fluid. In a vertical well, the drilling fluid moves upward through a roughly concentric annulus, gravity acts along the flow direction, and cuttings that are not lifted simply fall back toward the bit. In an inclined or horizontal well the picture changes fundamentally: gravity

acts across the flow, the drillstring lies on the low side of the hole creating a strongly eccentric annulus, and cuttings settle a short radial distance to form a bed that can grow until it causes high torque and drag, packing off, stuck pipe or lost circulation (Tomren *et al*., 1986; Sifferman and Becker, 1992) [258, 266].

Drilling fluids are designed to be non-Newtonian. Polymer-based water muds, bentonite suspensions, oil-based and synthetic-based muds all exhibit shear-thinning behaviour, many show a yield stress, and most are thixotropic to some degree. These properties are deliberate: low viscosity at the high shear rates found in the drillstring and bit nozzles reduces pump pressure, while high viscosity and a yield stress at the low shear rates of the annulus help suspend cuttings when circulation stops. The same properties, however, make the flow field difficult to predict. Velocity profiles in an eccentric annulus with a yield-stress fluid contain plug regions and nearly stagnant zones in the narrow gap, which is exactly where cuttings accumulate (Haciislamoglu and Langlinais, 1990; Escudier *et al*., 2002) [103, 116].

Heat transfer adds a further layer of coupling. As the fluid circulates it cools the bottom of the hole and heats the upper section, while viscous dissipation and bit friction add heat. Rheological parameters of both water-based and oil-based muds vary strongly with temperature and pressure (Alderman *et al*., 1988; Rommetveit and Bjørkevoll, 1997) [30, 252], so the annular temperature profile directly influences pressure losses, ECD and cuttings transport. In HPHT and geothermal wells, accurate prediction of circulating temperature is also required for selecting fluid additives, cement slurries, elastomers and downhole electronics (Kabir *et al*., 1996) [123].

Drilling performance also sits within a wider context of upstream asset development and operational integrity. Field development planning, capital budgeting, mature-asset evaluation and reservoir forecasting determine the well trajectories and lateral lengths that drilling fluids must serve (Nwangwu *et al*., 2021; Nwangwu *et al*., 2023; Nwangwu *et al*., 2022; Nwangwu *et al*., 2020) [155, 156, 157, 159], while operational integrity frameworks for high-risk drilling stress that hydraulic and thermal margins must be balanced against productivity and safety compliance (Nwangwu *et al*., 2018) [158]. Offshore and deepwater developments, where narrow pressure windows and long step-outs are common, add constraints from front-end engineering design, floating production facilities and deepwater equipment reliability (Makut *et al*., 2021c; Makut *et al*., 2021a; Makut *et al*., 2022a) [140, 141, 142], and enhanced recovery schemes such as CO_2 utilisation in mature fields create new drilling and workover demands (Ijiga *et al*., 2023a) [120].

Several reviews have addressed parts of this problem, for example experimental cuttings transport studies (Li and Luft, 2014) [138] or CFD of annular flow (Epelle and Gerogiorgis, 2017) [100]. What is still missing is a single treatment that brings flow, cuttings transport and heat transfer together, connects the mathematical models with the numerical methods used to solve them, and links both to the engineering and operational decisions they are meant to inform. This review sets out to fill that gap. It is guided by four research questions:

- **RQ1.** Which mathematical models are used to describe non-Newtonian drilling fluid flow, cuttings transport and heat transfer in horizontal and inclined wellbores, and how well are they supported by evidence?
- **RQ2.** What numerical methods are used to solve these models, and what are their relative strengths, costs and validation status?
- **RQ3.** How are the models applied in engineering practice, and how do they connect with integrity, safety, environmental and supply chain considerations?
- **RQ4.** What integrated framework and research agenda would best close the remaining gaps?

The remainder of the paper is organised as follows. Section 2 describes the research method. Section 3 presents the results and discussion: the synthesis of the literature on rheology, annular flow, cuttings transport, heat transfer, numerical methods and engineering applications, an integrated conceptual model, a discussion of the findings and their implications. Section 4 concludes the paper and states its limitations and directions for future research. Related analytical and numerical studies of nanofluid transport under comparable thermal, magnetic and slip conditions provide relevant precedent (Agbaje *et al*., 2025; Shamshuddin *et al*., 2025) [21, 254].

2. Research Method

2.1. Review Design

An integrative (semi-systematic) review design was adopted. The topic spans rheology, fluid mechanics, heat transfer, numerical analysis and drilling operations, and the studies differ widely in geometry, fluid type, scale and method. These differences rule out a quantitative meta-analysis, but they suit an integrative approach, which combines a structured search with thematic synthesis and allows theoretical, experimental, numerical and field studies to be considered together and used to build a conceptual framework.

2.2. Sources and Search Strategy

Literature was identified from OnePetro (covering SPE, IADC and AADE papers), Scopus, Web of Science, ScienceDirect and Google Scholar. Search strings combined fluid terms with geometry and process terms, for example ("drilling fluid" OR "drilling mud") AND ("non-Newtonian" OR "Herschel-Bulkley" OR "yield power law") AND ("annulus" OR "eccentric" OR "horizontal well" OR "inclined"), together with ("cuttings transport" OR "hole cleaning"), ("circulating temperature" OR "wellbore heat transfer"), and ("CFD" OR "CFD-DEM" OR "spectral quasilinearization" OR "machine learning"). Backward and forward citation tracking from foundational works such as Metzner and Reed (1955) [149], Fredrickson and Bird (1958) [110], Ramey (1962) [248], Tomren *et al*. (1986) [266] and Gavignet and Sobey (1989) [111] was used to capture work missed by keyword searches. A second, thematic search extended the corpus into adjacent fields that bear on how flow and thermal models are used in practice: equipment integrity, process and occupational safety, environmental management, predictive analytics and operational technology, the energy transition, and supply chain and project delivery. The search covered publications up to the end of 2025.

2.3. Inclusion and Exclusion Criteria

Table 1: Inclusion and exclusion criteria.

Criterion	Included	Excluded
Topic	Non-Newtonian flow, cuttings transport or heat transfer relevant to wellbores; numerical methods for such flows; studies on how these models are applied in operations	Purely Newtonian studies with no transferable insight; topics with no link to well construction
Source type	Peer-reviewed journal articles, conference papers (SPE, IADC, AADE), standards, textbooks and book chapters	Unpublished theses, non-technical media, patents
Period	1922 to 2025, with emphasis on 2015 to 2025 for numerical and data-driven work	Publications dated after 2025
Language	English, plus seminal non-English constitutive work (Herschel and Bulkley, 1926) [118]	Other non-English sources
Evidence	Studies stating governing equations, method and validation or a clearly defined framework	Studies without enough detail to judge method or relevance

2.4. Data Extraction, Appraisal and Synthesis

For each core source, information was extracted on problem type, constitutive model, geometry, governing equations, solution method, validation evidence and engineering application. Sources were appraised for relevance and evidential strength and assigned to one of three tiers: core sources that model drilling fluid flow, cuttings or heat transfer directly; methodological sources that develop constitutive models or numerical techniques transferable to wellbore problems; and contextual sources that inform how model outputs are used in integrity, safety, environmental, digital and supply chain decisions. The core and methodological literature was synthesised into six strands (Sections 3.1 to 3.6), and cross-strand analysis was then used to derive the conceptual model in Section 3.7.

2.5. Profile of the Corpus

The final corpus comprises 273 sources published between 1922 and 2025, of which 229 appeared in 2015 or later. Table 2 summarises its composition by theme.

Table 2: Composition of the reviewed corpus by theme.

Theme	Sources	Tier
Drilling fluid rheology, annular hydraulics, cuttings transport, wellbore heat transfer and their numerical methods	51	Core
Non-Newtonian and nanofluid heat transfer; spectral numerical methods	10	Methodological
Computational and mechanical engineering, materials and reliability	34	Methodological
Oil and gas operations, offshore asset integrity and process safety	34	Contextual
Occupational safety and HSE management	38	Contextual
Predictive analytics, artificial intelligence and operational technology security	28	Contextual
Environmental management and health	14	Contextual
Energy transition and infrastructure monitoring	33	Contextual
Supply chain, procurement and project delivery	31	Contextual
Total	273	

3. Results and Discussion

This section presents the results of the review and discusses them. Sections 3.1 to 3.6 report the synthesis of the literature in six strands, moving from the constitutive description of drilling fluids (Section 3.1) through single-phase annular flow (Section 3.2), cuttings transport (Section 3.3) and heat transfer (Section 3.4) to the numerical methods used to solve the models (Section 3.5) and their engineering applications (Section 3.6). Section 3.7 presents the integrated conceptual model derived from the synthesis, Section 3.8 discusses the findings, and Section 3.9 sets out their implications.

3.1. Rheological Models for Drilling Fluids

3.1.1 Generalised Newtonian Constitutive Equations

Most engineering models for drilling fluids treat the mud as a generalised Newtonian fluid, in which the shear stress depends only on the instantaneous shear rate. For simple shear the general form is $\tau = \eta(\dot{\gamma})\,\dot{\gamma}$, where η is the apparent viscosity. In three dimensions, the deviatoric stress tensor is written as $\tau = 2\eta(\dot{\gamma})\mathrm{D}$, where D is the rate-of-deformation tensor and $\dot{\gamma} = (2\mathrm{D}:\mathrm{D})^{1/2}$ is its second invariant (Bird *et al.*, 2002) [73]. The models differ in how η depends on $\dot{\gamma}$.

The Bingham plastic model (Bingham, 1922) [72] remains the field standard in API practice because its two parameters, plastic viscosity and yield point, are read directly from a two-speed rotational viscometer:

$$\tau = \tau_y + \mu_p\dot{\gamma}, \text{ for } \tau > \tau_y; \qquad \dot{\gamma} = 0, \text{ for } \tau \le \tau_y \quad (1)$$

The power-law (Ostwald-de Waele) model captures shear-thinning but has no yield stress:

$$\tau = K\dot{\gamma}^n \quad (2)$$

where $n < 1$ for shear-thinning fluids. The Herschel-Bulkley (yield-power-law) model (Herschel and Bulkley, 1926) [118] combines both features and is widely regarded as the best three-parameter description of modern drilling muds (Kelessidis *et al.*, 2006; Zamora and Power, 2002) [125, 271]:

$$\tau = \tau_y + K\dot{\gamma}^n, \text{ for } \tau > \tau_y \quad (3)$$

The Robertson-Stiff model (Robertson and Stiff, 1976) [251] uses a shifted shear rate, $\tau = A(\dot{\gamma} + C)^B$, and the Casson model

(Casson, 1959) [75], $\tau^{1/2} = \tau_y^{1/2} + (\mu_\infty\dot{\gamma})^{1/2}$, is sometimes preferred for oil-based muds and cement slurries. API RP 13D (2017) recommends the Herschel-Bulkley model, with parameters fitted using the "unified" approach in which τ_y is estimated from low-shear readings as the low-shear yield point.

Beyond these classical drilling models, the wider non-Newtonian heat transfer literature uses constitutive laws that capture effects relevant to polymer-rich and oil-based muds. Viscoelastic models such as the Maxwell model describe stress relaxation and memory (Panda *et al*., 2025c) [241]. The Carreau model gives a smooth transition between zero-shear and infinite-shear viscosity plateaus without a singularity (Chhabra and Richardson, 2008) [76]. Third-grade formulations have been applied to inclined and stretching geometries with coupled heat and mass transfer (Agbaje *et al*., 2025) [21], and micropolar models account for the microrotation of suspended particles, which is relevant to cuttings-laden and weighted muds (Shamshuddin *et al*., 2025) [254]. These models are not yet standard in wellbore hydraulics, but they offer a route to representing elasticity and particle-scale effects that the generalised Newtonian models cannot capture.

Table 3: Common rheological models for drilling fluids.

Model	Constitutive equation	Parameters	Strengths and limitations
Bingham plastic	$\tau = \tau_y + \mu_p\dot{\gamma}$	τ_y, μ_p	Simple, standard field practice; overestimates τ_y and low-shear stress
Power law	$\tau = K\dot{\gamma}^n$	K, n	Good at moderate shear; no yield stress, underpredicts suspension
Herschel-Bulkley	$\tau = \tau_y + K\dot{\gamma}^n$	τ_y, K, n	Best overall fit for most muds; requires nonlinear fitting
Robertson-Stiff	$\tau = A(\dot{\gamma} + C)^B$	A, B, C	Good fit for muds and cements; less physical interpretation
Casson	$\tau^{1/2} = \tau_y^{1/2} + (\mu_\infty\dot{\gamma})^{1/2}$	τ_y, μ_∞	Suited to suspensions; limited flexibility
Papanastasiou (regularised)	$\tau = [\mu + \tau_y(1 - e^{-m\dot{\gamma}})/\dot{\gamma}]\dot{\gamma}$	τ_y, μ, m	Removes singularity at $\dot{\gamma} = 0$ for numerical use

3.1.2 Regularisation of Yield-Stress Models

The discontinuity of viscoplastic models at the yield surface causes the apparent viscosity to become infinite as $\dot{\gamma}$ approaches zero, which is unworkable in most numerical solvers. Two strategies are used. Regularisation replaces the discontinuous law with a smooth one; the exponential form of Papanastasiou (1987) [245] is the most common:

$$\eta(\dot{\gamma}) = K\dot{\gamma}^{n-1} + \frac{\tau_y[1-\exp(-m\dot{\gamma})]}{\dot{\gamma}} \quad (4)$$

where m is a large regularisation parameter. Commercial CFD codes more often apply a simple bi-viscosity cap, holding η at a maximum value below a critical shear rate. Both approaches blur the plug boundary, and the choice of m or of the viscosity cap can strongly influence predicted plug size and the extent of stagnant zones in the narrow side of an eccentric annulus. The alternative, augmented Lagrangian methods, resolves the true yield surface but at much greater cost and is rarely used for three-dimensional wellbore flows.

3.1.3 Temperature, Pressure and Time Dependence

Rheological parameters depend strongly on temperature and, for oil-based muds, on pressure. A common approach is an Arrhenius or exponential correction for each parameter, for example

$$K(T,p) = K_0\exp[\alpha_p(p - p_0) + \beta(\frac{1}{T} - \frac{1}{T_0})] \quad (5)$$

with analogous expressions for τ_y and n. Alderman *et al*. (1988) [30] showed that water-based mud viscosity falls with temperature while the yield stress can increase at high temperature because of clay flocculation. Rommetveit and Bjørkevoll (1997) [252] demonstrated that ignoring these effects in deep wells can produce ECD errors large enough to matter in narrow pore-fracture pressure windows. Thixotropy, the time-dependent build-up and breakdown of gel structure, is usually handled with structural-kinetic models in which a structure parameter λ evolves according to $d\lambda/dt = a(1 - \lambda) - b\lambda\dot{\gamma}$, but such models are still rarely coupled to wellbore simulators even though gel strength governs surge, swab and pump start-up pressures.

3.2. Single-Phase Flow in Horizontal and Inclined Annuli

3.2.1 Governing Equations

For an incompressible fluid the continuity and momentum equations are

$$\nabla \cdot \mathrm{u} = 0 \quad (6)$$

$$\rho(\frac{\partial \mathrm{u}}{\partial t} + \mathrm{u} \cdot \nabla \mathrm{u}) = -\nabla p + \nabla \cdot \tau + \rho g \quad (7)$$

For fully developed, steady, axial laminar flow in a straight annulus without rotation, these reduce to a two-dimensional Poisson-type problem in the cross-section, $\nabla \cdot [\eta(\dot{\gamma})\nabla w] = dp/dz$, where w is the axial velocity. In a horizontal or inclined annulus the gravity term has a component normal to the axis, $\rho g \sin\theta$, which drives cuttings settling and, in non-isothermal flow, secondary buoyancy-driven circulation. For single-phase isothermal flow it affects only the hydrostatic pressure, so horizontal and inclined single-phase flows can usually be modelled with the same cross-sectional equations as vertical flow; the inclination becomes decisive once solids or temperature gradients are present. Studies of non-Newtonian flow and heat transfer over inclined surfaces show that the angle of inclination changes the balance between buoyancy and forced convection and therefore alters both velocity and temperature fields (Oluwaseun *et al*., 2023; Agbaje *et al*., 2025) [21, 233], which supports the need to retain inclination explicitly in coupled thermal-hydraulic wellbore models.

3.2.2 Concentric Annulus Solutions

For a concentric annulus, Fredrickson and Bird (1958) [110] obtained exact solutions for power-law and Bingham fluids. Because the exact solutions are implicit, drilling practice usually uses the narrow-slot approximation, which treats the annulus as flow between parallel plates with gap $(D_o - D_i)/2$. This is accurate within a few percent when $D_i/D_o > 0.3$, a condition met in most drilling geometries. For a power-law

fluid in slot flow, the wall shear rate and the generalised Reynolds number are

$$\dot{\gamma}_w = \frac{2n+1}{3n} \cdot \frac{12v}{D_o - D_i} \quad (8)$$

$$\mathrm{Re}_{MR} = \frac{\rho v^{2-n} D_{hn}}{8^{n-1} K [\frac{3n+1}{4n}]^n} \quad (9)$$

Equation (9) is the Metzner and Reed (1955) [149] generalised Reynolds number, written here for pipe geometry with $D_h = D_o - D_i$; for the slot the geometric factor (3n + 1)/(4n) is replaced by (2n + 1)/(3n). For Herschel-Bulkley fluids no closed form exists, and iterative procedures or explicit approximations such as those of Kelessidis *et al*. (2006) [125] and Founargiotakis *et al*. (2008) [109] are used. API RP 13D (2017) adopts a geometry-shape-factor formulation that allows a single framework for pipe and annulus.

3.2.3 Eccentricity

In horizontal and inclined wells, gravity pushes the drillstring toward the low side, and eccentricity values of 0.5 to 0.9 are normal. Eccentricity is defined as $e = \delta/(R_o - R_i)$, where δ is the distance between pipe and hole centres. At fixed flow rate, eccentricity lowers frictional pressure loss because flow redistributes into the wide gap, but it also starves the narrow gap of flow. For yield-stress fluids, part of the narrow gap can become completely unyielded, so a stationary layer forms even without any cuttings.

