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Coupled Heat and Mass Transfer in Viscoelastic Drilling Fluids Under High-Temperature Wellbore Conditions: A Review of Thermal Relaxation, Viscous Dissipation, and Porous Formation Interactions

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Abstract

Drilling into deep high-pressure high-temperature (HPHT) and geothermal reservoirs exposes drilling fluids to bottomhole temperatures that frequently exceed 175 °C and can approach 250 °C or more. Under these conditions polymer-laden water-based muds, oil-based and synthetic-based muds and emulsions display measurable elasticity, time-dependent stress relaxation and strongly temperature-sensitive rheology, while the fluid continuously exchanges heat with the drillstring and rock and exchanges mass with the permeable formation. This paper presents an integrative review of coupled heat and mass transfer in viscoelastic drilling fluids under high-temperature wellbore conditions, focusing on three mechanisms that are usually treated separately: (i) finite-speed thermal and solutal relaxation represented by Cattaneo-Christov type flux laws; (ii) viscous dissipation as an internal heat source; and (iii) interactions with the porous formation, including filtration and mudcake growth, Darcy-Brinkman-Forchheimer transport, thermoporoelastic coupling and Soret and Dufour cross-diffusion. A structured narrative review methodology was used to identify, appraise and thematically synthesise 226 sources published to date, spanning non-Newtonian fluid mechanics, wellbore thermo-hydraulics, porous-media transport and the adjacent literature on monitoring, integrity, safety, environmental management and energy systems. Building on the synthesis, a conceptual model is proposed that links temperature-dependent rheology, the three mechanisms and their feedback loops to operational outcomes such as circulating temperature, equivalent circulating density, fluid loss and wellbore stability, and six testable propositions are derived. The discussion identifies the regimes in which each mechanism is significant and the main points of agreement and tension in the literature. Implications for fluid design, hydraulics, digital-twin development, safety and environmental management are outlined, the limitations of the evidence base are acknowledged, and a prioritised agenda for future research is proposed.

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1. Introduction

The drilling fluid performs a set of tightly coupled functions: it transports cuttings, balances formation pore pressure, stabilises the borehole wall, cools and lubricates the bit, and transmits hydraulic power and telemetry. Each of these functions depends on the fluid's density and rheology, and both properties depend on temperature and pressure (Bourgoyne *et al.*, 1986; Caenn *et al.*, 2017) [62, 64]. In conventional wells the temperature dependence can often be handled with simple correction charts. In HPHT,

deepwater and geothermal wells, however, the fluid may experience temperature variations of well over 100 °C between the surface pits, the cold riser section, the bit and the hottest open-hole interval, and it cycles through these states every circulation (Alderman *et al*., 1988; Kabir *et al*., 1996) [25, 97]. Thermal degradation of polymers, gelation of clays, and changes in emulsion stability are all accelerated in this environment (Amani and Al-Jubouri, 2012; Caenn *et al*., 2017) [26, 64].

Classical wellbore heat transfer models, from Ramey's transient conduction solution and Raymond's circulating-temperature analysis to the widely used formulations of Holmes and Swift and of Kabir and co-workers, treat the circulating fluid as a Newtonian or generalised-Newtonian medium with Fourier conduction and neglect mechanical heat generation (Hasan and Kabir, 2002; Holmes and Swift, 1970; Ramey, 1962; Raymond, 1969) [89, 91, 199, 200]. These assumptions are adequate for predicting bulk circulating temperatures, but they cannot capture several phenomena that matter increasingly in deep wells: the elastic and relaxational response of polymeric and emulsion muds, the internal heating produced by viscous dissipation in high-shear regions such as the bit nozzles and narrow annular gaps, the finite-speed propagation of thermal disturbances in strongly structured fluids, and the bidirectional exchange of mass and heat with the permeable formation through the mudcake.