Haciislamoglu and Langlinais (1990) [116] developed a widely used correlation for the ratio of eccentric to concentric pressure loss in laminar flow of power-law fluids:

$$R_{lam} = 1 - 0.072\frac{e}{n}\left(\frac{D_i}{D_o}\right)^{0.8454} - 1.5e^2\sqrt{n}\left(\frac{D_i}{D_o}\right)^{0.1852} + 0.96e^3\sqrt{n}\left(\frac{D_i}{D_o}\right)^{0.2527} \quad (10)$$

More rigorous treatments solve the cross-sectional problem directly. Bipolar coordinate transformations, variable-width slot models in which the eccentric annulus is "unwrapped" into a slot whose height varies with angle, and full finite-element or finite-volume solutions have all been used (Escudier *et al*., 2002) [103]. The variable-slot approach is attractive for real-time use because it is fast and captures the key effect of local plug formation, although it neglects azimuthal shear.

3.2.4 Drillpipe Rotation and Motion

Drillstring rotation introduces a tangential velocity component that couples to the axial flow through the shear-dependent viscosity. In a concentric annulus with a shear-thinning fluid, rotation reduces the apparent viscosity and therefore the axial pressure gradient in laminar flow. In an eccentric annulus, however, rotation can increase frictional pressure loss, because it generates secondary flows and drags fluid from the wide to the narrow gap; at higher speeds Taylor-type vortices may also appear (Ahmed and Miska, 2008; Erge *et al*., 2015) [25, 101]. Saasen (2014) [253] reviewed these mechanisms and noted that in field conditions the drillstring does not simply rotate about its own axis but whirls and moves laterally, so laboratory results with fixed-axis rotation can underestimate the effect. Erge *et al*. (2015) [101] found that drillstring buckling and orbital motion change annular pressure losses for yield-power-law fluids substantially compared with a straight rotating pipe. Related analyses of rotating-disk and rotating-boundary flows show how rotation, wall slip and magnetic or Hall effects reshape both the velocity and the thermal boundary layers (Oluwaseun *et al*., 2024; Oluwaseun and Agbaje, 2025) [232, 234], giving useful reference solutions for the rotation-driven heat transfer near a spinning drillstring.

3.2.5 Flow Regime Transition and Turbulence

Flow regime determines both frictional losses and the effectiveness of cuttings removal. For non-Newtonian fluids the laminar-turbulent transition depends on *n*, and for yield-stress fluids also on the Hedström number. A practical criterion is the one of Dodge and Metzner (1959) [91], in which the critical Reynolds number rises as *n* decreases. In the turbulent regime the Dodge-Metzner implicit friction law is commonly used:

$$\frac{1}{\sqrt{f}} = \frac{4.0}{n^{0.75}}\log_{10}[\mathrm{Re}_{MR} f^{1-n/2}] - \frac{0.4}{n^{1.2}} \quad (11)$$

Reed and Pilehvari (1993) [250] and Founargiotakis *et al*. (2008) [109] proposed unified approaches that cover laminar, transitional and turbulent regimes for Herschel-Bulkley fluids in annuli. In eccentric annuli the transition is not uniform across the section: the wide gap can be turbulent while the narrow gap remains laminar or unyielded, which helps explain why turbulent flow does not always eliminate cuttings beds.

3.3. Cuttings Transport in Inclined and Horizontal Wellbores

3.3.1 Physical Mechanisms

Experimental flow loop studies established that cuttings transport depends on inclination in a markedly non-monotonic way (Tomren *et al*., 1986; Sifferman and Becker, 1992) [258, 266]. In near-vertical wells (0 to 30 degrees) cuttings are carried in suspension and transport efficiency depends mainly on the difference between annular velocity and slip velocity. Between about 30 and 60 degrees, a bed forms on the low side and may slide back down the hole when circulation stops, an avalanching behaviour that makes this range the most troublesome. Above about 60 degrees, the bed is stable and the problem becomes one of eroding or rolling cuttings along it. The key controlling variables are flow rate, fluid rheology and density, cuttings size and density, pipe rotation, eccentricity, rate of penetration and hole size.

Table 4: Inclination ranges and dominant cuttings transport behaviour.

Inclination	Dominant mechanism	Main design levers
0 to 30°	Suspension; settling against upward flow	Annular velocity above slip velocity; low-shear viscosity
30 to 60°	Bed formation with sliding and avalanching	High flow rate, pipe rotation, avoid static periods
60 to 90°	Stationary or moving bed; rolling and saltation	Turbulence or high rotation, sweeps, fluid density

3.3.2 Empirical and Dimensionless Correlations

Early design tools were empirical. Larsen *et al*. (1997) [137] developed a correlation for the critical transport velocity, the minimum annular velocity at which no stationary bed exists, for angles from 55 to 90 degrees, with correction factors for inclination, cuttings size and mud weight. Such correlations are fast and easy to use but are tied to the geometries and fluids of the data sets from which they were derived, and they generally do not account explicitly for yield stress, eccentricity or rotation beyond a simple multiplier.

3.3.3 Mechanistic Layer Models

Mechanistic models divide the annular cross-section into layers and write mass and momentum balances for each. The two-layer model of Gavignet and Sobey (1989) [111] assumes a stationary bed of cuttings beneath a suspension layer. The momentum balance for the upper (suspension) layer and for the bed can be written as

$$A_1\left(\frac{dp}{dz}\right) = -\tau_1 S_1 - \tau_i S_i - \rho_1 A_1 g\cos\theta \tag{12}$$

$$A_2\left(\frac{dp}{dz}\right) = -\tau_2 S_2 + \tau_i S_i - \rho_2 A_2 g\cos\theta - F_s \tag{13}$$

where A_j and S_j are layer areas and wetted perimeters, τ_i is the interfacial shear stress, θ is the inclination from vertical, and F_s is the static Coulomb friction force on the bed, proportional to the submerged bed weight and the friction coefficient. The bed is stationary when the driving force cannot overcome F_s. Clark and Bickham (1994) [77] proposed a mechanistic model based on the forces acting on individual particles, distinguishing settling, lifting and rolling modes. Nguyen and Rahman (1998) [153] extended the layer concept to three layers: a stationary bed, a moving bed and a heterogeneous suspension, which reproduces the transition between stationary and moving beds observed in flow loops. Kamp and Rivero (1999) [124] added a cuttings diffusion term for exchange between layers.

A key ingredient of all layer models is the interfacial friction factor and the treatment of the non-Newtonian fluid in the irregular upper layer. Most models use a hydraulic-diameter approach with a generalised Reynolds number, which is a weak assumption when the upper layer has a crescent shape and the fluid has a yield stress. Layer models also usually ignore pipe rotation, or include it through empirical multipliers, despite experimental evidence that rotation is one of the most effective hole cleaning tools in horizontal wells (Ozbayoglu *et al*., 2008) [240].

3.3.4 Transient Transport

Real drilling is transient: flow rate, rate of penetration and rotation change continuously, and connections interrupt circulation. Transient one-dimensional models write a cuttings mass conservation equation for each layer,

$$\frac{\partial(A_j C_j)}{\partial t} + \frac{\partial(A_j C_j v_{s,j})}{\partial z} = \Gamma_j \tag{14}$$

where C_j is cuttings concentration, $v_{s,j}$ the solids velocity and Γ_j the exchange term between layers through deposition and erosion. These equations, coupled to the momentum equations, are solved along the well using finite-difference or finite-volume schemes, giving a time history of bed height, ECD and torque that can be compared with real-time data.

3.4. Heat Transfer in Circulating Wellbores

3.4.1 Thermal System

During circulation, cool fluid enters the drillpipe at the surface, is heated as it descends, exits through the bit, and returns up the annulus. Heat is exchanged between the drillpipe fluid and the annular fluid through the pipe wall, and between the annular fluid and the formation through the casing, cement or open hole. The formation temperature field, initially following the geothermal gradient, is disturbed by circulation in a region that grows with time. The bottom-hole circulating temperature is therefore usually well below the static formation temperature, and the maximum annular temperature occurs some distance above the bit.

3.4.2 Analytical Models

Ramey (1962) [248] laid the foundation for wellbore heat transmission by combining a steady-state energy balance in the wellbore with a transient radial conduction solution in the formation, expressed through a dimensionless time function *f*(t). Raymond (1969) [249] developed a numerical model for drillpipe and annulus temperatures during circulation. Holmes and Swift (1970) [119] derived an analytical steady-state solution for coupled drillpipe and annulus temperatures, assuming a linear geothermal gradient and constant heat transfer coefficients. The energy balances for the two streams take the form

$$\rho C_p Q \frac{dT_p}{dz} = 2\pi r_p U_p (T_a - T_p) \tag{15}$$

$$\rho C_p Q \frac{dT_a}{dz} = 2\pi r_p U_p (T_a - T_p) - 2\pi r_w U_a (T_f - T_a) \tag{16}$$

with T_p, T_a and T_f the drillpipe, annulus and formation temperatures. Kabir *et al*. (1996) [123] extended this framework to transient conditions using an analytical formation solution, and the approach is described comprehensively by Hasan and Kabir (2002) [117]. These analytical models remain useful for quick estimates and as benchmarks, but they assume constant fluid properties and do not resolve the non-Newtonian velocity field.

3.4.3 Numerical Transient Models

Keller *et al*. (1973) [126], Marshall and Bentsen (1982) [147] and Corre *et al*. (1984) [78] developed numerical models that discretise the wellbore and the surrounding formation in two dimensions (radial and axial), solving the transient conduction equation in the formation and the convection-conduction equations in the pipe and annulus:

$$\rho C_p\left(\frac{\partial T}{\partial t} + w\frac{\partial T}{\partial z}\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \Phi \tag{17}$$

where $\Phi = \tau : \nabla\mathbf{u}$ is the viscous dissipation term. For shear-thinning fluids in the drillpipe and bit nozzles, viscous heating can be significant, and frictional heat from the bit and from drillstring rotation against the borehole wall adds further sources. Later models have included lost circulation (Yang *et al*., 2013) [270], mud pit heat exchange, tripping and static periods, and multi-string casing configurations. The importance of viscous dissipation for non-Newtonian fluids has been demonstrated in many boundary-layer studies, where dissipative heating noticeably raises fluid temperature and modifies wall heat flux (Oluwaseun *et al*., 2023; Panda *et al*., 2025a, 2025b) [233, 242, 243]. Wall slip, which occurs in

drilling fluids at smooth steel surfaces and with oil-based muds, also changes both shear stress and heat transfer and has been incorporated in several such models (Oluwaseun and Agbaje, 2025) [232]. Non-Fourier (Cattaneo-Christov) heat flux, which allows for a finite thermal relaxation time, may also be relevant to rapid thermal transients during pump start-up.

3.4.4 Convective Heat Transfer for non-Newtonian Fluids

The coupling between the fluid and the solid walls is represented through convective coefficients. For laminar flow of power-law fluids, Nusselt numbers are typically corrected from the Newtonian value with a factor $\delta = (3n + 1)/(4n)$ raised to a small power; for turbulent flow, Dittus-Boelter or Gnielinski type correlations are applied with a generalised Reynolds number and a Prandtl number based on the wall apparent viscosity (Chhabra and Richardson, 2008) [76]. These correlations were developed for pipes and are uncertain in eccentric annuli, where the local heat transfer coefficient in the narrow gap can be much lower than in the wide gap. CFD studies show that ignoring this asymmetry can lead to errors in the predicted temperature of the low side of the hole, which matters for both cuttings bed behaviour and wellbore stability.

3.4.5 Thermo-Rheological Coupling

Because rheological parameters vary with temperature, the hydraulic and thermal problems are coupled. A typical iterative scheme computes the temperature profile with current properties, updates K, τ_y and n along the well, recomputes pressure losses and velocity, and repeats until convergence. Rommetveit and Bjørkevoll (1997) [252] showed that this coupling is essential for accurate ECD prediction in deep wells. In horizontal sections the temperature is nearly uniform along the lateral, so axial coupling matters less there, but the vertical and build sections that precede the lateral still set the fluid temperature and rheology entering it.

3.4.6 Nanoparticle-Enhanced Drilling Fluids and Entropy Generation

Nanoparticles are increasingly added to drilling fluids to improve thermal conductivity, fluid-loss control, rheological stability at high temperature and lubricity. Their thermal behaviour is commonly modelled with single-phase effective-property models or with the two-phase Buongiorno approach, which includes Brownian diffusion and thermophoresis. Hybrid and ternary hybrid nanofluids, combining two or three particle types, have been shown to give larger heat transfer enhancement than mono nanofluids (Oluwaseun *et al*., 2025; Panda *et al*., 2025c) [232, 241], while thermophoretic particle deposition affects how particles accumulate near hot or cold walls (Baithalu *et al*., 2025) [70]. Oluwaseun *et al*. (2024) [234] analysed SiO_2/kerosene nanofluid flow between rotating disks, a configuration with parallels to oil-based mud near rotating drillstring components. Second-law (entropy generation) analysis offers a way to identify where irreversibility arises from viscous friction, heat conduction and mass transfer, and has been applied to non-Newtonian and nanofluid flows (Oluwaseun *et al*., 2023) [233]. Applying this framework to the drillpipe-annulus-formation system could help optimise flow rate and fluid design for minimum energy loss in HPHT and geothermal wells.

3.5. Numerical Methods

3.5.1 One-Dimensional Wellbore Simulators

Industrial hydraulics, thermal and hole cleaning software is mostly built on one-dimensional, cross-sectionally averaged models solved with finite-difference or finite-volume methods along the well path. Closure relations (friction factors, eccentricity corrections, heat transfer coefficients, bed shear stresses) come from the analytical and empirical work described earlier. These simulators run quickly enough for planning and real-time use and can include transient events, but their accuracy depends entirely on the closures.

3.5.2 Cross-Sectional and Three-Dimensional Single-Phase CFD

Finite-volume (Patankar, 1980) [246] and finite-element solvers are used to compute fully developed flow in eccentric annuli and to generate closure relations. Three-dimensional CFD with commercial or open-source codes resolves the effects of rotation, orbital motion, tool joints and washouts. Key numerical issues include the treatment of the yield stress (Section 3.1.2), mesh resolution in the narrow gap, and turbulence modelling for non-Newtonian fluids, where standard k-ε and k-ω models calibrated for Newtonian flow can misrepresent drag reduction and the transition region.

Wider computational engineering practice offers tools that complement these solvers. Advances in thermofluid simulation for heat transfer optimisation in compact devices (Adewoyin *et al*., 2020b) [16], CFD-driven design of fluid-particle separation and filtration systems (Adewoyin *et al*., 2021; Ogunnowo *et al*., 2023b) [17, 202], and AI-based optimisation of multiphysics fluid dynamics (Adewoyin *et al*., 2024) [19] show how flow solvers are being coupled with design optimisation, which is directly relevant to solids-control equipment and to the separation of cuttings from the circulating mud. Reliability-centred design using finite-element analysis, topology optimisation (Ogunnowo *et al*., 2023a; Ogunnowo *et al*., 2024c) [206, 211], dynamic mechanical analysis for material selection (Adewoyin *et al*., 2020a; Ogunnowo *et al*., 2021b) [15, 208], and models of microstructural evolution in superalloys (Ogunnowo *et al*., 2022a; Ogunnowo *et al*., 2022b) [205, 209] are relevant to the drillstring and downhole tools that bound the annular flow domain. Simulation-based optimisation of HVAC systems using heat-flow analytics and thermodynamic control strategies (Ogunnowo *et al*., 2021a; Sunday *et al*., 2019) [204, 261] provides transferable approaches for the design of surface mud cooling systems.

3.5.3 Multiphase CFD: Euler-Euler and Euler-Lagrange

Two families of methods dominate the simulation of cuttings transport. In the **Euler-Euler (two-fluid) approach**, the fluid and cuttings are treated as interpenetrating continua with separate conservation equations and interphase momentum exchange terms. The kinetic theory of granular flow provides the solids pressure and viscosity (Gidaspow, 1994) [112]. Ofei *et al*. (2014) [201], Epelle and Gerogiorgis (2017) [100] and Pang *et al*. (2019) [244] used this approach to study the effects of eccentricity, rotation, orbital motion and fluid rheology on cuttings concentration and pressure loss in horizontal annuli. Sun *et al*. (2014) [259] used CFD to show the effect of drillpipe rotation on cuttings transport in complex structure wells.

In the Euler-Lagrange (CFD-DEM) approach, the fluid is solved on a grid while each particle is tracked individually,

with particle-particle and particle-wall contacts computed by the discrete element method of Cundall and Strack (1979) [79]. Akhshik *et al*. (2015) [26] applied CFD-DEM to investigate drillpipe rotation in cuttings transport, revealing particle-scale mechanisms such as particles being lifted from the bed by the rotating pipe and carried into the high-velocity region. Busch and Johansen (2020) [74] studied the effect of rotation and lateral pipe motion on bed behaviour. CFD-DEM is the most physically detailed approach but is limited to short sections, typically a few metres, and relatively small particle numbers.

Table 5: Comparison of numerical approaches.

Approach	Typical use	Advantages	Limitations
1D FD/FV simulators	Well planning, real-time ECD, transient hole cleaning	Fast; full well length; transient	Depends on empirical closures
2D cross-section solvers	Eccentric annulus closures, plug zones	Accurate local velocity and stress	Fully developed flow only
3D single-phase CFD	Rotation, tool joints, washouts	Resolves secondary flows	Costly; yield stress regularisation
Euler-Euler CFD	Cuttings concentration, bed height	Handles high solids loading	Granular closures uncertain
CFD-DEM	Particle-scale bed dynamics	Explicit contact physics	Very costly; short domains
Spectral methods (SQLM)	Benchmark solutions, parametric studies	Very high accuracy, low cost	Simple geometries only
ML / PINN surrogates	Real-time prediction, inversion	Fast once trained	Needs data; extrapolation risk

3.5.4 Coupled Thermal-Hydraulic Solvers

Coupled models solve the wellbore and formation energy equations simultaneously with the hydraulics, typically using implicit finite-difference schemes on structured radial-axial grids. Operator splitting, in which flow and temperature are solved sequentially within each time step, is common. Three-dimensional conjugate heat transfer CFD that resolves the non-Newtonian velocity field, the pipe walls and part of the formation is possible but rarely applied beyond short sections.

3.5.5 Spectral and Semi-Analytical Methods

For the nonlinear ordinary and partial differential equations that arise from similarity reductions and simplified wellbore geometries, spectral methods offer very high accuracy with few grid points. The spectral quasilinearization method (SQLM) linearises the governing equations iteratively and solves each linear system with Chebyshev collocation; it has been applied to third-grade and hybrid nanofluid flows with coupled heat and mass transfer (Agbaje *et al*., 2025; Panda *et al*., 2025a) [21, 242]. Overlapping-grid variants divide the domain into overlapping subintervals, which improves conditioning and accuracy on large domains, and the bivariate simple iteration method extends the approach to unsteady problems in two independent variables (Oluwaseun *et al*., 2025) [232]. Other recent work has used shooting and finite-difference-based solvers for hydromagnetic nanofluid flows with slip and Hall current (Oluwaseun and Agbaje, 2025) [232]. These methods are well suited to producing accurate benchmark solutions against which CFD codes and simplified wellbore models can be verified.

3.5.6 Data-Driven and Physics-Informed Approaches

Machine learning methods, including artificial neural networks, gradient boosting and support vector regression, have been trained on flow loop and field data to predict pressure loss, cuttings concentration and bottom-hole temperature. Physics-informed neural networks (Raissi *et al*., 2019) [247] embed the governing equations in the loss function, which reduces data requirements and helps keep predictions physically consistent. A promising direction is the use of high-fidelity CFD to generate training data for fast surrogates that can be embedded in one-dimensional simulators or real-time advisory systems. Generalisation to fluids and geometries outside the training set remains the main concern. Experience from other data-intensive fields stresses that model quality depends as much on the data pipeline (measurement, cleaning, feature construction and validation) as on the learning algorithm itself (Aladegba and Ayinde, 2024) [27], a lesson that applies directly to drilling data, which are often noisy and incomplete.

The broader predictive analytics literature gives methodological guidance for drilling data. Comparative reviews of predictive forecasting and of national analytics capacity (Unamma *et al*., 2018; Unamma *et al*., 2021) [267, 268], data-driven lifecycle performance, anomaly detection and performance-intelligence models (Adelanwa *et al*., 2023a; Adelanwa *et al*., 2023b; Adelanwa *et al*., 2024) [11, 12, 13] describe how predictive models are embedded in operational decisions. Forecasting work in the energy sector, including renewable yield forecasting, hybrid deep learning for wind power, deep learning load prediction, interpretable machine learning for early failure prediction, and machine-learning predictive maintenance with cloud analytics (Ezeugwa *et al*., 2023; Komi, 2021; Komi, 2023; Komi and Adamolekun, 2021; Mayo *et al*., 2021) [104, 127, 128, 129, 148], uses techniques that transfer directly to forecasting standpipe pressure, bottom-hole temperature and hole-cleaning state. Artificial intelligence for detecting process failures across oil and gas facilities (Asibor, 2025) [52] and AI-augmented corrosion modelling (Adewoyin *et al*., 2023) [18] demonstrate industrial deployment. Human-in-the-loop decision systems, analysts acting as brokers of AI transformation, and AI-assisted risk and incident analysis (Ashore-Onisemo *et al*., 2025; Alieme *et al*., 2025; Unamma *et al*., 2025) [31, 51, 269] address how model outputs should be presented to drilling engineers. Context-aware data curation for fine-tuning (Oyesiji *et al*., 2024) [239], and on-device small language models for edge intelligence (Nwakamma *et al*., 2025) [154] point to emerging tools for rig-site advisory systems, while work on adversarial machine learning, AI-augmented threat detection in industrial control systems, continuous AI-enabled control and threat-indicator de-duplication (Adebayo *et al*., 2022; Adebayo *et al*., 2023; Adebayo *et al*., 2025) [2, 3, 4] warns that AI-enabled control loops must also be secured.

3.5.7 Validation

Validation remains a weak point across all methods. Most experimental data come from flow loops with transparent pipes, limited lengths, simplified fluids such as polymer solutions, and artificial cuttings. Field data are noisy and rarely include direct bed height or temperature profile measurements. Few data sets combine non-Newtonian rheology, eccentricity, rotation, inclination and heat transfer, so coupled models are usually validated piece by piece.

3.6. Engineering Applications

3.6.1 Hydraulics Design and ECD Management

Accurate annular pressure loss prediction is required to keep ECD between pore pressure and fracture gradient. In extended-reach and deepwater wells this window can be narrow, and the combined effects of eccentricity, rotation, cuttings loading and temperature on rheology can each shift ECD by amounts comparable to the window. Modern hydraulics programs therefore combine Herschel-Bulkley rheology, eccentricity and rotation corrections, cuttings loading and temperature-dependent properties (API RP 13D, 2017; Mitchell and Miska, 2011) [42, 150].

3.6.2 Hole Cleaning

Hole cleaning design uses critical velocity correlations or mechanistic layer models to select flow rate, rotation speed, fluid properties and sweep strategy. Field practice in horizontal wells relies on high rotation speeds, typically above 100 to 120 rpm where the equipment allows, combined with maximum feasible flow rate. Models show that a moderate yield stress and low-shear-rate viscosity help suspension in the vertical section and during connections, but can hinder bed erosion in the horizontal section, so fluid design must balance these effects. High-viscosity, weighted and fibre sweeps are used to remove beds, and transient models help schedule them.

3.6.3 Managed Pressure and Underbalanced Drilling

Managed pressure drilling controls bottom-hole pressure by adjusting surface back pressure, relying on a real-time hydraulics model to compute the annular friction and the required set point. Errors in the non-Newtonian friction model or in the temperature profile translate directly into bottom-hole pressure errors. Thermal transients during pump start-up and after connections, combined with gel breaking, are important in these operations.

3.6.4 HPHT and Geothermal Drilling

In HPHT and geothermal wells, circulating temperatures can exceed the limits of measurement-while-drilling electronics, motor elastomers and fluid additives. Thermal models are used to design cooling strategies, including surface mud coolers, insulated drillpipe, and optimised flow rates. Rheological degradation at high temperature changes both hydraulics and cuttings transport, so coupled thermo-hydraulic models are particularly important here (Kabir *et al*., 1996; Hasan and Kabir, 2002) [117, 123].

3.6.5 Cementing and Well Construction

The same annular flow models are used for mud displacement during cementing, where a spacer and cement slurry must displace non-Newtonian mud from an eccentric annulus. Incomplete displacement in the narrow gap of horizontal wells, where mud may remain unyielded, leaves mud channels that compromise zonal isolation. Circulating temperature models also determine the temperature used for cement slurry design.

3.6.6 Real-Time Monitoring and Digital Twins

Increasing availability of downhole pressure and temperature measurements, along with wired drillpipe, allows models to be calibrated continuously. Digital twin systems combine one-dimensional transient hydraulic, thermal and cuttings transport models with real-time data to detect bed build-up, pack-off risk and kicks or losses. Surrogate models derived from high-fidelity CFD and machine learning are increasingly used to speed up these systems.

Digital twin technology is maturing across engineering sectors, with frameworks for real-time monitoring of mechanical systems (Ogunnowo *et al*., 2024a) [207], closed-loop process control (Olodo *et al*., 2025) [231], and tiered predictive diagnostics at resource-constrained energy sites (Komi and Adeniji, 2023) [132], while edge intelligence supports resilient local control (Komi and Ganiu, 2023) [134]. Condition monitoring and predictive maintenance practice, including vibration-based monitoring of rotating machinery, sensor-based fault detection, IoT-enabled monitoring, reliability-centred maintenance and the move from reactive to predictive strategies (Adaramola *et al*., 2018; Omoegun *et al*., 2023; Sunday and Omoegun, 2022; Sunday *et al*., 2020; Obetta *et al*., 2025a) [1, 170, 236, 262, 264], offers proven methods for the mud pumps, top drives and solids-control equipment that set the boundary conditions of hydraulic models. Surface infrastructure linked to well pads, such as flowlines, pipelines and power corridors, is increasingly monitored with UAV, LiDAR and GIS systems and with deep learning image analysis (Dagodzo, 2018a; Dagodzo, 2018b; Dagodzo and Ahiaeke Patrick, 2020; Dagodzo and Ahiaeke Patrick, 2021a; Dagodzo and Ahiaeke Patrick, 2021b; Dagodzo and Ahiaeke Patrick, 2022; Dagodzo and Ahiaeke Patrick, 2023a; Dagodzo and Ahiaeke Patrick, 2023b; Dagodzo and Ahiaeke Patrick, 2025; Dagodzo *et al*., 2022) [80, 81, 83, 84, 85, 86, 87, 88, 89].

Because real-time drilling models depend on networked sensors and control systems, the security of operational technology is an integral part of the digital twin. Reviews and frameworks covering SCADA and industrial control system threat detection, IT and OT convergence, NERC CIP compliance, zero-trust architecture, vulnerability governance, AI-driven security operations, cyber-risk quantification, continuous compliance, deep learning anomaly detection, blockchain-assisted data exchange and resilience of digital substations (Adegbite *et al*., 2020; Adegbite *et al*., 2022; Adegbite *et al*., 2023; Adegbite *et al*., 2024a; Adegbite *et al*., 2024b; Adegbite *et al*., 2025; Ahmed *et al*., 2021; Amadi, 2025; Amadi *et al*., 2025a; Amadi *et al*., 2025b; Amadi *et al*., 2025c; Shittu *et al*., 2024; Shittu *et al*., 2022) [5, 6, 7, 8, 9, 10, 24, 32, 33, 34, 35, 255, 257], together with physics-informed ransomware defence using digital twins (Ojukwu *et al*., 2023) [215], provide the security foundation that connected drilling control and managed pressure systems require.

3.6.7 Environmental and Health Considerations

Drilling fluids and cuttings contain base oils, polymers, heavy metals and other additives, and their handling and disposal carry environmental and occupational health implications. Flow and transport models influence this indirectly: better hole cleaning reduces fluid losses and the volume of contaminated waste, and accurate temperature

prediction helps select additives that remain stable rather than degrading into harmful by-products. Conceptual models that couple exposure biomarkers with individual susceptibility, and AI-enabled early-warning and decision-support tools for exposed communities, provide methods that could be adapted for drilling waste sites (Aladegba *et al*., 2021, 2025) [28, 29]. Integrating such environmental risk models with drilling fluid design and waste management is a promising direction for responsible well construction.

Produced water shares many treatment challenges with spent water-based drilling fluids and has been studied through lifecycle risk assessment, physicochemical and bio-based treatment, decentralised treatment for remote assets, resource recovery and data-driven optimisation (Falegan and Aniebonam, 2022; Falegan and Aniebonam, 2023; Falegan and Aniebonam, 2024; Falegan and Aniebonam, 2025) [105, 106, 107, 108]. Data-driven modelling of subsurface contamination pathways, vapour intrusion and contaminant migration (Azeez and Badmus, 2018; Azeez and Badmus, 2024b; Lamidi and Olamide, 2018) [66, 67, 136], integrated remote-sensing early warning for environmental compliance (Badmus, 2025) [69], and evidence on pollution and community health in resource-extraction regions (Osinem *et al*., 2025) [238] are directly relevant to drilling waste and cuttings disposal sites. Frameworks for environmental risk control through waste handling, sustainable practices within safety management systems, and environmental compliance in construction and infrastructure projects (Arumosoye *et al*., 2025; Obogo *et al*., 2024b; Obogo *et al*., 2024a) [50, 176, 180] connect these assessments to field operations. Emissions associated with drilling and production, including flaring, flare-gas recovery and conversion, methane reduction, vapour recovery, flare loss detection and decarbonisation of process facilities (Amarahobu *et al*., 2025b; Asibor and Isong, 2020; Asibor and Olisakwe, 2022; Ekelemu and Akano, 2025b; Makut and Olisakwe, 2022) [37, 54, 57, 96, 141], together with greenhouse gas inventory and carbon accounting methods (Azeez and Badmus, 2024a; Lamidi, 2023) [65, 135] and carbon removal technologies (Liadi *et al*., 2024) [139], define the wider environmental performance expected of modern well construction.

3.6.8 Equipment Integrity, Erosion and Corrosion

Drilling fluids carrying abrasive cuttings and weighting materials at high velocity erode and corrode drillpipe, casing, pumps and surface lines, and the temperature profiles predicted by thermal models directly influence corrosion rates. Non-destructive testing and integrity management methods for refineries, welds and critical infrastructure, together with predictive corrosion models built from inspection data (Atta *et al*., 2020; Atta *et al*., 2021; Ogunnowo *et al*., 2020; Ogunnowo *et al*., 2024b; Ogunnowo *et al*., 2024d) [63, 64, 203, 210, 212], welding inspection and quality assurance practice (Atta *et al*., 2022) [59], and green corrosion inhibitors derived from agricultural extracts (Atta *et al*., 2018) [60] support the detection and control of wear before failure. Experience with offshore static equipment, including risk-based and non-intrusive inspection of pressure vessels, fitness-for-service assessment, reliability-centred and condition-based maintenance, CMMS optimisation, cause-tree failure analysis, spare parts standardisation, corrosion management for marine export equipment, and integrity of turret moorings and offloading hoses (Obetta, 2018; Obetta, 2019; Obetta, 2020; Obetta and Ninduwezuor-Ehiobu, 2018; Obetta and Ninduwezuor-Ehiobu, 2019; Obetta *et al*., 2020; Obetta *et al*., 2021; Obetta *et al*., 2022; Obetta *et al*., 2023; Obetta *et al*., 2024; Obetta *et al*., 2025b) [160, 161, 162, 163, 164, 166, 167, 168, 169, 171], provides inspection and maintenance frameworks that transfer to high-pressure mud systems. Lifecycle reliability assessment (Makut *et al*., 2024) [145], reliability engineering and failure analysis of complex systems (Gideon *et al*., 2019) [115], environmental degradation mechanisms (Atta *et al*., 2025; Gideon and Erhimefe, 2025) [61, 113], semiconductor risk mitigation (Gideon, 2025) [113], advanced materials and manufacturing processes (Erhimefe and Gideon, 2025) [102] and safe semiconductor process optimisation (Ogunnowo *et al*., 2025) [213] are relevant to the downhole electronics and sensors whose survival depends on the predicted circulating temperature.

3.6.9 Process Safety and Occupational Health in Drilling Operations

Drilling fluid hydraulics are central to well control and therefore to process safety. Underestimating ECD can induce losses, overestimating it can allow an influx, and poor hole cleaning can lead to stuck pipe and hazardous recovery work. Operational integrity frameworks for high-risk drilling (Nwangwu *et al*., 2018) [158] and process safety models that integrate human factors into offshore commissioning (Oduro, 2023) [200] stress that engineering models must sit within a safety management system. Risk-based process engineering, HAZOP and reliability integration, and management-of-change effectiveness (Asibor and Isong, 2019; Asibor *et al*., 2023; Makut *et al*., 2022b) [53, 55, 146], control-room alarm management, shift handovers, safe process protocols, operational decision-making in process upsets and the supervisor as a human barrier (Ekelemu, 2025a; Ekelemu, 2025b; Ekelemu, 2025c; Ekelemu *et al*., 2025a; Ekelemu *et al*., 2025c) [92, 93, 94], and permit-to-work and gas testing for hot work (Ekelemu and Akano, 2025a; Ekelemu *et al*., 2025b) [93, 95] provide lessons that transfer to rig operations.

Occupational safety research adds further dimensions: heat stress in extreme environments (Arumosoye and Obriki, 2018) [43], near-miss and hazard observation data (Arumosoye and Obriki, 2019; Obogo *et al*., 2021a) [44, 175], contractor and subcontractor safety governance (Arumosoye and Obriki, 2020; Obogo *et al*., 2021c; Obriki and Arumosoye, 2024a) [45, 186, 193], organisational learning and the institutionalisation of safe practice (Arumosoye and Obriki, 2021; Obriki and Arumosoye, 2021) [46, 190], lifting, rigging and crane operations (Arumosoye and Obriki, 2022; Obogo *et al*., 2020b) [47, 173], emergency response readiness and evacuation (Arumosoye and Obriki, 2023; Obriki *et al*., 2022b) [48, 198], safety leadership and culture (Arumosoye and Obriki, 2024; Obogo *et al*., 2023; Obogo *et al*., 2019a; Obriki and Arumosoye, 2019) [49, 177, 183, 188], predictive and data-driven safety analytics (Obriki and Arumosoye, 2018; Obriki and Arumosoye, 2023; Obriki *et al*., 2023a; Obriki *et al*., 2025) [187, 192, 195, 196], QHSE audit and occupational safety management systems in oil and gas maintenance (Obogo *et al*., 2020a; Obogo *et al*., 2020c; Obogo *et al*., 2021b; Obogo *et al*., 2022) [172, 174, 178, 179], hazard identification and construction risk governance (Obogo *et al*., 2025a; Obogo *et al*., 2025b; Obogo *et al*., 2019b; Obogo *et al*., 2019c) [181, 182, 184, 185], human error and unsafe behaviour (Obriki and Arumosoye, 2020; Obriki and Arumosoye, 2022; Obriki *et al*., 2023b) [189, 191, 199], incident investigation (Obriki and Arumosoye, 2024b) [194], and workforce training and

technician mentorship (Obriki *et al*., 2022a; Amarahobu *et al*., 2025a) [36, 197]. Using model-predicted ECD margins, bed height and circulating temperature as leading safety indicators is a promising way to connect these approaches with the hydraulic and thermal models reviewed here.