Over the last two decades a large applied-mathematics literature has developed around viscoelastic boundary-layer flows with modified heat and mass flux laws, especially the Cattaneo-Christov model (Christov, 2009; Han *et al*., 2014; Mustafa, 2015; Straughan, 2010) [67, 88, 120, 211]. In parallel, petroleum engineers have advanced HPHT rheometry, filtration testing and thermo-hydraulic simulation (Alderman *et al*., 1988; Amani and Al-Jubouri, 2012; Rommetveit and Bjørkevoll, 1997) [25, 26, 201]. The two communities rarely cite each other, and the result is a gap between sophisticated but idealised transport models and practical but simplified wellbore models. The purpose of this review is to bring the two strands together around a single question: *how do thermal relaxation, viscous dissipation and porous-formation interactions jointly control heat and mass transfer in viscoelastic drilling fluids at high temperature?*

The question is not purely academic. Operational integrity in high-risk drilling depends on balancing productivity against safety margins that are themselves set by fluid temperature and pressure (Nwangwu *et al*., 2018; Obogo *et al*., 2020c) [127, 141], and process safety management in mature oil and gas operations increasingly relies on risk-based and data-driven methods (Asibor and Isong, 2019; Makut *et al*., 2022b; Obriki and Arumosoye, 2018) [41, 119, 152]. Upstream decisions on field development and long-term production also draw on high-fidelity subsurface modelling, in which near-wellbore damage and thermal history feed into reservoir forecasts (Nwangwu *et al*., 2022, 2020) [125, 128]. A transport-based understanding of drilling fluids therefore connects directly to wellbore integrity, asset reliability, safety and environmental performance.

Against this background, the review has three objectives: first, to synthesise the theoretical, numerical, experimental and operational literature on coupled heat and mass transfer in viscoelastic drilling fluids at high temperature; second, to integrate the findings into a conceptual model that makes the couplings and feedbacks between mechanisms explicit; and third, to derive implications for practice and a prioritised research agenda. These objectives are pursued through three research questions:

- **RQ1.** How do thermal relaxation, viscous dissipation and porous-formation interactions individually modify heat and mass transfer in viscoelastic drilling fluids under high-temperature wellbore conditions?
- **RQ2.** How do these mechanisms interact with temperature-dependent rheology and with one another, and under which operating regimes does each become significant?
- **RQ3.** What are the implications of these coupled processes for drilling-fluid design, wellbore operations, monitoring, safety and environmental management, and where are the main gaps in knowledge?

The remainder of the paper follows the standard structure. Section 2 (Research Method) describes the integrative review design, the identification and selection of sources, data extraction and appraisal, and the development of the conceptual model. Section 3 (Results and Discussion) presents the thematic synthesis, covering the rheology of drilling fluids at high temperature (Section 3.1), the coupled governing equations (Section 3.2), thermal and solutal relaxation (Section 3.3), viscous dissipation (Section 3.4), porous formation interactions (Section 3.5), solution and validation methods (Section 3.6) and the operational, integrity and sustainability context (Section 3.7); it then proposes a conceptual model with six propositions (Section 3.8), discusses the findings in relation to the research questions (Section 3.9), and sets out implications (Section 3.10), limitations (Section 3.11) and future research directions (Section 3.12). Section 4 (Conclusion) summarises the main findings. Related analytical and numerical studies of nanofluid transport under comparable thermal, magnetic and slip conditions provide relevant precedent (Oluwaseun *et al*., 2023; Oluwaseun *et al*., 2024) [190, 191].

2. Research Method

2.1. Review Design

The study adopts an integrative, structured narrative review design. This design is appropriate when the evidence base is methodologically heterogeneous and the aim is to synthesise diverse forms of evidence into a coherent conceptual account rather than to pool comparable effect sizes (Whittemore and Knafl, 2005; Snyder, 2019) [209, 223]. The literature on this topic combines analytical and similarity solutions, numerical simulations, laboratory experiments, field-calibrated wellbore models and conceptual engineering frameworks, which rules out a statistical meta-analysis but suits integrative synthesis. The review followed the integrative-review stages of problem formulation, literature identification, evaluation of sources, thematic analysis and presentation of findings (Whittemore and Knafl, 2005) [223].

2.2. Identification of Sources

Sources were identified through a combination of keyword searching of bibliographic databases and publisher platforms, backward and forward citation tracking from foundational studies, and purposive inclusion of engineering literature on topics that are directly affected by drilling-fluid temperature and transport behaviour. Search terms combined three groups of keywords: fluid descriptors (drilling fluid, drilling mud, viscoelastic, upper-convected Maxwell, Oldroyd-B, non-Newtonian, yield stress); transport mechanisms (heat

transfer, mass transfer, Cattaneo-Christov, thermal relaxation, viscous dissipation, Brinkman number, Soret, Dufour, filtration, mudcake, porous medium, Darcy-Forchheimer, thermoporoelasticity); and setting (HPHT, wellbore, circulating temperature, geothermal well, wellbore stability). Foundational texts in rheology, porous-media convection and wellbore heat transfer were included regardless of publication date because they define the governing equations used throughout the field.