3.6.10 Supply Chain, Project Delivery and the Energy Transition

Applying these models in practice also depends on the timely supply of fluid materials, additives and equipment, and on sound project governance. Procurement and supply chain research in energy and gas processing covers supply chain risk and resilience (Agbabiaka *et al*., 2019; Ogunwole *et al*., 2021) [20, 214], GIS-enabled procurement and vendor evaluation (Ahiaeke Patrick *et al*., 2020; Ahiaeke Patrick *et al*., 2021) [22, 23], strategic sourcing, dual sourcing and pandemic resilience for energy equipment and fuel (Asibor *et al*., 2019; Asibor *et al*., 2021; Babayemi *et al*., 2020) [53, 58, 68], digital supply chain governance, predictive procurement, ERP adoption and automation (Okonkwo *et al*., 2024a; Okonkwo *et al*., 2024b; Okonkwo *et al*., 2024c; Okonkwo *et al*., 2024d; Okonkwo *et al*., 2024e; Okonkwo *et al*., 2024f; Okonkwo *et al*., 2025; Okonkwo *et al*., 2023b) [216, 217, 218, 219, 220, 221, 224, 225], port logistics (Okonkwo *et al*., 2020) [222], materials readiness, asset lifecycle and inventory availability (Okonkwo *et al*., 2021a; Okonkwo *et al*., 2023a; Okonkwo *et al*., 2018b) [223, 226, 229], regulatory-compliant and strategic procurement in oil and gas (Okonkwo *et al*., 2021b; Okonkwo *et al*., 2018a) [227, 228], vendor governance (Okonkwo *et al*., 2019) [230], and energy-efficient logistics (Opara *et al*., 2024) [237]. Project governance for multinational infrastructure and energy projects (Amayo *et al*., 2023; Amayo *et al*., 2024a) [38, 39], project management for solar deployments (Amayo *et al*., 2024b; Amayo *et al*., 2025) [40, 41], critical-path scheduling and predictive schedule risk (Makut *et al*., 2021b; Zhou *et al*., 2024; Zhou *et al*., 2025) [144, 272, 273] inform how well construction programmes are planned and controlled.

Drilling fluid flow and thermal modelling are also moving beyond oil and gas as the energy system changes. Geothermal exploration uses remote sensing interpretation of hydrothermal alteration (Dagodzo, 2018c) [82], and geothermal and hydrogen storage wells must fit within broader low-carbon systems, including hydrogen infrastructure and grid integration (Monye *et al*., 2025b; Shittu *et al*., 2019) [152, 256], hybrid solar-diesel and solar microgrids (Ijiga *et al*., 2023b; Sunday and Omoegun, 2018; Sunday and Omoegun, 2019; Komi and Adeniji, 2020) [121, 131, 260, 261], smart grids, battery storage and control of distributed energy resources (Adenuga, 2022; Komi and Adamolekun, 2022; Komi and Ganiu, 2022) [14, 130, 133], utility-scale portfolio optimisation (Ilesanmi *et al*., 2024) [122], renewable propane (Monye *et al*., 2025a) [151], power electronics (Tackie *et al*., 2023) [265], photovoltaic materials (Atta *et al*., 2024) [62], and alternative fuels (Bello *et al*., 2023) [71]. The thermal and hydraulic models reviewed here are a shared foundation for drilling across this wider portfolio of energy wells.

3.7. Integrated Conceptual Model

The synthesis shows that rheology, hydraulics, cuttings transport and heat transfer are usually modelled separately, while in the well they interact continuously. Figure 1 proposes an integrated conceptual model that makes these interactions explicit and connects them with the solution methods, predicted well states and decisions identified in Sections 3.1 to 3.6.

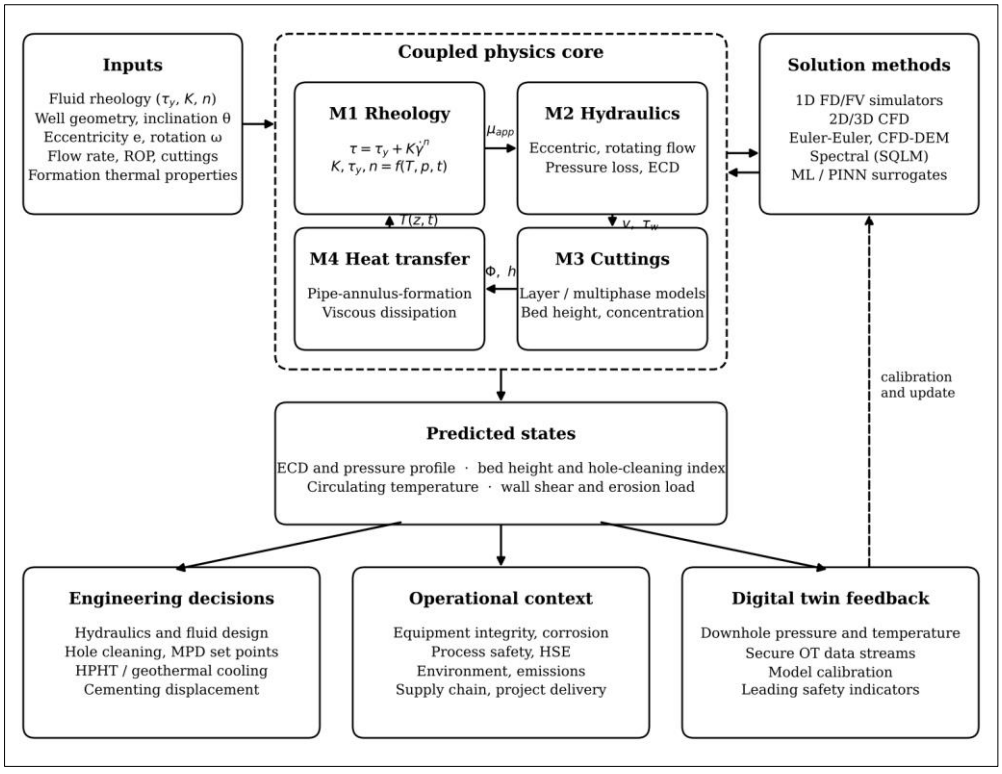


Fig 1: Integrated conceptual model of coupled non-Newtonian drilling fluid flow, cuttings transport and heat transfer in horizontal and inclined wellbores.

3.7.1 Structure of the Model

The model has five layers. The input layer holds fluid rheology, well geometry and inclination, eccentricity and rotation, operating parameters (flow rate, rate of penetration and cuttings properties) and formation thermal properties. The coupled physics core contains four modules. M1 (rheology) supplies the apparent viscosity through a Herschel-Bulkley law whose parameters depend on temperature, pressure and shear history (Section 3.1). M2 (hydraulics) computes the eccentric, rotating annular flow and returns velocity, wall shear stress, frictional pressure loss and ECD (Section 3.2). M3 (cuttings transport) uses these to predict bed height and cuttings concentration, which in turn reduce the open flow area seen by M2 (Section 3.3). M4 (heat transfer) computes pipe, annulus and formation temperatures, including viscous dissipation and convective coefficients that depend on the flow and bed state, and feeds temperature back to M1 (Section 3.4).

If Θ denotes the vector of well states (temperature, pressure and bed profiles along the well), the core can be written as a fixed-point problem solved iteratively within each time step:

$$\Theta^{(k+1)} = M_4 \circ M_3 \circ M_2 \circ M_1(\Theta^{(k)}) \qquad (18)$$

The solution layer selects a method according to the fidelity and speed required: one-dimensional simulators for planning and real-time use, cross-sectional and three-dimensional CFD and CFD-DEM for closure development, spectral methods for verification benchmarks, and machine learning surrogates for fast inference (Section 3.5). The output layer gives the predicted states: ECD and pressure profile, bed height and a hole-cleaning index, circulating temperature, and wall shear and erosion load. The decision layer maps these outputs onto engineering decisions (hydraulics, hole cleaning, managed pressure set points, cooling and cementing) and onto the operational context of equipment integrity, process safety, environmental performance and supply chain delivery (Section 3.6). Finally, a feedback loop uses downhole pressure and temperature data, carried over secure operational technology networks, to calibrate the model in the manner of a digital twin (Ogunnowo *et al*., 2024a; Adegbite *et al*., 2024b) [9, 207].

3.7.2 Propositions

The model leads to five propositions that can be tested in future work.

- **P1.** In eccentric annuli with yield-stress fluids, the extent of the unyielded region in the narrow gap is a leading indicator of bed formation, and should be reported as a hole-cleaning output in its own right.
- **P2.** In deep, HPHT and geothermal wells, neglecting the M4 to M1 coupling introduces errors in ECD comparable to or larger than those arising from the choice between three-parameter rheological models.
- **P3.** High-fidelity CFD and CFD-DEM add most value as generators of closure relations and training data for faster models, rather than as direct design tools.
- **P4.** The engineering value of hydraulic and thermal models is realised only when their outputs are connected to operational decision layers through calibrated, secure feedback.
- **P5.** Spectral and analytical solutions provide inexpensive verification benchmarks that should accompany the release of new numerical codes.

3.8. Discussion of Findings

3.8.1 Areas of Consensus

Across the reviewed literature there is broad agreement on several points. The Herschel-Bulkley model is the accepted constitutive basis for modern muds (Kelessidis *et al*., 2006; API RP 13D, 2017) [42, 125]. Slot and variable-slot approximations give acceptable accuracy for single-phase hydraulics at a fraction of the cost of full solutions. The non-monotonic dependence of cuttings transport on inclination, with the most difficult range between about 30 and 60 degrees, is well established experimentally (Tomren *et al*., 1986; Sifferman and Becker, 1992) [258, 266]. Layer models provide a sound physical basis for cuttings transport, and transient numerical wellbore-formation models have replaced steady analytical solutions for thermal design (Corre *et al*., 1984; Kabir *et al*., 1996; Hasan and Kabir, 2002) [78, 117, 123].

3.8.2 Contradictions and Unresolved Questions

Several findings remain contested. The effect of drillstring rotation on pressure loss changes sign with geometry and fluid: rotation reduces losses in concentric annuli with shear-thinning fluids but can increase them in eccentric annuli, and orbital motion and buckling alter the picture further (Ahmed and Miska, 2008; Erge *et al*., 2015; Saasen, 2014) [25, 101, 253]. Turbulent flow does not guarantee bed removal, because the narrow gap may remain laminar or unyielded. Predicted plug zones are sensitive to the regularisation parameters used in numerical codes (Papanastasiou, 1987) [245], so results from different codes are not always comparable. Empirical critical-velocity correlations transfer poorly beyond their data sets, and convective heat transfer correlations derived for pipes are of uncertain accuracy in eccentric annuli.

3.8.3 Fidelity Versus Usability

A recurring tension is between physical fidelity and practical usability. One-dimensional simulators run in real time but rely on closures, while CFD-DEM resolves particle physics but only for a few metres of well. The conceptual model resolves this tension by assigning methods to roles: high-fidelity tools generate closures and training data, and fast models carry them to the rig. Physics-informed and hybrid surrogates are the most promising bridge (Raissi *et al*., 2019) [247], provided their uncertainty is quantified and their outputs are presented in ways that support human judgement (Ashore-Onisemo *et al*., 2025) [51].

3.8.4 Transferability from Adjacent Literature

Boundary-layer studies of non-Newtonian and nanofluid flows over stretching sheets, inclined surfaces and rotating disks (Agbaje *et al*., 2025; Oluwaseun *et al*., 2023; Oluwaseun and Agbaje, 2025) [21, 232, 233] show clearly how constitutive behaviour, viscous dissipation, slip and particle effects alter heat transfer, and the spectral methods used to solve them are highly accurate. Their geometries differ from an eccentric annulus with cuttings, however, so their quantitative results should be treated as mechanistic insight and verification material rather than as design values.

Similarly, much of the contextual literature on integrity, safety, analytics and supply chains is conceptual. Its value for this review lies in framing how model outputs should be used, not in providing quantitative evidence about drilling fluid behaviour.

3.8.5 Data and Validation as the Main Bottleneck

The single most important constraint across all strands is the shortage of high-quality validation data. Flow loops use short sections, simplified fluids and artificial cuttings; field data rarely include direct measurements of bed height or of temperature profiles; and few data sets combine non-Newtonian rheology, eccentricity, rotation, inclination and heat transfer. Until such data are available, coupled models will continue to be validated piece by piece, and the propositions in Section 3.7.2 will remain only partly tested.

3.9. Implications

3.9.1 Implications for Research

Researchers should report rheological parameters, regularisation settings, eccentricity, rotation and thermal boundary conditions in full, so that studies can be compared and combined. Coupled models should be developed and tested against the couplings listed in Table 6 rather than against single-physics benchmarks alone, and new codes should be verified against analytical and spectral solutions before validation against experiments.

Table 6: Couplings in the conceptual model.

Link	Variables passed	Mechanism	Main supporting literature
M1 to M2	Apparent viscosity, yield stress	Shear-thinning and plug formation in eccentric gap	Haciislamoglu and Langlinais (1990) [116]; Escudier *et al*. (2002) [103]
M2 to M3	Velocity, wall and bed shear	Bed erosion, deposition and sliding	Gavignet and Sobey (1989) [111]; Nguyen and Rahman (1998) [153]
M3 to M2	Bed height, open flow area	Flow area reduction raises friction and ECD	Larsen *et al*. (1997) [137]; Kamp and Rivero (1999) [124]
M2/M3 to M4	Velocity field, dissipation, h	Convection, viscous heating, bed insulation	Corre *et al*. (1984) [78]; Kabir *et al*. (1996) [123]
M4 to M1	Temperature profile	Temperature and pressure dependence of K, τ_y, n	Alderman *et al*. (1988) [30]; Rommetveit and Bjørkevoll (1997) [252]

3.9.2 Implications for Drilling Engineering Practice

For engineers, the review supports using temperature-corrected Herschel-Bulkley rheology together with eccentricity and rotation corrections as the minimum standard for ECD prediction in horizontal and inclined wells. Hole-cleaning plans should treat flow rate, rotation and fluid properties together, and should pay particular attention to the 30 to 60 degree range and to static periods. In HPHT and geothermal wells, coupled thermal-hydraulic modelling should be routine rather than exceptional. Model outputs can also serve as leading indicators within safety and integrity programmes (Nwangwu *et al*., 2018; Obriki *et al*., 2025) [158, 196].

3.9.3 Implications for Operators, Regulators and Industry

Operators and service companies can capture more value from models by linking them with real-time data, condition monitoring and secure operational technology (Adaramola *et al*., 2018; Adegbite *et al*., 2024b) [1, 9], and by integrating model-based planning with procurement and logistics so that the fluids and equipment the models call for are available when needed (Agbabiaka *et al*., 2019; Okonkwo *et al*., 2024c) [20, 218]. Regulators and industry bodies could accelerate progress by supporting open benchmark data sets and by encouraging the use of validated coupled models in well design reviews for high-risk wells, including those that handle environmental and waste-management obligations (Falegan and Aniebonam, 2022) [105].

3.9.4 Implications for Education and Workforce Development

The growing complexity of coupled models and digital tools requires drilling engineers who understand both the physics and the limits of the models. Structured training and mentorship (Obriki *et al*., 2022a; Amarahobu *et al*., 2025a) [36, 197] should therefore include non-Newtonian fluid mechanics, numerical methods and the interpretation of model-based advice alongside traditional drilling practice.

4. Conclusion

Non-Newtonian drilling fluid flow and heat transfer in horizontal and inclined wellbores involves strongly coupled physics: viscoplastic and shear-thinning rheology, eccentric annular geometry with a rotating and moving drillstring, gravity-driven cuttings settling, and transient heat exchange with a formation whose temperature varies with depth. The Herschel-Bulkley model, with temperature and pressure corrections, has become the accepted rheological basis. Slot and variable-slot approximations, eccentricity and rotation corrections, and generalised Reynolds number criteria provide efficient single-phase hydraulics. Two-layer and three-layer mechanistic models provide a physical basis for cuttings transport that empirical correlations lack. Heat transfer modelling has moved from steady analytical solutions to transient numerical wellbore-formation models, yet treatment of non-Newtonian convective heat transfer in eccentric annuli remains approximate.

Using an integrative review of 273 sources, this paper has addressed four research questions. On RQ1, it found that the main model families are mature individually but are rarely coupled. On RQ2, it found that the available numerical methods span a wide range of fidelity and cost, and that validation is their weakest link. On RQ3, it showed that model outputs inform a wide set of engineering and operational decisions, from hydraulics design to integrity, safety, environmental and supply chain management. On RQ4, it proposed an integrated conceptual model, five testable propositions and a research agenda.

Numerical methods now span one-dimensional simulators for planning and real-time use, two- and three-dimensional CFD for closure development, and Euler-Euler and CFD-DEM

methods for multiphase detail, with machine learning surrogates emerging to connect them. The main challenge for the coming years is integration: coupled thermo-hydraulic-cuttings models validated against high-quality benchmark data, capable of running in real time, and robust enough for HPHT, extended-reach and geothermal wells. Progress in this direction will directly improve well safety, reduce non-productive time, and lower the cost of drilling the complex wells on which future energy supply increasingly depends.

4.1. Limitations

This review has several limitations. First, it follows an integrative rather than a fully systematic protocol; screening counts were not recorded in a PRISMA-style flow diagram, so the corpus cannot be reproduced exactly. Second, the search was limited to English-language sources in the databases listed in Section 2.2, which may have excluded relevant work published in other languages, particularly from China, Russia and Brazil, and the review may reflect publication bias towards positive results. Third, the heterogeneity of geometries, fluids and methods prevented quantitative meta-analysis, so the conclusions rest on qualitative synthesis. Fourth, much of the contextual literature consists of conceptual frameworks rather than empirical studies, and its transfer to drilling operations is inferential. Fifth, the conceptual model and its propositions have not yet been tested against field data. Finally, the fields of machine learning and digital twins are moving quickly, and work published after the 2025 cut-off is not included.

4.2. Future Research Directions

Building on the gaps identified in the review and on the propositions of the conceptual model, the following research priorities are proposed.