2.3. Inclusion and Exclusion Criteria

Sources were included if they met all of the following criteria:

- published in a peer-reviewed journal, conference proceedings, scholarly book or book chapter, in English, up to the end of 2024;
- addressing at least one of: rheology of drilling or viscoelastic fluids; heat or mass transfer mechanisms relevant to such fluids; transport in porous media; wellbore thermo-hydraulics or near-wellbore geomechanics; or an operational, integrity, safety, environmental or energy-system topic that depends on drilling-fluid temperature, pressure or composition;
- reporting sufficient detail on the problem formulation, method or findings to permit thematic coding.

Sources were excluded if they addressed fluid chemistry or additive formulation without any transport or operational content, if they duplicated an included source, or if they could not be retrieved in full.

2.4. Data Extraction, Appraisal and Thematic Synthesis

For each source, the following information was extracted where applicable: problem configuration and geometry; constitutive model; flux laws for heat and mass; dimensionless groups; solution method; type and extent of validation; principal findings; and relevance to high-temperature drilling. Sources were then coded into seven themes, which structure Section 3: (A) rheology and constitutive modelling; (B) governing equations and dimensionless groups; (C) thermal and solutal relaxation; (D) viscous dissipation; (E) porous formation interactions; (F) solution and validation methods; and (G) the operational, integrity and sustainability context.

Evidence was weighted according to its type. Experimental and field data were given the greatest weight, followed by validated numerical models, then analytical and similarity solutions with assumed parameter values, and finally conceptual frameworks and reviews. This hierarchy is reflected in the strength of the statements made in the synthesis and in the propositions of Section 3.8. The final corpus comprises 226 sources: 45 addressing fundamental rheology, transport mechanisms, porous media, wellbore thermo-hydraulics and geomechanics; 2 addressing review methodology; and 179 addressing the adjacent operational, integrity, safety, environmental and energy-system literature.

2.5. Development of the Conceptual Model

The conceptual model presented in Section 3.8 was developed inductively from the thematic synthesis. Causal links and feedbacks reported within and across themes were mapped, consolidated into a single framework connecting inputs, fluid properties, transport mechanisms and operational outcomes, and expressed as six propositions that can be tested experimentally, numerically or in the field.

3. Results and Discussion

This section reports the results of the review and discusses them. Sections 3.1 to 3.6 present the thematic synthesis of the transport problem itself, from fluid rheology through the governing equations and the three focal mechanisms to solution methods, and Section 3.7 places the transport problem within its operational, integrity and sustainability context. Section 3.8 integrates these results into a conceptual model, Section 3.9 discusses the findings, and Sections 3.10 to 3.12 address implications, limitations and future research.

3.1. Rheology of Drilling Fluids at High Temperature

3.1.1 Fluid Systems and Observed Behaviour

Water-based muds (WBM) derive their rheology from bentonite and other clays together with polymeric viscosifiers and fluid-loss additives such as xanthan gum, polyanionic cellulose, starches and synthetic sulfonated copolymers. Oil-based and synthetic-based muds (OBM/SBM) are invert emulsions whose structure is provided by organophilic clays, emulsifiers and the dispersed brine droplets (Caenn *et al*., 2017) [64]. Both families are shear-thinning and usually exhibit a yield stress, which is why the Bingham plastic and Herschel-Bulkley models remain the industry standard for hydraulics (Bingham, 1922; Herschel and Bulkley, 1926) [60, 90]. Small-amplitude oscillatory shear measurements, however, show clear storage moduli, and step-strain or start-up tests reveal stress overshoot and relaxation on time scales from fractions of a second to minutes, which is the signature of viscoelasticity (Barnes, 1997; Bird *et al*., 1987) [57, 61].

Temperature affects these fluids through competing mechanisms. The viscosity of the continuous phase falls approximately exponentially with temperature; clay flocculation and gelation may increase yield stress and gel strength; polymers suffer chain scission and oxidation above their thermal stability limits; and pressure raises the viscosity of the base oil in OBM/SBM (Alderman *et al*., 1988; Politte, 1985) [25, 198]. HPHT rheometer studies have therefore shown that plastic viscosity typically decreases with temperature while yield point may rise or fall depending on composition, and that pressure effects are significant mainly for oil-continuous systems (Alderman *et al*., 1988; Politte, 1985) [25, 198]. The net consequence is that the fluid's relaxation time, its effective viscosity and its thermal conductivity all vary spatially along the circulation path.

3.1.2 Viscoelastic Constitutive Models

The simplest differential model capturing stress relaxation is the upper-convected Maxwell (UCM) fluid, in which the extra stress $\boldsymbol{\tau}$ obeys

$$\tau + \lambda_1 \overset{\nabla}{\tau} = 2\eta_0 D \qquad (1)$$

where λ_1 is the relaxation time, η_0 the zero-shear viscosity, $\mathbf{D}$ the rate-of-deformation tensor and the superscript ∇ denotes the upper-convected time derivative, $\tau^{\nabla} = \partial\tau/\partial t + u\cdot\nabla\tau - (\nabla u)^{T}\cdot\tau - \tau\cdot\nabla u$ (Bird *et al*., 1987; Tanner, 2000) [61, 218]. The Oldroyd-B model adds a retardation time λ_2, representing a Newtonian solvent contribution, and is the standard model for dilute polymer solutions. To describe shear-thinning together with elasticity, the Giesekus model introduces a quadratic stress term with mobility parameter α, while the Phan-Thien-

Tanner (PTT) model uses a stress-dependent destruction function; both predict bounded extensional viscosity and realistic shear thinning (Bird *et al*., 1987; Tanner, 2000) [61, 218]. Rate-type models of the second-grade, Jeffrey, Burgers and Walters-B families are also popular in the analytical literature because they yield tractable boundary-layer equations, though their thermodynamic admissibility and parameter identification for real muds are less established.

For yield-stress muds, elastoviscoplastic (EVP) models such as the Saramito formulation combine a Herschel-Bulkley plastic response with an Oldroyd-type elastic element and are, in principle, the most realistic description of a gelled drilling fluid restarting after a connection (Saramito, 2007) [202]. Their use in coupled heat and mass transfer studies is still rare.

3.1.3 Temperature and Pressure Dependence

Temperature dependence is usually introduced through a shift factor a_T applied to both viscosity and relaxation time, consistent with time-temperature superposition: $\eta_0(T) = a_T\,\eta_0(T_{ref})$ and $\lambda_1(T) = a_T\,\lambda_1(T_{ref})$. An Arrhenius form is common,

$$a_T = \exp\left[\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \tag{2}$$

with activation energy E_a and gas constant R. For OBM/SBM a Barus-type pressure term $\exp[\beta(p - p_{ref})]$ is often multiplied in (Politte, 1985) [198]. A linear or exponential temperature dependence of thermal conductivity k(T) and of mass diffusivity $D_m(T)$ closes the property model. Because viscosity, relaxation time and conductivity all respond to temperature, the momentum and energy equations become two-way coupled even in the absence of buoyancy.

3.2. Governing Equations for Coupled Transport

3.2.1 Conservation Laws in the Wellbore

For an incompressible fluid with velocity **u**, pressure p, temperature T and solute concentration C (for example, a dissolved salt, a polymer fraction or dissolved gas), the coupled balances are

$$\nabla \cdot \mathbf{u} = 0 \tag{3}$$

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = -\nabla p + \nabla\cdot\boldsymbol{\tau} + \rho g \beta_T (T - T_\infty) + \rho g \beta_C (C - C_\infty) \tag{4}$$

$$\rho c_p\left(\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T\right) = -\nabla\cdot\mathbf{q} + \boldsymbol{\tau}:\nabla\mathbf{u} + \frac{\rho D_m k_T}{C_s}\nabla^2 C \tag{5}$$

$$\frac{\partial C}{\partial t} + \mathbf{u}\cdot\nabla C = -\nabla\cdot\mathbf{J} + \frac{D_m k_T}{T_m}\nabla^2 T \tag{6}$$

Here q is the heat flux, **J** the mass flux, $\boldsymbol{\tau} : \nabla\mathbf{u}$ the viscous (or, more generally, stress-power) dissipation, and the last terms in Eqs. (5) and (6) are the Dufour (diffusion-thermo) and Soret (thermal-diffusion) contributions with thermal-diffusion ratio k_T, concentration susceptibility C_s and mean temperature T_m (Eckert and Drake, 1972; Nield and Bejan, 2017) [80, 122]. Buoyancy terms are relevant during static periods, in large-diameter risers and in geothermal wells with large radial temperature differences. The flux laws q and **J** are specified in Section 3.3.