- **Fully coupled models.** Few models couple non-Newtonian annular flow, cuttings transport and heat transfer with temperature-dependent rheology in a single framework validated at field scale. Thermal effects on bed behaviour in horizontal sections are almost unexplored.
- **Yield stress and thixotropy.** Regularisation parameters strongly affect predicted plug zones and stagnant regions. Thixotropic models are needed for pump start-up, surge and swab, and post-connection hole cleaning, but are rarely included.
- **Drillstring dynamics.** Realistic whirl, lateral vibration, buckling and tool joints influence both flow and heat transfer but are computationally expensive to resolve. Reduced models that capture their average effect are needed.
- **Turbulence in non-Newtonian fluids.** Turbulence models for shear-thinning and viscoplastic fluids in eccentric annuli with rotation are not well validated, particularly in the transitional regime.
- **Granular closures.** Euler-Euler models depend on closures for solids stress, drag in non-Newtonian fluids, and bed friction that were developed for Newtonian or gas-solid systems.
- **Benchmark data.** There is a pressing need for open, standardised experimental and field data sets with well-characterised rheology, geometry, rotation, temperature and cuttings measurements to support model comparison.
- **Advanced constitutive models and nanofluids.** Viscoelastic, Carreau, micropolar and nanoparticle-enhanced fluid models, so far studied mainly in simplified geometries, need to be tested in eccentric annuli with cuttings and validated against real mud data.
- **Integration with operations.** Hydraulic and thermal models need to be linked with integrity management, process safety systems, secure operational technology and supply chain planning so that model outputs reach the decisions they are meant to inform.
- **Hybrid physics and data methods.** Physics-informed machine learning and reduced-order models can bridge high-fidelity simulation and real-time use, but require careful uncertainty quantification.
- **New applications.** Geothermal, closed-loop geothermal, carbon storage and hydrogen storage wells introduce new fluids, temperatures and geometries that existing correlations may not cover.

Table 7: Nomenclature

Symbol	Description	Symbol	Description
C_p	Specific heat capacity, J/(kg·K)	Re	Reynolds number
D_h	Hydraulic diameter, m	T	Temperature, K
e	Eccentricity (dimensionless)	U	Overall heat transfer coefficient
f	Fanning friction factor	v	Mean velocity, m/s
h	Convective heat transfer coefficient	θ	Inclination from vertical
K	Consistency index, Pa·s^n	$\dot{\gamma}$	Shear rate, 1/s
k	Thermal conductivity, W/(m·K)	μ_p	Plastic viscosity, Pa·s
n	Flow behaviour index	ρ	Density, kg/m^3
Nu	Nusselt number	τ	Shear stress, Pa
Pr	Prandtl number	τ_y	Yield stress, Pa
Q	Volumetric flow rate, m^3/s	ω	Drillpipe rotation speed, rad/s

References

1. Adaramola TS, Fadero S, Gideon EN. Predictive maintenance and condition monitoring in critical power and energy infrastructure. Iconic Research and Engineering Journals. 2018;2(5):454-477. doi:10.64388/IREV2I5-1722489
2. Adebayo A, Adegbite MP, Ahmed MO. Adversarial machine learning in critical infrastructure: A conceptual framework for threat modeling AI enabled OT systems. World Journal of Innovation and Modern Technology. 2022;6(1):184-234. doi:10.56201/wjimt.v6.no1.2022.pg184.234
3. Adebayo A, Adegbite MP, Ahmed MO. AI augmented threat detection in industrial control systems: A systematic review of machine learning approaches for ICS anomaly detection. International Journal of

Engineering and Modern Technology. 2023;9(3):287-340. doi:10.56201/ijcsmt.v9.no3.2023.pg287.340
4. Adebayo A, Amadi C, Ijagbemi AO. From audit to continuous control: Implementation pathways, governance, and organizational readiness for AI-enabled compliance in critical infrastructure. International Journal of Computer Science and Mathematical Theory. 2025;11(8):88-134. doi:10.56201/ijcsmt.vol.11.no8.2025.pg88.134
5. Adegbite MP, Adebayo A, Ahmed MO. Securing operational technology networks in electric utilities: A systematic review of NERC CIP compliance and architectural threat mitigation. International Journal of Engineering and Modern Technology. 2020;6(3):103-146. doi:10.56201/ijemt.vol.6.no3.2020.pg103.146
6. Adegbite MP, Adebayo A, Ahmed MO. A security architecture model for IT and OT convergence in regulated energy networks: Design principles and governance alignment. International Journal of Computer Science and Mathematical Theory. 2022;8(2):81-132. doi:10.56201/ijcsmt.v8.no2.2022.pg81.132
7. Adegbite MP, Adebayo A, Ahmed MO. ICS and SCADA threat detection architectures in energy sector networks: A systematic review of SIEM, NDR, and anomaly detection approaches. World Journal of Innovation and Modern Technology. 2023;7(2):121-182. doi:10.56201/wjimt.v7.no2.2023.pg121.182
8. Adegbite MP, Adebayo A, Ahmed MO. A vulnerability governance architecture for power and utilities corporations: From exposure mapping to remediation verification. World Journal of Innovation and Modern Technology. 2024;8(6):185-246. doi:10.56201/wjimt.v8.no6.2024.pg185.246
9. Adegbite MP, Adebayo A, Ahmed MO. An AI driven security operations architecture for utility sector SOCs: Integrating threat intelligence, behavioral analytics, and automated response. International Journal of Engineering and Modern Technology. 2024;10(11):197-256. doi:10.56201/ijemt.v10.no11.2024.pg197.256
10. Adegbite MP, Adebayo A, Ahmed MO. A cyber risk quantification and governance architecture for critical infrastructure: From posture measurement to executive reporting. International Journal of Computer Science and Mathematical Theory. 2025;11(12):232-293. doi:10.56201/ijcsmt.vol.11.no12.2025.pg232.293
11. Adelanwa A, Basnet A, Anene UN. Data driven digital transformation models for lifecycle performance management in infrastructure delivery. International Journal of Advanced Multidisciplinary Research and Studies. 2023;3(6):2646-2662. doi:10.62225/2583049X.2023.3.6.5968
12. Adelanwa A, Basnet A, Anene UN. Predictive analytics models for financial risk detection and fraud prevention in public systems. International Journal of Advanced Multidisciplinary Research and Studies. 2023;3(6). doi:10.62225/2583049X.2023.3.6.5969
13. Adelanwa A, Basnet A, Anene UN. Performance intelligence models for optimization and outcome measurement in large scale public services. Shodhshauryam, International Scientific Refereed Research Journal. 2024;6(1).
14. Adenuga OM. Smart grid architectures and energy distribution for high renewable penetration: A comprehensive review of technologies, operations, and deployment pathways. International Journal of Engineering and Modern Technology. 2022;8(5):125-155. doi:10.56201/ijemt.v8.no5.2022.pg125.155
15. Adewoyin MA, Ogunnowo EO, Fiemotongha JE, Igunma TO, Adeleke AK. A conceptual framework for dynamic mechanical analysis in high-performance material selection. Iconic Research and Engineering Journals. 2020;4(5):137-155.
16. Adewoyin MA, Ogunnowo EO, Fiemotongha JE, Igunma TO, Adeleke AK. Advances in thermofluid simulation for heat transfer optimization in compact mechanical devices. Iconic Research and Engineering Journals. 2020;4(6):116-133.
17. Adewoyin MA, Ogunnowo EO, Fiemotongha JE, Igunma TO, Adeleke AK. Advances in CFD-driven design for fluid-particle separation and filtration systems in engineering applications. Iconic Research and Engineering Journals. 2021;5(3):347-365.
18. Adewoyin MA, Ogunnowo EO, Fiemotongha JE, Igunma TO, Adeleke AK. Systematic review of AI-augmented corrosion modeling techniques in infrastructure and manufacturing systems. Journal of Frontiers in Multidisciplinary Research. 2023;4(1):362-380. doi:10.54660/.JFMR.2023.4.1.362-380
19. Adewoyin MA, Ogunnowo EO, Fiemotongha JE, Igunma TO, Adeleke AK. Advances in AI-based optimization for multiphysics fluid dynamics in product design engineering. International Journal of Scientific Research in Science and Technology. 2024;11(2):1046-1081. doi:10.32628/IJSRST251222713
20. Agbabiaka J, Okonkwo CS, Ogunwole O, Mayo W, Okeke OT. Supply chain risk management model for EPC and gas processing projects. Iconic Research and Engineering Journals. 2019;3(2):968-980. doi:10.64388/IREV3I2-1713124
21. Agbaje TM, Oluwaseun F, Mishra SR, Baithalu R, Panda S. Analyzing radiative heat on third-grade fluids over an expanding inclined sheet subject to higher-order chemical reaction: An overlapping grid spectral quasilinearization approach. Partial Differential Equations in Applied Mathematics. 2025;13:101098. doi:10.1016/j.padiff.2025.101098
22. Ahiaeke Patrick MC, Okonkwo CS, Mayo W, Okeke OT. A GIS enabled framework for modern ERP procurement processes. International Journal of Multidisciplinary Research and Growth Evaluation. 2020;1(5):499-508. doi:10.54660/IJMRGE.2020.1.5.499-508
23. Ahiaeke Patrick MC, Okonkwo CS, Mayo W, Okeke OT. Model for data driven vendor evaluation and bid selection using geospatial intelligence. Shodhshauryam, International Scientific Refereed Research Journal. 2021;4(4):426-443. doi:10.32628/SHISRRJ214461
24. Ahmed MO, Adegbite MP, Adebayo A. Zero trust architecture for operational technology in North American critical infrastructure: A framework for implementation and resilience optimization. International Journal of Engineering and Modern Technology. 2021;7(1):66-113. doi:10.56201/ijemt.vol.7.no1.2021.pg66.113
25. Ahmed RM, Miska SZ. Experimental study and modeling of yield power-law fluid flow in annuli with

drillpipe rotation. IADC/SPE Drilling Conference, Orlando, SPE-112604-MS; 2008.
26. Akhshik S, Behzad M, Rajabi M. CFD-DEM approach to investigate the effect of drill pipe rotation on cuttings transport behavior. Journal of Petroleum Science and Engineering. 2015;127:229-244.
27. Aladegba OA, Ayinde M. From analytical chemistry to predictive toxicology: A review of data pipelines linking environmental measurement to health prediction. International Journal of Technology, Management and Humanities. 2024;10(3):185-216. doi:10.21590/10.03.15
28. Aladegba OA, Ayinde M, Agwuna LU. Toward personalized prevention of environmentally induced cancers: A conceptual model coupling exposure biomarkers with individual susceptibility. Indian Journal of Environment & Development. 2021;12(1):1-28. doi:10.21590/ijed.12.01.01
29. Aladegba OA, Ayinde M, Agwuna LU. AI-enabled early-warning and decision support for environmentally induced cancer in e-waste and automobile-recycling communities: A conceptual public-health framework. Journal of Contemporary Science and Technology Management. 2025;1(4):79-124. doi:10.66592/9nf8wx05
30. Alderman NJ, Gavignet A, Guillot D, Maitland GC. High-temperature, high-pressure rheology of water-based muds. SPE Annual Technical Conference and Exhibition, Houston, SPE-18035-MS; 1988.
31. Alieme JI, Sule A, Obukadata VO. The business analyst as an AI-transformation broker: A framework for stakeholder alignment, responsible automation, and value realization in small and medium-sized enterprises. International Journal of Economics and Business Management. 2025;11(8):299-355. doi:10.56201/ijebm.vol.11.no8.2025.pg299.355
32. Amadi C. An autonomous, continuously-learning framework for real-time cyber-physical threat prevention in legacy SCADA systems. World Journal of Innovation and Modern Technology. 2025;9(8):148-183. doi:10.56201/wjimt.v9.no8.2025.pg148.183
33. Amadi C, Adebayo A, Ijagbemi AO. AI-based security posture management as an enabling layer for real-time NIST Cybersecurity Framework adherence: A theory-grounded conceptual framework. World Journal of Innovation and Modern Technology. 2025;9(8):99-147. doi:10.56201/wjimt.v9.no8.2025.pg99.147
34. Amadi C, Adebayo A, Ijagbemi AO. Deep learning architectures for anomaly detection in SCADA networks: A comparative analysis of LSTM, CNN, and hybrid LSTM-autoencoder models. International Journal of Engineering and Modern Technology. 2025;11(8):352-392. doi:10.56201/ijemt.vol.11.no8.2025.pg352.392
35. Amadi C, Adebayo A, Ijagbemi AO. The cyber-physical attack surface of legacy SCADA networks: A systematic review of vulnerabilities, threats, and detection gaps in critical infrastructure. International Journal of Computer Science and Mathematical Theory. 2025;11(8):135-169. doi:10.56201/ijcsmt.vol.11.no8.2025.pg135.169
36. Amarahobu C, Ekelemu O, Akano OA, Adikwu FE. Structured mentorship models in on-the-job technician development: A review of advancement and promotion coaching schemes, workplace learning theory and the leadership interface in continuous processing environments. International Journal of Social Sciences and Management Research. 2025;11(8):626-656. doi:10.56201/ijssmr.vol.11no8.2025.pg626.656
37. Amarahobu C, Ekelemu O, Akano OA, Adikwu FE. Transition management and flare reduction across the liquefaction operating cycle: Gas disposition, valve sequencing and procedural complexity in start-up, shutdown and mode change. International Journal of Engineering and Modern Technology. 2025;11(8):516-543. doi:10.56201/ijemt.vol.11.no8.2025.pg516.543
38. Amayo EB, Owulade OA, Isi LR. Optimizing project governance in multinational infrastructure projects: Insights from General Electric's global operations. International Journal of Multidisciplinary Research and Growth Evaluation. 2023;4(1):975-983. doi:10.54660/.IJMRGE.2023.4.1.975-983
39. Amayo EB, Owulade OA, Isi LR. Effective project governance in multinational infrastructure projects: A case study from General Electric. Iconic Research and Engineering Journals. 2024;8(5):1305-1324.
40. Amayo EB, Owulade OA, Isi LR. Strategic project management approaches for successful solar energy deployments in emerging markets: Lessons from West Africa. Iconic Research and Engineering Journals. 2024;7(11):783-803.
41. Amayo EB, Owulade OA, Isi LR. Project management strategies in renewable energy deployments: A focus on solar power in West Africa. International Journal of Management and Entrepreneurship Research. 2025;7(3):266-284. doi:10.51594/ijmer.v7i3.1845
42. American Petroleum Institute. API RP 13D: Rheology and Hydraulics of Oil-Well Drilling Fluids, 7th ed. API, Washington, DC. 2017.
43. Arumosoye OM, Obriki OD. Development of an integrated heat stress risk conceptual model for industrial operations in extreme environments. Iconic Research and Engineering Journals. 2018;1(12):141-160. doi:10.64388/IREV1I12-1714415
44. Arumosoye OM, Obriki OD. Systematic review of near-miss and hazard observation data utilization in industrial safety management. Iconic Research and Engineering Journals. 2019;3(2):981-999. doi:10.64388/IREV3I2-1714417
45. Arumosoye OM, Obriki OD. A governance-oriented conceptual model for contractor safety performance in multi-contract industrial projects. International Journal of Multidisciplinary Research and Growth Evaluation. 2020;1(5):728-740. doi:10.54660/.IJMRGE.2020.1.5.728-740
46. Arumosoye OM, Obriki OD. Organizational learning-based conceptual maturity model for continuous safety performance improvement. International Journal of Multidisciplinary Research and Growth Evaluation. 2021;2(1):970-980. doi:10.54660/.IJMRGE.2021.2.1.970-980
47. Arumosoye OM, Obriki OD. Conceptual risk pathway model for lifting and rigging operations in heavy industrial construction. Gyanshauryam, International Scientific Refereed Research Journal. 2022;5(5):346-369. doi:10.32628/GISRRJ2256237
48. Arumosoye OM, Obriki OD. Conceptual model for emergency response readiness and capability in energy and process facilities. International Journal of Scientific