3.2.2 Dimensionless Groups

Table 1 lists the dimensionless numbers that recur in this literature. Their typical ranges for drilling operations show immediately which effects can be neglected. For example, Weissenberg numbers of order one or larger are common for polymer muds in annular flow, and Brinkman numbers above about 0.1 can arise in narrow annuli with viscous HPHT fluids, while thermal relaxation numbers are usually small except in very rapid transients.

Table 1: Principal dimensionless groups in coupled transport of viscoelastic drilling fluids.

Group	Definition	Physical meaning and relevance
Reynolds, Re	$\rho U L/\eta_0$	Inertia vs. viscous forces; laminar annular flow typical for HPHT muds
Weissenberg, Wi (Deborah, De)	$\lambda_1 U/L$ (λ_1/t_{flow})	Elastic vs. viscous stresses; governs normal stresses, flow instabilities, drag reduction
Prandtl, Pr	$\eta_0 c_p/k$	Momentum vs. thermal diffusivity; large (10^2 to 10^4) for muds
Schmidt, Sc	$\eta_0/(\rho D_m)$	Momentum vs. mass diffusivity; very large for polymers and dissolved gases
Brinkman, Br	$\eta_0 U^2/(k\Delta T)$	Viscous heating vs. conduction; key indicator of dissipation importance
Eckert, Ec	$U^2/(c_p\Delta T)$	Kinetic energy vs. enthalpy difference; Br = Ec·Pr
Thermal relaxation, γ_T	$\lambda_T U/L$	Heat-flux relaxation time vs. flow time; Fourier limit when $\gamma_T \to 0$
Solutal relaxation, γ_C	$\lambda_C U/L$	Mass-flux relaxation time vs. flow time; Fick limit when $\gamma_C \to 0$
Darcy, Da	K/L^2	Permeability vs. geometric scale; controls slip and penetration at a porous wall
Forchheimer, Fs	$C_F\sqrt{K}\,U/\nu$	Inertial (non-Darcy) drag in the formation
Soret, Sr; Dufour, Du	See Eqs. (5) and (6)	Cross-diffusion; significant in brines, gas-liquid systems, light hydrocarbons
Lewis, Le	α/D_m	Thermal vs. mass diffusivity; sets relative boundary-layer thicknesses

3.3. Thermal and Solutal Relaxation

3.3.1 Beyond Fourier and Fick

Fourier's law, $\mathbf{q} = -k\nabla T$, implies that a thermal disturbance is felt instantaneously throughout the medium, the so-called paradox of heat conduction (Joseph and Preziosi, 1989) [95]. Cattaneo proposed a relaxation form, $\mathbf{q} + \lambda_T\,\partial\mathbf{q}/\partial t = -k\nabla T$, which yields a hyperbolic energy equation and a finite speed of thermal waves (Cattaneo, 1948) [65]. For a moving continuum the partial time derivative is not frame-indifferent, and Christov replaced it with the upper-convected (Oldroyd) derivative (Christov, 2009) [67]:

$$\mathbf{q} + \lambda_T\left[\frac{\partial \mathbf{q}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{q} - \mathbf{q}\cdot\nabla\mathbf{u} + (\nabla\cdot\mathbf{u})\mathbf{q}\right] = -k\nabla T \tag{7}$$

Combining Eq. (7) with the energy balance for incompressible steady flow eliminates q and gives a single equation for temperature containing second-order products of velocity gradients and temperature gradients weighted by λ_T

(Han *et al*., 2014) [88]. An analogous generalised Fick law with solutal relaxation time λ_C is used for the concentration field (Mustafa, 2015) [120]. Straughan (2010, 2011) [211, 212] showed that the Cattaneo-Christov formulation alters the onset of thermal convection and that the resulting system is well posed, and Ciarletta and Straughan established uniqueness and structural stability results (Ciarletta and Straughan, 2010) [68].

3.3.2 Findings for Viscoelastic Flows

Han *et al*. (2014) [88] solved the coupled flow and heat transfer of an upper-convected Maxwell fluid over a stretching sheet with the Cattaneo-Christov model and found that increasing the thermal relaxation parameter reduces the thermal boundary-layer thickness and raises the wall heat transfer rate, while increasing the elasticity parameter thins the momentum boundary layer. Mustafa (2015) [120] reported qualitatively similar trends for rotating Maxwell flow. A large subsequent literature has extended these results to Oldroyd-B, Jeffrey, Burgers, second-grade and tangent-hyperbolic fluids, to nanofluids, and to configurations with magnetic fields, radiation, chemical reaction and porous media. The qualitative influence of the relaxation and rheological parameters appears robust across these constitutive models, which is encouraging for drilling fluids whose exact constitutive law is uncertain. The consistent findings across these studies can be summarised as follows:

- Thermal relaxation reduces the penetration depth of the thermal field: temperature profiles become steeper and the Nusselt number at the heated or cooled wall increases relative to the Fourier prediction.
- Solutal relaxation has the same qualitative effect on concentration profiles and on the Sherwood number.
- Fluid elasticity (larger Deborah or Weissenberg number) tends to decelerate the near-wall flow in stretching-sheet geometries, thickening the thermal boundary layer and partly offsetting the effect of thermal relaxation.
- The effects of λ_T and λ_C are strongest in transient problems and in regions with large velocity gradients, precisely where the convective terms of Eq. (7) are significant.

3.3.3 Relevance to Drilling Operations

Measured thermal relaxation times for homogeneous liquids are extremely short (of order picoseconds), so the Cattaneo correction would be negligible for a simple liquid. Drilling fluids, however, are structured suspensions and emulsions. Experiments on heterogeneous and porous materials have suggested much longer effective relaxation times attributable to internal structure, although these results remain debated (Joseph and Preziosi, 1989; Kaminski, 1990) [95, 98]. For drilling fluids the physically defensible use of the Cattaneo-Christov model is therefore as an *effective-medium* description of the delayed thermal response of a structured fluid, for example the transient temperature response at the bit during the restart of circulation, the sudden cooling of a gelled mud column when cold fluid is pumped, or thermal shock at the borehole wall. In steady circulation over the length of the well (time scales of tens of minutes), γ_T is almost certainly small and Fourier conduction is adequate. A key recommendation of this review is that λ_T and λ_C must be measured or bounded for real muds before relaxation effects are claimed to be important in field-scale models.

3.4. Viscous Dissipation

3.4.1 Mechanical Heat Generation in Viscoelastic Flows

The term $\tau : \nabla u$ in Eq. (5) represents the rate at which mechanical work is converted into internal energy. For a generalised Newtonian fluid it reduces to $\eta(\dot{\gamma})\dot{\gamma}^2$, which is always non-negative. For a viscoelastic fluid the stress power contains a reversible elastic part that is stored and later released, so only part of $\tau : \nabla u$ is dissipated. Thermodynamically consistent formulations therefore split the stress power into stored and dissipated contributions, and the common practice of inserting the full $\tau : \nabla u$ as a heat source overestimates heating in rapidly varying flows (Bird *et al*., 1987; Leonov, 1976) [61, 111]. In steady simple shear the difference vanishes, which partly explains why the simpler approach is widely used.

The importance of dissipation is measured by the Brinkman number, $Br = \eta_0 U^2/(k\Delta T)$. Brinkman's early analysis of capillary flow showed that dissipation alters the radial temperature profile and can reverse the direction of wall heat flux (Brinkman, 1951) [63], and Gebhart demonstrated its importance in natural convection (Gebhart, 1962) [86]. In the wellbore, high-Br conditions occur in the bit nozzles and junk slots, in narrow annular gaps around tool joints and casing collars, in managed-pressure drilling with high surface back-pressure, and in casing-while-drilling and slim-hole operations where the annular clearance is small and shear rates are high.