Research in Computer Science, Engineering and Information Technology. 2023;9(3):897-917. doi:10.32628/CSEIT25112791
49. Arumosoye OM, Obriki OD. Conceptual model of safety leadership influence in large temporary project organizations. International Journal of Advanced Multidisciplinary Research and Studies. 2024;4(6):3034-3047. doi:10.62225/2583049X.2024.4.6.5895
50. Arumosoye OM, Obriki OD, Ozobu CO. Conceptual framework for environmental risk control and ESG performance through waste handling and operational discipline. Gyanshauryam, International Scientific Refereed Research Journal. 2025;8(4):177-198. doi:10.32628/GISRRJ258367
51. Ashore-Onisemo F, Unamma UML, Okwesa IJ. Human-in-the-loop decision systems: Advances and future directions. International Journal of Social Sciences and Management Research. 2025;11(8):565-608. doi:10.56201/ijssmr.vol.11no8.2025.pg565.608
52. Asibor E. Artificial intelligence applications for detecting process failures across oil and gas facilities. International Journal of Technology, Health and Sustainability. 2025;1(2):350-373.
53. Asibor E, Isong DE. Risk-based process engineering framework for strengthening reliability across complex natural gas infrastructure systems. Iconic Research and Engineering Journals. 2019;3(2):1020-1060. doi:10.64388/IREV3I2-1723153
54. Asibor E, Isong DE. Flare-gas recovery technologies for advancing energy security, environmental performance, and resource efficiency. Iconic Research and Engineering Journals. 2020;4(1):369-410. doi:10.64388/IREV4I1-1723154
55. Asibor E, Ninduwezuor-Ehiobu N, Olisakwe HC. Integrating HAZOP, reliability analysis, and risk-based decision-making into critical energy infrastructure design. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. 2023;9(1):958-999. doi:10.32628/CSEIT2391574
56. Asibor E, Ojeakhena F, Uwagboe FM, Babayemi DG. Strategic sourcing and contract design for reliable fuel and equipment supply in energy operations. Iconic Research and Engineering Journals. 2019;3(5):710-714. doi:10.64388/IREV3I5-1724088
57. Asibor E, Olisakwe HC. Methane emissions reduction strategies for safer and more efficient petroleum production operations. International Journal of Multidisciplinary Research and Growth Evaluation. 2022;3(4):739-763. doi:10.54660/.IJMRGE.2022.3.4.739-763
58. Asibor E, Uwagboe FM, Ojeakhena F, Babayemi DG. Dual sourcing for critical energy equipment under exchange-rate and fuel-price volatility. International Journal of Multidisciplinary Research and Growth Evaluation. 2021;2(6):1307-1330. doi:10.54660/.IJMRGE.2021.2.6.1307-1330
59. Atta S, Adjaklo E, Asomani E, Adenuga OM. Advances in welding inspection standards and quality assurance practices in large-scale power generation projects. International Journal of Engineering and Modern Technology. 2022;8(5):101-124. doi:10.56201/ijemt.v8.no5.2022.pg101.124
60. Atta S, Asomani E, Adenuga OM. A systematic review of green corrosion inhibitors from agricultural extracts for mild steel protection in acidic and alkaline media. International Journal of Engineering and Modern Technology. 2018;4(1):64-97. doi:10.56201/ijemt.vol.4.no1.2018.pg64.97
61. Atta S, Kerubo ML, Sabisa NE, Adu-Gyamfi D, Appiah S, Onyishi E. Environmental corrosion and long-term degradation of crystalline silicon solar cells: Mechanisms, climate effects and mitigation strategies. Current Journal of Applied Science and Technology. 2025;44(10):9-18.
62. Atta S, Onyishi EE, Appiah SA, Adenuga OM. Theoretical analysis of charge transport and recombination losses in thin film solar cell architectures. International Journal of Engineering and Modern Technology. 2024;10(10):147-170. doi:10.56201/ijemt.v10.no10.2024.pg147.170
63. Atta S, Tofah P, Adenuga OM. Advances in non-destructive testing methods for weld integrity evaluation in high-capacity power infrastructure. International Journal of Engineering and Modern Technology. 2021;7(1):20-47. doi:10.56201/ijemt.vol.7.no1.2021.pg20.47
64. Atta S, Tofah P, Kankam MA, Adenuga OM. A critical review of NDT-based integrity management and corrosion risk assessment strategies for refinery process equipment. International Journal of Engineering and Modern Technology. 2020;6(2):19-46. doi:10.56201/ijemt.vol.6.no2.2020.pg19.46
65. Azeez LO, Badmus O. Innovative data integration method for enhancing GHG inventory reporting accuracy and reliability. Global Multidisciplinary Perspectives Journal. 2024;1(6):166-181.
66. Azeez LO, Badmus O. Predictive analytical framework for identifying vapor intrusion risks across urban redevelopment zones. International Journal of Scientific Research in Humanities and Social Sciences. 2024;1(1):524-555.
67. Azeez LO, Badmus OB. Data-driven framework for predicting subsurface contamination pathways in complex remediation projects. Iconic Research and Engineering Journals. 2018;2(5):312-335.
68. Babayemi DG, Asibor E, Okonkwo C. Maintaining essential energy supplies during pandemic disruptions: A procurement resilience framework. Iconic Research and Engineering Journals. 2020;4(4):466-470. doi:10.64388/IREV4I4-1724087
69. Badmus O. Integrated predictive and remote-sensing framework for early warning and regulatory compliance in environmentally sensitive urban zones. IIARD International Journal of Geography and Environmental Management. 2025;11(12):212-239.
70. Baithalu R, Oluwaseun F, Agbaje TM, Mishra SR, Panda S. Thermophoretic particle deposition in a mixed convective bioconvection nanofluid with thermal radiation and chemical reaction over an exponential stretching sheet. Multiscale and Multidisciplinary Modeling, Experiments and Design. 2025;8(4):220. doi:10.1007/s41939-025-00805-3
71. Bello KA, Azeez TM, Tawose OM, Odesanya KO, Odumosu OA, Oyelaran OA. Investigating the influence of rubber seed oil and used cooking oil on diesel. E3S

Web of Conferences. 2023;430:01217. doi:10.1051/e3sconf/202343001217
72. Bingham EC. Fluidity and Plasticity. McGraw-Hill, New York; 1922.
73. Bird RB, Stewart WE, Lightfoot EN. Transport Phenomena, 2nd ed. Wiley, New York. 2002.
74. Busch A, Johansen ST. Cuttings transport: On the effect of drill pipe rotation and lateral motion on the cuttings bed. Journal of Petroleum Science and Engineering. 2020;191:107136.
75. Casson N. A flow equation for pigmented-oil suspensions of the printing ink type. In: Mill, C.C. (Ed.), Rheology of Disperse Systems. Pergamon Press, London; 1959. p. 84-104.
76. Chhabra RP, Richardson JF. Non-Newtonian Flow and Applied Rheology, 2nd ed. Butterworth-Heinemann, Oxford. 2008.
77. Clark RK, Bickham KL. A mechanistic model for cuttings transport. SPE Annual Technical Conference and Exhibition, New Orleans, SPE-28306-MS; 1994.
78. Corre B, Eymard R, Guenot A. Numerical computation of temperature distribution in a wellbore while drilling. SPE Annual Technical Conference and Exhibition, Houston, SPE-13208-MS; 1984.
79. Cundall PA, Strack ODL. A discrete numerical model for granular assemblies. Géotechnique. 1979;29(1):47-65.
80. Dagodzo D. A conceptual framework for UAV integration into national power grid inspection programs. Iconic Research and Engineering Journals. 2018;2(5):391-412. doi:10.64388/IREV2I5-1716082
81. Dagodzo D. A review of UAV applications in electrical transmission line inspection: Methods, technologies, and challenges. Iconic Research and Engineering Journals. 2018;2(6):234-254. doi:10.64388/IREV2I6-1716083
82. Dagodzo D. Hydrothermal alteration interpretation of LANDSAT and ASTER data. Lambert Academic Publishing; 2018.
83. Dagodzo D, Ahiaeke Patrick MC. UAV-based pipeline and corridor monitoring: A review of current practices and emerging technologies. Iconic Research and Engineering Journals. 2020;3(10):574-597. doi:10.64388/IREV3I10-1716084
84. Dagodzo D, Ahiaeke Patrick MC. A review of GIS applications in utility asset management and infrastructure planning. Iconic Research and Engineering Journals. 2021;5(3):468-492. doi:10.64388/IREV5I3-1716085
85. Dagodzo D, Ahiaeke Patrick MC. An integrated framework for UAV, LiDAR, and GIS in infrastructure corridor management. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. 2021;7(5):497-524. doi:10.32628/CSEIT217566
86. Dagodzo D, Ahiaeke Patrick MC. A review of right-of-way encroachment detection methods using geospatial technologies. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. 2022;8(1):638-667. doi:10.32628/CSEIT2281226
87. Dagodzo D, Ahiaeke Patrick MC. A framework for integrating drone operations into enterprise GIS systems for utility companies. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. 2023;9(4):924-957. doi:10.32628/CSEIT23564536
88. Dagodzo D, Ahiaeke Patrick MC. A review of UAV regulatory frameworks in developing economies: Progress, gaps, and recommendations. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. 2023;9(4):958-994. doi:10.32628/CSEIT23564537
89. Dagodzo D, Ahiaeke Patrick MC. A framework for national-scale UAV deployment in power infrastructure: Lessons from developing economies. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. 2025;11(4):779-824. doi:10.32628/CSEIT251116286
90. Dagodzo D, Ahiaeke Patrick MC, Aliliele C. AI and deep learning for vegetation classification in power corridor management: A review. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. 2022;8(1):668-698. doi:10.32628/CSEIT2281227
91. Dodge DW, Metzner AB. Turbulent flow of non-Newtonian systems. AIChE Journal. 1959;5(2):189-204.
92. Ekelemu O. Control room alarm management and human factors in large liquefied natural gas facilities: A comprehensive review of rationalization frameworks, operator response, and the elimination of standing and inhibited alarms. International Journal of Engineering and Modern Technology. 2025;11(8):352-396. doi:10.56201/ijemt.vol.11.no8.2025.pg352.396
93. Ekelemu O. Cross-shift information loss and the standardization of logbook handovers: A critical review of communication failure and continuity protocols in continuous processing operations. International Journal of Engineering and Modern Technology. 2025;11(8):397-424. doi:10.56201/ijemt.vol.11.no8.2025.pg397.424
94. Ekelemu O. Embedding ensure safe process protocols in daily panel operations: A conceptual framework for the transition from reactive alert handling to proactive trend analysis. International Journal of Engineering and Modern Technology. 2025;11(8):425-457. doi:10.56201/ijemt.vol.11.no8.2025.pg425.457
95. Ekelemu O, Akano OA. Isolation control certificates and permit-to-work compliance in turnaround projects: A technical review of barrier health verification during complex train turnarounds and brownfield tie-ins. International Journal of Social Sciences and Management Research. 2025;11(8):565-596. doi:10.56201/ijssmr.vol.11no8.2025.pg565.596
96. Ekelemu O, Akano OA. Loss detection and integrity surveying in liquefaction header systems: Flare hunting, attribution and programme design for unintended flow to flare. International Journal of Engineering and Modern Technology. 2025;11(8):458-487. doi:10.56201/ijemt.vol.11.no8.2025.pg458.487
97. Ekelemu O, Akano OA, Adikwu FE, Amarahobu C. Operational decision-making in high-consequence process upsets: A comparative analysis of intervention dynamics, diagnostic constraint and the location of authority. International Journal of Social Sciences and Management Research. 2025;11(8):597-625. doi:10.56201/ijssmr.vol.11no8.2025.pg597.625
98. Ekelemu O, Akano OA, Adikwu FE, Amarahobu C. Standardized gas testing protocols for authorized gas

safety inspectors in high-risk hot work operations: A conceptual model for pre-shift testing and the maintenance of zero-incident boundaries. International Journal of Engineering and Modern Technology. 2025;11(8):488-515. doi:10.56201/ijemt.vol.11.no8.2025.pg488.515

99. Ekelemu O, Akano OA, Adikwu FE, Amarahobu C. The shift supervisor as an active human barrier: A conceptual treatment of human barriers as critical integrity controls in process bowtie models for loss of primary containment. International Journal of Social Sciences and Management Research. 2025;11(8):657-689. doi:10.56201/ijssmr.vol.11no8.2025.pg657.689
100. Epelle EI, Gerogiorgis DI. A multiparametric CFD analysis of multiphase annular flows for oil and gas drilling applications. Computers & Chemical Engineering. 2017;106:645-661.
101. Erge O, Ozbayoglu EM, Miska SZ, Yu M, Takach N, Saasen A, *et al*. The effects of drillstring-eccentricity, -rotation, and -buckling configurations on annular frictional pressure losses while circulating yield-power-law fluids. SPE Drilling & Completion. 2015;30(3):257-271.
102. Erhimefe DE, Gideon E. Developing advanced materials and manufacturing processes for high-performance, energy-efficient, and scalable 3D integrated circuits (ICs) and devices. International Journal of Research Publication and Reviews. 2025;6(4):2624-2630. doi:10.55248/gengpi.6.0425.1402
103. Escudier MP, Oliveira PJ, Pinho FT. Fully developed laminar flow of purely viscous non-Newtonian liquids through annuli, including the effects of eccentricity and inner-cylinder rotation. International Journal of Heat and Fluid Flow. 2002;23(1):52-73.
104. Ezeugwa EC, Oluokun OA, Ogunnowo E. Predictive modeling framework for renewable energy yield forecasting. Iconic Research and Engineering Journals. 2023;6(9):514-544.
105. Falegan OC, Aniebonam SO. Conceptual framework for lifecycle risk assessment in offshore produced water management. Gyanshauryam, International Scientific Refereed Research Journal. 2022;5(5):322-345.
106. Falegan OC, Aniebonam SO. Integrated physicochemical and bio-based treatment strategies for produced water in arid environments: A review. Gyanshauryam, International Scientific Refereed Research Journal. 2023;6(1):425-443.
107. Falegan OC, Aniebonam SO. Decentralized produced water treatment systems for remote energy assets: A conceptual design framework. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. 2024;10(3):1133-1151.
108. Falegan OC, Aniebonam SO. Resource recovery and beneficial reuse of produced water in energy operations: A review of sustainable pathways. International Journal of Advanced Multidisciplinary Research and Studies. 2025;5(6):1959-1969. doi:10.62225/2583049X.2025.5.6.5678
109. Founargiotakis K, Kelessidis VC, Maglione R. Laminar, transitional and turbulent flow of Herschel-Bulkley fluids in concentric annulus. Canadian Journal of Chemical Engineering. 2008;86(4):676-683.
110. Fredrickson AG, Bird RB. Non-Newtonian flow in annuli. Industrial & Engineering Chemistry. 1958;50(3):347-352.
111. Gavignet AA, Sobey IJ. Model aids cuttings transport prediction. Journal of Petroleum Technology. 1989;41(9):916-921.
112. Gidaspow D. Multiphase Flow and Fluidization: Continuum and Kinetic Theory Descriptions. Academic Press, San Diego; 1994.
113. Gideon E, Erhimefe DE. Damage mechanisms in semiconductor materials caused by non-ionizing energy in space-based solar systems. International Journal of Research Publication and Reviews. 2025;6(4):5940-5949. doi:10.55248/gengpi.6.0425.14128
114. Gideon EN. Evaluation of semiconductor risk mitigation strategies in the electric vehicle supply chain. International Journal of Research Publication and Reviews. 2025;6(4):5934-5939. doi:10.55248/gengpi.6.0425.14129
115. Gideon EN, Adaramola TS, Fadero S. Reliability engineering and failure analysis in complex engineering systems. Iconic Research and Engineering Journals. 2019;2(11):703-727. doi:10.64388/IREV2I11-1722490
116. Haciislamoglu M, Langlinais J. Non-Newtonian flow in eccentric annuli. Journal of Energy Resources Technology. 1990;112(3):163-169.
117. Hasan AR, Kabir CS. Fluid Flow and Heat Transfer in Wellbores. Society of Petroleum Engineers, Richardson, TX; 2002.
118. Herschel WH, Bulkley R. Konsistenzmessungen von Gummi-Benzollösungen. Kolloid-Zeitschrift. 1926;39:291-300.
119. Holmes CS, Swift SC. Calculation of circulating mud temperatures. Journal of Petroleum Technology. 1970;22(6):670-674.
120. Ijiga OM, Enyejo LA, Jinadu SO, Akinleye KE, Onwusi CN, Raphael FO. Engineering atmospheric CO2 utilization strategies for revitalizing mature American oil fields and creating economic resilience. Engineering Science and Technology Journal. 2023;4(6):741-760.
121. Ijiga OM, Oladoye SO, Bamigwojo OV, Ogboji AJ. Techno-economic evaluation of hybrid solar-diesel microgrids for underserved communities using simulation-based load forecasting. Engineering Science and Technology Journal. 2023;4:1-28.
122. Ilesanmi MO, Okoh OF, Balogun SA, Ijiga OM. Data-driven portfolio optimization for utility-scale solar, wind, and battery energy storage systems (BESS): Integrating performance analytics with investor EBITDA targets. International Journal of Scientific Research and Modern Technology. 2024;3(11):141-155.
123. Kabir CS, Hasan AR, Kouba GE, Ameen MM. Determining circulating fluid temperature in drilling, workover, and well-control operations. SPE Drilling & Completion. 1996;11(2):74-79.
124. Kamp AM, Rivero M. Layer modeling for cuttings transport in highly inclined wellbores. SPE Latin American and Caribbean Petroleum Engineering Conference, Caracas, SPE-53942-MS; 1999.
125. Kelessidis VC, Maglione R, Tsamantaki C, Aspirtakis Y. Optimal determination of rheological parameters for Herschel-Bulkley drilling fluids and impact on pressure drop, velocity profiles and penetration rates during

drilling. Journal of Petroleum Science and Engineering. 2006;53(3-4):203-224.
126. Keller HH, Couch EJ, Berry PM. Temperature distribution in circulating mud columns. SPE Journal. 1973;13(1):23-30.
127. Komi NM. Hybrid deep learning for wind power forecasting: From grid stability to market equity for small generators. International Journal of Multidisciplinary Research and Growth Evaluation. 2021;2(6):989-1014. doi:10.54660/.IJMRGE.2021.2.6.989-1014
128. Komi NM. When accurate forecasts are not fair forecasts: Deep learning load prediction and equity across districts. Shodhshauryam, International Scientific Refereed Research Journal. 2023;6(6):476-546. doi:10.32628/SHISRRJ247102
129. Komi NM, Adamolekun A. Interpretable machine learning for early failure prediction in distributed renewable energy assets. International Journal of Multidisciplinary Research and Growth Evaluation. 2021;2(6):1015-1038. doi:10.54660/.IJMRGE.2021.2.6.1015-1038
130. Komi NM, Adamolekun A. Hierarchical, decentralized, or hybrid? A systematic review of control architectures for distributed energy resources. International Journal of Engineering and Modern Technology. 2022;8(5):141-195. doi:10.56201/ijemt.v8.no5.2022.pg141.195
131. Komi NM, Adeniji IO. Co-optimizing technical performance and community affordability in smart solar microgrids for underserved regions. International Journal of Engineering and Modern Technology. 2020;6(3):173-212. doi:10.56201/ijemt.vol.6.no3.2020.pg173.212
132. Komi NM, Adeniji IO. A tiered digital twin that brings predictive diagnostics to resource-constrained renewable energy sites. International Journal of Engineering and Modern Technology. 2023;9(3):287-347. doi:10.56201/ijemt.v9.no3.2023.pg287.347
133. Komi NM, Ganiu OS. Grid-connected battery storage in hot and weak-grid regions: Advances, degradation challenges, and lifecycle equity. International Journal of Multidisciplinary Research and Growth Evaluation. 2022;3(6):1072-1095. doi:10.54660/.IJMRGE.2022.3.6.1072-1095
134. Komi NM, Ganiu OS. Edge intelligence for resilient microgrid control: Advances, energy sovereignty, and open challenges. Gyanshauryam, International Scientific Refereed Research Journal. 2023;6(3):525-586. doi:10.32628/GISRRJ236339
135. Lamidi OBA. Comprehensive evaluation model for improving carbon accounting accuracy in corporate sustainability programs. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. 2023;10(1):825-853. doi:10.32628/IJSRCSEIT
136. Lamidi OBA, Olamide A. Spatially explicit risk modeling framework for tracking subsurface contaminant migration in data-limited remediation sites. Iconic Research and Engineering Journals. 2018;2(6):178-198.
137. Larsen TI, Pilehvari AA, Azar JJ. Development of a new cuttings-transport model for high-angle wellbores including horizontal wells. SPE Drilling & Completion. 1997;12(2):129-136.
138. Li J, Luft B. Overview of solids transport studies and applications in oil and gas industry: Experimental work. SPE Russian Oil and Gas Exploration & Production Technical Conference, Moscow, SPE-171285-MS; 2014.
139. Liadi KO, Opara IS, Elumilade RA, Shittu H, Adeniji IO. A comprehensive review of direct air capture technologies for carbon removal. International Journal of Advanced Multidisciplinary Research and Studies. 2024;4(6):2961-2967. doi:10.62225/2583049X.2024.4.6.5737
140. Makut SO, Ojeakhena F, Obetta PC, Olisakwe HC. Engineering design optimization of floating production, storage, and offloading facilities for improved safety and production reliability. International Journal of Multidisciplinary Research and Growth Evaluation. 2021;2(6):1285-1306. doi:10.54660/.IJMRGE.2021.2.6.1285-1306
141. Makut SO, Ojeakhena F, Obetta PC, Olisakwe HC. A systems engineering framework for mechanical equipment reliability and operational risk reduction in deepwater production facilities. International Journal of Science, Technology and Society. 2022;6(1):101-127. doi:10.18091/ijsts.v6i1-140
142. Makut SO, Ojeakhena F, Olisakwe HC. Risk-based front-end engineering design for improving safety and operational efficiency in offshore oil and gas production facilities. International Journal of Humanities and Information Technology(Special Issue 1) 104-130; 2021. doi:10.21590/ijhit.spcl.01.07
143. Makut SO, Olisakwe HC. Engineering optimization of gas gathering and vapor recovery systems for flare reduction in onshore oil and gas facilities. International Journal of Multidisciplinary Research and Growth Evaluation. 2022;3(6):1281-1303. doi:10.54660/.IJMRGE.2022.3.6.1281-1303
144. Makut SO, Olutimehin AO, Bankole AO. Integrating critical path scheduling and resource optimization in building construction projects: A risk-based project delivery framework. International Journal of Science, Technology and Society. 2021;5(1&2):172-196. doi:10.18091/ijsts.v5i1&2.16
145. Makut SO, Olutimehin AO, Bankole AO. Integrating building information modeling and lifecycle reliability assessment for sustainable building infrastructure: A conceptual framework. International Journal of Technology Management & Humanities. 2024;10(3):255-280. doi:10.21590/ijtmh.10.03.469
146. Makut SO, Uwagboe FM, Olisakwe HC. Process safety management and management of change effectiveness in mature oil and gas production operations. International Journal of Multidisciplinary Research and Growth Evaluation. 2022;3(6):1304-1326. doi:10.54660/.IJMRGE.2022.3.6.1304-1326
147. Marshall DW, Bentsen RG. A computer model to determine the temperature distributions in a wellbore. Journal of Canadian Petroleum Technology. 1982;21(1):63-75.
148. Mayo W, Ogbole JI, Okoruwa PO, Babatope OM. Designing an AI-predictive maintenance model for e-commerce systems using machine learning and cloud analytics. International Journal of Scientific Research in Computer Science, Engineering and Information

Technology. 2021;7(5):416-440. doi:10.32628/IJSRCSEIT
149. Metzner AB, Reed JC. Flow of non-Newtonian fluids: Correlation of the laminar, transition, and turbulent-flow regions. AIChE Journal. 1955;1(4):434-440.
150. Mitchell RF, Miska SZ, editors. Fundamentals of Drilling Engineering. SPE Textbook Series Vol. 12, Society of Petroleum Engineers, Richardson, TX; 2011.
151. Monye SI, Bello KA, Omotehinse SA, Ikumapayi OM, Tawose OM, Adeleke TB, *et al*. Achieving energy sustainability in Nigeria's telecommunications industry through renewable propane. NIPES Journal of Science and Technology Research. 2025;7(2):3320-3325. doi:10.37933/nipes/7.4.2025.SI398
152. Monye SI, Daniyan IA, Monye NS, Ikumapayi OM, Bello KA, Boboye O, *et al*. Hydrogen infrastructure for a sustainable future: Challenges, innovations, and global opportunities. NIPES Journal of Science and Technology Research. 2025;7(2):3302-3308. doi:10.37933/nipes/7.4.2025.SI395
153. Nguyen D, Rahman SS. A three-layer hydraulic program for effective cuttings transport and hole cleaning in highly deviated and horizontal wells. SPE Drilling & Completion. 1998;13(3):182-189.
154. Nwakamma S, Ojukwu J, Oyesiji SO. On-device multimodal small language models for privacy-preserving edge intelligence through quantization, pruning, distillation, and energy-efficient inference. World Journal of Innovation and Modern Technology. 2025;9(12):271-302. doi:10.56201/wjimt.v9.no12.2025.pg271.302
155. Nwangwu CV, Duvbiama-Owasanoye OA, Akano OA. Aligning capital budgeting with field development execution in the upstream petroleum sector. Gyanshauryam, International Scientific Refereed Research Journal. 2021;4(4):259-282.
156. Nwangwu CV, Duvbiama-Owasanoye OA, Akano OA. Resource discovery in mature asset portfolios: A review of longitudinal data trends for subsurface value extraction. Gyanshauryam, International Scientific Refereed Research Journal. 2022;5(3):503-524.
157. Nwangwu CV, Duvbiama-Owasanoye OA, Akano OA. Technical due diligence and supply chain integration in energy M&A: A review of large-scale asset acquisitions. Shodhshauryam, International Scientific Refereed Research Journal. 2023;6(2):513-539.
158. Nwangwu CV, Duvbiama-Owasanoye OA, Onwumere A. A framework for operational integrity in high-risk drilling: Balancing productivity and safety compliance. Iconic Research and Engineering Journals. 2018;2(5):436-453.
159. Nwangwu CV, Duvbiama-Owasanoye OA, Onwumere A. High-fidelity reservoir forecasting: A technical review of multimodal modeling for long-term production estimates. Iconic Research and Engineering Journals. 2020;4(5):390-409.
160. Obetta PC. A risk-based inspection concept for fitness-for-service assessment of ageing pressure vessels on offshore joint venture facilities. Iconic Research and Engineering Journals. 2018;2(5):497-520. doi:10.64388/IREV2I5-1722578
161. Obetta PC. Reliability and integrity management of fired heaters, boilers and furnaces in upstream oil and gas: A review. Iconic Research and Engineering Journals. 2019;3(5):599-626. doi:10.64388/IREV3I5-1722580
162. Obetta PC. A reliability-centered maintenance (RCM) concept for static mechanical equipment in offshore oil and gas operations. International Journal of Multidisciplinary Futuristic Development. 2020;1(1):74-91. doi:10.54660/IJMFD.2020.1.1.74-91
163. Obetta PC, Ninduwezuor-Ehiobu N. A condition-based maintenance concept for CALM buoy bearings and swivels to improve offshore crude export availability. Iconic Research and Engineering Journals. 2018;2(6):385-410. doi:10.64388/IREV2I6-1722579
164. Obetta PC, Ninduwezuor-Ehiobu N. Integrity assurance of FSO turret mooring systems: A review of inspection, monitoring and life-extension strategies. Iconic Research and Engineering Journals. 2019;3(6):599-629. doi:10.64388/IREV3I6-1722581
165. Obetta PC, Ninduwezuor-Ehiobu N, Olisakwe HC. Corrosion management and material selection for crude oil export equipment in marine environments: A review. International Journal of Multidisciplinary Futuristic Development. 2020;1(1):92-110. doi:10.54660/IJMFD.2020.1.1.92-110
166. Obetta PC, Ninduwezuor-Ehiobu N, Olisakwe HC. Advances in non-intrusive inspection of pressure vessels: Reducing shutdown frequency and OPEX in oil and gas operations. International Journal of Multidisciplinary Research and Growth Evaluation. 2021;2(6):1137-1153. doi:10.54660/.IJMRGE.2021.2.6.1137-1153
167. Obetta PC, Ninduwezuor-Ehiobu N, Olisakwe HC. A conceptual framework for optimizing tandem offloading operations of FSO units in deepwater fields. International Journal of Multidisciplinary Research and Growth Evaluation. 2022;3(6):1219-1238. doi:10.54660/.IJMRGE.2022.3.6.1219-1238
168. Obetta PC, Ninduwezuor-Ehiobu N, Olisakwe HC. A CMMS-based concept for optimizing preventive and corrective maintenance of static mechanical equipment. International Journal of Engineering and Modern Technology. 2023;9(3):287-319. doi:10.56201/ijcsmt.v9.no3.2023.pg287.319
169. Obetta PC, Ninduwezuor-Ehiobu N, Olisakwe HC. Cause-tree failure analysis of pressure vessel breakdowns: A review of root-cause-driven maintenance frameworks. Research Journal of Pure Science and Technology. 2024;7(6):120-174. doi:10.56201/rjpst.v7.no6.2024.pg120.174
170. Obetta PC, Ninduwezuor-Ehiobu N, Olisakwe HC. Advances in IoT-enabled condition monitoring for offshore static mechanical maintenance programs. International Journal of Technology, Health and Sustainability. 2025;1(2):142-159.
171. Obetta PC, Ninduwezuor-Ehiobu N, Olisakwe HC. Advances in risk-based inspection of offloading hose strings in offshore crude export systems. International Journal of Technology, Health and Sustainability. 2025;1(2):160-177.
172. Obogo SF, Arumosoye OM, Obriki OD. Advances in internal QHSE audit systems for industrial engineering operations. Iconic Research and Engineering Journals. 2020;4(4):399-417. doi:10.64388/IREV4I4-1715499
173. Obogo SF, Arumosoye OM, Obriki OD. Conceptual risk management model for heavy lifting and crane

installation engineering operations. Shodhshauryam, International Scientific Refereed Research Journal. 2020;3(4):122-144. doi:10.32628/SHISRRJ214441
174. Obogo SF, Arumosoye OM, Obriki OD. Critical review of occupational safety management systems in oil and gas maintenance projects. Shodhshauryam, International Scientific Refereed Research Journal. 2020;3(4):145-166. doi:10.32628/SHISRRJ214442
175. Obogo SF, Arumosoye OM, Obriki OD. Advances in proactive hazard recognition and near miss reporting systems. International Journal of Multidisciplinary Research and Growth Evaluation. 2021;2(6):835-846. doi:10.54660/IJMRGE.2021.2.6.835-846
176. Obogo SF, Arumosoye OM, Obriki OD. Review of sustainable environmental practices in occupational safety management systems. International Journal of Scientific Research in Civil Engineering. 2024;8(3):164-196. doi:10.32628/IJSRCE248420
177. Obogo SF, Nwafor MI, Ozobu CO. Conceptual leadership model for safety culture development in construction and engineering projects. International Journal of Scientific Research in Civil Engineering. 2023;7(6):121-153. doi:10.32628/IJSRCE237554
178. Obogo SF, Obriki OD, Arumosoye OM. Conceptual model for incident prevention in industrial maintenance engineering environments. International Journal of Multidisciplinary Research and Growth Evaluation. 2021;2(6):847-858. doi:10.54660/IJMRGE.2021.2.6.847-858
179. Obogo SF, Obriki OD, Arumosoye OM. Conceptual safety governance model for large commercial facility operations. Gyanshauryam, International Scientific Refereed Research Journal. 2022;5(6):383-410. doi:10.32628/GISRRJ225639
180. Obogo SF, Ozobu CO, Nwafor MI. Conceptual environmental safety compliance framework for construction and infrastructure projects. International Journal of Scientific Research in Civil Engineering. 2024;8(3):132-163. doi:10.32628/IJSRCE248419
181. Obogo SF, Ozobu CO, Nwafor MI, Adio SA. Advances in hazard identification systems for large scale construction operations. International Journal of Scientific Research in Civil Engineering. 2025;9(6):37-70. doi:10.32628/IJSRCE2154969
182. Obogo SF, Ozobu CO, Sanusi AN, Ajirotutu RO. Conceptual integrated safety management model for multi zone urban infrastructure projects. International Journal of Scientific Research in Civil Engineering. 2025;9(5):22-55. doi:10.32628/IJSRCE2593012
183. Obogo SF, Ozobu CO, Uduokhai DO. Advances in leadership driven safety culture transformation in large construction workforces. Iconic Research and Engineering Journals. 2019;3(5):507-523. doi:10.64388/IREV3I5-1715497
184. Obogo SF, Ozobu CO, Uduokhai DO. Development of a construction safety risk governance model for multi contractor high rise projects. Iconic Research and Engineering Journals. 2019;2(9):502-522. doi:10.64388/IREV2I9-1715495
185. Obogo SF, Uduokhai DO, Ozobu CO. Systematic review of hazard identification and risk control practices in urban construction projects. Iconic Research and Engineering Journals. 2019;2(12):666-681. doi:10.64388/IREV2I12-1715496
186. Obogo SF, Uduokhai DO, Ozobu CO. Review of contractor safety compliance systems in infrastructure engineering projects. International Journal of Scientific Research in Civil Engineering. 2021;5(4):76-100. doi:10.32628/IJSRCE215412
187. Obriki OD, Arumosoye OM. Conceptual modeling of data-driven occupational safety risk control in large-scale energy infrastructure projects. Iconic Research and Engineering Journals. 2018;1(7):169-189. doi:10.64388/IREV1I7-1714414
188. Obriki OD, Arumosoye OM. A conceptual framework linking management safety walkthrough frequency and coverage to safety culture outcomes in mega projects. Iconic Research and Engineering Journals. 2019;2(8):355-374. doi:10.64388/IREV2I8-1714416
189. Obriki OD, Arumosoye OM. Conceptual framework for human error causation in high-risk construction and industrial activities. International Journal of Multidisciplinary Research and Growth Evaluation. 2020;1(5):715-727. doi:10.54660/.IJMRGE.2020.1.5.715-727
190. Obriki OD, Arumosoye OM. Conceptual model for institutionalizing life-preserving safety practices across project-based organizations. International Journal of Multidisciplinary Research and Growth Evaluation. 2021;2(1):961-969. doi:10.54660/.IJMRGE.2021.2.1.961-969
191. Obriki OD, Arumosoye OM. Conceptual framework explaining recurrence mechanisms of unsafe behaviors in high-hazard worksites. Shodhshauryam, International Scientific Refereed Research Journal. 2022;5(3):380-402. doi:10.32628/SHISRRJ225489
192. Obriki OD, Arumosoye OM. Conceptual framework for proactive hazard identification using digital safety data streams. Gyanshauryam, International Scientific Refereed Research Journal. 2023;6(3):457-481. doi:10.32628/GISRRJ236336
193. Obriki OD, Arumosoye OM. Conceptual governance framework for subcontractor safety performance management. International Journal of Advanced Multidisciplinary Research and Studies. 2024;4(6):3020-3033. doi:10.62225/2583049X.2024.4.6.5894
194. Obriki OD, Arumosoye OM. Systematic review of incident investigation approaches and prevention-oriented learning in industrial operations. Shodhshauryam, International Scientific Refereed Research Journal. 2024;7(4):239-263. doi:10.32628/SHISRRJ247163
195. Obriki OD, Arumosoye OM, Obogo SF. Advances in continuous hazard monitoring systems for workplace safety. International Journal of Advanced Multidisciplinary Research and Studies. 2023;3(6):2742-2759. doi:10.62225/2583049X.2023.3.6.6075
196. Obriki OD, Arumosoye OM, Ozobu CO. Conceptual model linking leading safety signals to sustained injury-free project performance. International Journal of Scientific Research in Humanities and Social Sciences. 2025;2(3):233-254. doi:10.32628/IJSRHSS252342
197. Obriki OD, Obogo SF, Arumosoye OM. Advances in workforce safety training models for operational risk reduction. Gyanshauryam, International Scientific

Refereed Research Journal. 2022;5(6):349-382. doi:10.32628/GISRRJ225638
198. Obriki OD, Obogo SF, Arumosoye OM. Review of emergency preparedness and evacuation systems in high density commercial buildings. Gyanshauryam, International Scientific Refereed Research Journal. 2022;5(6):411-438. doi:10.32628/GISRRJ225640
199. Obriki OD, Obogo SF, Arumosoye OM. Review of behavioral safety programs for risk reduction in large workforces. International Journal of Advanced Multidisciplinary Research and Studies. 2023;3(6):2760-2775. doi:10.62225/2583049X.2023.3.6.6076
200. Oduro M. Process safety model integrating human factors within offshore pipeline commissioning operations systems. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. 2023;10(1):934-957.
201. Ofei TN, Irawan S, Pao W. CFD method for predicting annular pressure losses and cuttings concentration in eccentric horizontal wells. Journal of Petroleum Engineering. 2014;2014:486423.
202. Ogunnowo E, Awodele D, Parajuli V, Zhang N. CFD simulation and optimization of a cake filtration system. In: Proceedings of the ASME 2023 International Mechanical Engineering Congress and Exposition (IMECE2023) (Paper No. IMECE2023-112836); 2023. doi:10.1115/IMECE2023-112836
203. Ogunnowo EO, Adewoyin MA, Fiemotongha JE, Igunma TO, Adeleke AK. Systematic review of non-destructive testing methods for predictive failure analysis in mechanical systems. Iconic Research and Engineering Journals. 2020;4(4):207-222.
204. Ogunnowo EO, Adewoyin MA, Fiemotongha JE, Igunma TO, Adeleke AK. A conceptual model for simulation-based optimization of HVAC systems using heat flow analytics. Iconic Research and Engineering Journals. 2021;5(2):206-221.
205. Ogunnowo EO, Adewoyin MA, Fiemotongha JE, Igunma TO, Adeleke AK. Advances in predicting microstructural evolution in superalloys using directed energy deposition data. Journal of Frontiers in Multidisciplinary Research. 2022;3(1):258-274. doi:10.54660/.JFMR.2022.3.1.258-274
206. Ogunnowo EO, Adewoyin MA, Fiemotongha JE, Igunma TO, Adeleke AK. A conceptual framework for reliability-centered design of mechanical components using FEA and DFMEA integration. Journal of Frontiers in Multidisciplinary Research. 2023;4(1):342-361. doi:10.54660/.JFMR.2023.4.1.342-361
207. Ogunnowo EO, Adewoyin MA, Fiemotongha JE, Igunma TO, Adeleke AK. A conceptual framework for digital twin deployment in real-time monitoring of mechanical systems. International Journal of Advanced Multidisciplinary Research and Studies. 2024;4(6):2350-2367. doi:10.62225/2583049X.2024.4.6.4353
208. Ogunnowo EO, Ogu E, Egbumokei PI, Dienagha IN, Digitemie WN. Theoretical framework for dynamic mechanical analysis in material selection for high-performance engineering applications. Open Access Research Journal of Multidisciplinary Studies. 2021;1(2):117-131. doi:10.53022/oarjms.2021.1.2.0027
209. Ogunnowo EO, Ogu E, Egbumokei PI, Dienagha IN, Digitemie WN. Theoretical model for predicting microstructural evolution in superalloys under directed energy deposition (DED) processes. Magna Scientia Advanced Research and Reviews. 2022;5(1):76-89. doi:10.30574/msarr.2022.5.1.0040
210. Ogunnowo EO, Ogu E, Egbumokei PI, Dienagha IN, Digitemie WN. Conceptual model for failure analysis and prevention in critical infrastructure using advanced non-destructive testing. Iconic Research and Engineering Journals. 2024;7(10):444-464.
211. Ogunnowo EO, Ogu E, Egbumokei PI, Dienagha IN, Digitemie WN. Conceptual model for topology optimization in mechanical engineering to enhance structural efficiency and material utilization. Iconic Research and Engineering Journals. 2024;7(12):523-543.
212. Ogunnowo EO, Ogu E, Egbumokei PI, Dienagha IN, Digitemie WN. Development of a predictive model for corrosion behavior in infrastructure using non-destructive testing data. International Journal of Multidisciplinary Research and Growth Evaluation. 2024;5(1):1223-1235. doi:10.54660/IJMRGE.2024.4.6.1223-1235
213. Ogunnowo EO, Ogu E, Egbumokei PI, Dienagha IN, Digitemie WN. A theoretical framework for ensuring safety in semiconductor manufacturing through process optimization and risk assessment. Journal of Materials Science Research and Reviews. 2025;8(1):173-193. doi:10.9734/jmsrr/2025/v8i1388
214. Ogunwole O, Okonkwo CS, Agbabiaka J, Mayo W, Okeke OT. Supply chain resilience framework for critical infrastructure and gas processing plants. Shodhshauryam, International Scientific Refereed Research Journal. 2021;4(4):444-461. doi:10.32628/SHISRRJ214462
215. Ojukwu J, Oyesiji SO, Nwakamma S. Cyber-physical ransomware defense in operational technology using physics-informed detection, digital twins, network telemetry, and resilient recovery. International Journal of Computer Science and Mathematical Theory. 2023;9(5):193-228. doi:10.56201/ijcsmt.v9.no5.2023.pg193.228
216. Okonkwo CS, Agbabiaka J, Mayo W, Okeke OT. Conceptual framework for digital supply chain governance in energy and infrastructure sectors. Gyanshauryam, International Scientific Refereed Research Journal. 2024;7(4):335-356. doi:10.32628/GISRRJ247423
217. Okonkwo CS, Agbabiaka J, Mayo W, Okeke OT. Framework for secure and scalable supply chain systems supporting national energy reliability. International Journal of Advanced Multidisciplinary Research and Studies. 2024;4(6):2816-2826. doi:10.62225/2583049X.2024.4.6.5494
218. Okonkwo CS, Agbabiaka J, Mayo W, Okeke OT. Model for predictive procurement planning to sustain operational uptime. International Journal of Scientific Research in Humanities and Social Sciences. 2024;1(2):909-928. doi:10.32628/IJSRSSH242772
219. Okonkwo CS, Agbabiaka J, Mayo W, Okeke OT. Review of advances in procurement strategy, ERP adoption, and logistics performance. International Journal of Advanced Multidisciplinary Research and

Studies. 2024;4(6):2827-2835. doi:10.62225/2583049X.2024.4.6.5495
220. Okonkwo CS, Agbabiaka J, Mayo W, Okeke OT. Review of digital supply chain models for cost control and operational continuity. International Journal of Advanced Multidisciplinary Research and Studies. 2024;4(6):2836-2846. doi:10.62225/2583049X.2024.4.6.5496
221. Okonkwo CS, Agbabiaka J, Mayo W, Okeke OT. Supply chain automation framework using service management platforms. Shodhshauryam, International Scientific Refereed Research Journal. 2024;7(2):157-177. doi:10.32628/SHISRRJ2472157
222. Okonkwo CS, Agbabiaka J, Ogunwole O, Mayo W, Okeke OT. Model for demurrage elimination and port logistics efficiency in emerging economies. International Journal of Multidisciplinary Research and Growth Evaluation. 2020;1(5):552-562. doi:10.54660/IJMRGE.2020.1.5.552-562
223. Okonkwo CS, Agbabiaka J, Ogunwole O, Mayo W, Okeke OT. Conceptual model for materials readiness and maintenance-driven supply chain performance. International Journal of Multidisciplinary Research and Growth Evaluation. 2021;2(6):584-594. doi:10.54660/IJMRGE.2021.2.6.584-594
224. Okonkwo CS, Agbabiaka J, Okeke OT, Mayo W. Framework for national-scale supply chain optimization through integrated IT and procurement systems. Gulf Journal of Advance Business Research. 2025;3(12):1610-1625. doi:10.51594/gjabr.v3i12.189
225. Okonkwo CS, Ahiaeke Patrick MC, Okeke OT, Mayo W. Framework for integrating IT systems engineering with supply chain operations. International Journal of Advanced Multidisciplinary Research and Studies. 2023;3(6):2580-2589. doi:10.62225/2583049X.2023.3.6.5500
226. Okonkwo CS, Mayo W, Okeke OT. Conceptual model for asset lifecycle management and inventory visibility. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. 2023;10(1):809-824. doi:10.32628/CSEIT2391568
227. Okonkwo CS, Ogunwole O, Mayo W, Okeke OT. Framework for regulatory-compliant procurement in high-risk energy environments. International Journal of Multidisciplinary Research and Growth Evaluation. 2021;2(6):595-605. doi:10.54660/IJMRGE.2021.2.6.595-605
228. Okonkwo CS, Ogunwole O, Okeke OT. Framework for strategic procurement optimization in oil and gas operations. Iconic Research and Engineering Journals. 2018;1(7):153-168. doi:10.64388/IREV1I7-1713119
229. Okonkwo CS, Ogunwole O, Okeke OT. Model for inventory availability and plant uptime improvement in energy facilities. Iconic Research and Engineering Journals. 2018;2(4):160-172. doi:10.64388/IREV2I4-1713120
230. Okonkwo CS, Ogunwole O, Okeke OT, Mayo W. Conceptual framework for cost reduction through contract negotiation and vendor governance. Iconic Research and Engineering Journals. 2019;2(9):468-482. doi:10.64388/IREV2I9-1713121
231. Olodo A, Akanbi O, Adenuga O. Conceptualizing a closed-loop digital twin for real-time plasma control in large-area magnetron sputtering systems. International Journal of Engineering and Modern Technology. 2025;11(12):205-227. doi:10.56201/ijemt.vol.11.no12.2025.pg205.227
232. Oluwaseun F, Agbaje TM. Numerical simulation of hydromagnetic flow and heat transfer of hybrid nanofluid over a rotating disk in a porous medium with slip conditions and Hall current: A Buongiorno model approach. Journal of Nanofluids. 2025;14(3):394-410. doi:10.1166/jon.2025.2248
233. Oluwaseun F, Goqo S, Mondal H. Entropy generation of unsteady magnetohydrodynamics nanofluid flow over a porous inclined stretching surface with velocity slip and viscous dissipation. Journal of Nanofluids. 2023;12(6):1666-1679. doi:10.1166/jon.2023.2025
234. Oluwaseun F, Goqo S, Mondal H. Unsteady squeezing flow and heat transport of SiO2/kerosene oil nanofluid around radially stretchable parallel rotating disks with upper disk oscillating. Propulsion and Power Research. 2024;13(1):64-79. doi:10.1016/j.jppr.2024.02.005
235. Oluwaseun F, Goqo S, Mondal H, Nzama S. Analysis of unsteady ternary hybrid nanofluid flow with magnetic dipole over an oscillatory stretching surface using the bivariate simple iteration method on overlapping grids. Hybrid Advances. 2025;10:100427. doi:10.1016/j.hybadv.2025.100427
236. Omoegun GO, Sunday EA, Essien MA, Oluokun OA. Vibration-based condition monitoring of rotating machinery using LabVIEW. International Journal of Scientific Research in Civil Engineering. 2023;7(6):82-108.
237. Opara IS, Elumilade RA, Liadi KO, Shittu H, Adeniji IO. A theoretical review of synergizing energy efficiency with transportation logistics optimization: Towards a sustainable US infrastructure. International Journal of Advanced Multidisciplinary Research and Studies. 2024;4(6):2968-2975. doi:10.62225/2583049X.2024.4.6.5738
238. Osinem HE, Eribenne F, Gbaraba SV, Peteranaba SF. Environmental pollution and community health in resource-extraction regions: Evidence, gaps, and intervention frameworks. International Journal of Technology, Health and Sustainability. 2025;1(2):178-191.
239. Oyesiji SO, Nwakamma S, Ojukwu J. A conceptual framework for context-aware data curation in fine-tuning pipelines. International Journal of Engineering and Modern Technology. 2024;10(11):197-228. doi:10.56201/ijemt.v10.no11.2024.pg197.228
240. Ozbayoglu EM, Saasen A, Sorgun M, Svanes K. Effect of pipe rotation on hole cleaning for water-based drilling fluids in horizontal and deviated wells. IADC/SPE Asia Pacific Drilling Technology Conference, Jakarta, SPE-114965-MS; 2008.
241. Panda S, Oluwaseun F, Agbaje TM, Baag S, Pattnaik PK. Enhanced thermal performance of magnetized Maxwell hybrid nanofluid transportation over a radiative stretching sheet with exponential heat source. In: Computational and Mathematical Techniques for Heat Transfer and Fluid Dynamics. CRC Press; 2025. p. 93-106. doi:10.1201/9781003642169-6
242. Panda S, Oluwaseun F, Agbaje TM, Baithalu R, Mishra SR. Hall current with multiple slip effects on the forced convection of hybridized nanoliquid with dissipative heat impact utilizing spectral quasi-linearization method.

Nano. 2025;21(2):2550049. doi:10.1142/s1793292025500493
243. Panda S, Oluwaseun F, Agbaje TM, Baithalu R, Mishra SR. Multiple slip effects with Hall current on the three-dimensional hybrid nanofluid flow combining dissipative heat impact over a slandering surface. Journal of Thermal Analysis and Calorimetry. 2025;150(14):11293-11304. doi:10.1007/s10973-025-14440-0
244. Pang B, Wang S, Jiang X, Lu H. Effect of orbital motion of drill pipe on the transport of non-Newtonian fluid-cuttings mixture in horizontal drilling annulus. Journal of Petroleum Science and Engineering. 2019;174:201-215.
245. Papanastasiou TC. Flows of materials with yield. Journal of Rheology. 1987;31(5):385-404.
246. Patankar SV. Numerical Heat Transfer and Fluid Flow. Hemisphere, Washington, DC; 1980.
247. Raissi M, Perdikaris P, Karniadakis GE. Physics-informed neural networks: A deep learning framework for solving forward and inverse problems involving nonlinear partial differential equations. Journal of Computational Physics. 2019;378:686-707.
248. Ramey HJ. Wellbore heat transmission. Journal of Petroleum Technology. 1962;14(4):427-435.
249. Raymond LR. Temperature distribution in a circulating drilling fluid. Journal of Petroleum Technology. 1969;21(3):333-341.
250. Reed TD, Pilehvari AA. A new model for laminar, transitional, and turbulent flow of drilling muds. SPE Production Operations Symposium, Oklahoma City, SPE-25456-MS; 1993.
251. Robertson RE, Stiff HA. An improved mathematical model for relating shear stress to shear rate in drilling fluids and cement slurries. SPE Journal. 1976;16(1):31-36.
252. Rommetveit R, Bjørkevoll KS. Temperature and pressure effects on drilling fluid rheology and ECD in very deep wells. SPE/IADC Middle East Drilling Technology Conference, Bahrain, SPE-39282-MS; 1997.
253. Saasen A. Annular frictional pressure losses during drilling: Predicting the effect of drillstring rotation. Journal of Energy Resources Technology. 2014;136(3):034501.
254. Shamshuddin M, Gamar F, Agbaje TM, Eid MR, Oluwaseun F, Elsaid EM. Mixed convection of non-Newtonian micropolar nanofluid in exponentially extendable absorptive surface by Darcy-Forchheimer model. Modern Physics Letters B. 2025;40(2):2550250. doi:10.1142/s0217984925502501
255. Shittu H, Olagunju F, Shittu MA. Cyber physical resilience in digital substations: IoT enabled adaptive protection for secure DER integration. International Journal of Science, Architecture, Technology and Environment. 2024;1(3):81-99. doi:10.63680/ijsate032532.08
256. Shittu H, Opara IS, Elumilade RA, Adeniji IO. Hydrogen as a secondary energy carrier: Modeling its integration in national grids. Iconic Research and Engineering Journals. 2019;3(1):628-643. doi:10.64388/IREV3I1-1713909
257. Shittu MA, Adeniji IO, Shittu H, Opara IS. Blockchain-assisted secure data exchange architectures for SCADA-controlled power systems. Iconic Research and Engineering Journals. 2022;6(3):359-379. doi:10.64388/IREV6I3-1714041
258. Sifferman TR, Becker TE. Hole cleaning in full-scale inclined wellbores. SPE Drilling Engineering. 1992;7(2):115-120.
259. Sun X, Wang K, Yan T, Shao S, Jiao J. Effect of drillpipe rotation on cuttings transport using computational fluid dynamics (CFD) in complex structure wells. Journal of Petroleum Exploration and Production Technology. 2014;4:255-261.
260. Sunday EA, Omoegun GO. Integrating solar power solutions in small-scale manufacturing industries in Nigeria. International Journal of Scientific Research in Science, Engineering and Technology. 2018;4(8):832-853.
261. Sunday EA, Omoegun GO. Optimizing electrical load distribution for hybrid solar installations in developing economies. International Journal of Scientific Research in Mechanical and Materials Engineering. 2019;3(6):27-47.
262. Sunday EA, Omoegun GO. Smart fault detection in HVAC systems using sensor-based monitoring. International Journal of Scientific Research in Science, Engineering and Technology. 2022;7(4):380-403.
263. Sunday EA, Omoegun GO, Essien MA, Oluokun OA. Thermodynamic efficiency and control strategies in residential air conditioning systems. International Journal of Scientific Research in Civil Engineering. 2019;3(3):52-76.
264. Sunday EA, Omoegun GO, Essien MA, Oluokun OA. Transitioning from reactive to predictive maintenance in mechanical systems. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. 2020;6(6):425-447.
265. Tackie SN, Komi NM, Ozerdem OC. 31-level single-phase cascaded inverter with minimal component count. International Journal on Technical and Physical Problems of Engineering. 2023;15(1):271-282.
266. Tomren PH, Iyoho AW, Azar JJ. Experimental study of cuttings transport in directional wells. SPE Drilling Engineering. 1986;1(1):43-56.
267. Unamma UML, Ashore-Onisemo F, Iwuanyanwu U, Okwesa IJ. Predictive forecasting for operational resource allocation: A comparative review. Iconic Research and Engineering Journals. 2018;1(9):493-508. doi:10.64388/IREV1I9-1722628
268. Unamma UML, Okwesa IJ, Iwuanyanwu U. Building national analytics capacity: Advances and future pathways. International Journal of Social Sciences and Management Research. 2021;7(4):69-99. doi:10.56201/ijssmr.v7.no4.2021.pg69.99
269. Unamma UML, Okwesa IJ, Oyesiji SO, Abdulmalik AU. AI-assisted risk and incident analysis: Advances and future opportunities. World Journal of Innovation and Modern Technology. 2025;9(8):99-142. doi:10.56201/wjimt.v9.no8.2025.pg99.142
270. Yang M, Meng Y, Li G, Li Y, Chen Y, Zhao X, *et al*. Estimation of wellbore and formation temperatures during the drilling process under lost circulation conditions. Mathematical Problems in Engineering. 2013;2013:579091.
271. Zamora M, Power D. Making a case for AADE hydraulics and the unified rheological model. AADE

Technical Conference, Houston, AADE-02-DFWM-HO-13; 2002.
272. Zhou J, Umekwe-Edevwie EO, Famakinwa C, Oduh P, Oduh P. Beyond traditional schedule assurance: A critical review of predictive schedule-risk methodologies for hyperscale AI data-center construction. International Journal of Advanced Multidisciplinary Research and Studies. 2024;4(6):3489-3505. doi:10.62225/2583049X.2024.4.6.6919
273. Zhou J, Umekwe-Edevwie EO, Famakinwa C, Oduh P, Oduh P. Leveraging historical schedule performance data to predict construction delays in hyperscale data center projects. World Journal of Innovation and Modern Technology. 2025;9(8):99-126. doi:10.56201/wjimt.v9.no8.2025.pg99.126

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