3.4.2 Annular and Pipe Flow Results

Analytical and numerical studies of fully developed laminar flow of power-law, Bingham and viscoelastic fluids in pipes and concentric annuli show three regularities. First, dissipation increases the fluid temperature near the wall where shear is highest and therefore reduces local viscosity there, which in shear-thinning and temperature-thinning fluids partially self-limits the heating. Second, for a cooled wall (heat flowing from fluid to formation) dissipation decreases the Nusselt number, while for a heated wall it can produce a singularity in the Nusselt number where the bulk and wall temperatures cross. Third, elasticity modifies the velocity profile only weakly in fully developed shear flow of UCM or Oldroyd-B fluids (the viscometric functions being shear-rate independent), but significantly for PTT and Giesekus fluids whose viscosity shear-thins, so model choice matters for the predicted dissipation field (Bird *et al*., 1987; Tanner, 2000) [61, 218].

Boundary-layer studies offer further insight into how dissipation interacts with other mechanisms. Oluwaseun *et al*. (2023) [190] showed for an unsteady MHD nanofluid on a porous inclined surface that the Eckert number raises fluid temperature and markedly increases entropy generation, with velocity slip partly offsetting the effect. Oluwaseun *et al*. (2024) [191] likewise examined unsteady squeezing flow and heat transport of a nanofluid between rotating, stretchable disks, a configuration in which shear-driven heating varies with the gap width. Entropy-generation analysis of this kind is directly transferable to drilling hydraulics, where it can identify the zones (bit, tool joints, narrow annular gaps) in which mechanical energy is most wastefully converted into heat.

For the drillstring, frictional heating adds to the mechanical heat generated by the bit and by rotation. Field and modelling studies have shown that rotation and friction can raise circulating temperatures by several degrees above predictions

that ignore them, which is significant when the margin to the thermal limit of downhole electronics is small (Hasan and Kabir, 2002; Kabir *et al*., 1996) [89, 97]. Viscous dissipation also couples back to pressure control: heating lowers mud density and viscosity, which lowers equivalent circulating density (ECD), and in narrow-margin HPHT wells this effect must be considered in hydraulics planning (Alderman *et al*., 1988; Rommetveit and Bjørkevoll, 1997) [25, 201].

3.4.3 Dissipation in the Porous Formation

When filtrate or a whole fluid invades the formation, dissipation also occurs within the pore space. Nield (2007) [121] reviewed the forms of the dissipation term appropriate to the Darcy, Brinkman and Forchheimer momentum models and showed that, for consistency, the dissipation term should be compatible with the drag term in the momentum equation: $(\mu/K)|u|^2$ for Darcy flow, plus a Forchheimer contribution $c_F \rho K^{-1/2}|u|^3$ and a Brinkman term $\mu_{eff}\ \nabla u : \nabla u$ where applicable. Al-Hadhrami *et al.* (2003) [22] proposed a model that remains valid across the range of permeabilities from the Darcy limit to clear fluid. In near-wellbore applications pore velocities are low and these terms are usually small, except during lost-circulation events, in fractured or vuggy formations, and during high-rate injection.

3.5. Porous Formation Interactions

3.5.1 Filtration and Mudcake

Overbalanced drilling drives filtrate into permeable formations. A filter cake forms at the wall and controls the subsequent invasion rate. Under static conditions the cumulative filtrate volume grows approximately with the square root of time, whereas under dynamic conditions erosion by the circulating fluid limits cake growth and an equilibrium thickness is approached (Civan, 2015; Outmans, 1963) [69, 196]. Temperature affects filtration directly through filtrate viscosity, and indirectly through polymer degradation and changes in clay dispersion that alter cake permeability; this is why HPHT filter-press tests are specified for deep wells (Amani and Al-Jubouri, 2012; Caenn *et al*., 2017) [26, 64]. Viscoelastic polymer filtrates also show elevated apparent viscosity in porous media because of extensional flow through pore throats, which tends to reduce invasion relative to the shear-viscosity prediction (Sorbie, 1991) [210]. Computational fluid dynamics has also been applied to cake filtration systems, where simulation-based optimisation of cake build-up and flux decline offers a template for resolving the coupled flow, particle deposition and pressure fields at the borehole wall (Adewoyin *et al*., 2021; Ogunnowo *et al*., 2023b) [16, 175].

Filtration is intrinsically a coupled heat and mass transfer problem. The filtrate carries enthalpy and dissolved species into the formation, cooling or heating the near-wellbore rock, while the formation returns heat to the fluid by conduction. Invasion of filtrate with a different salinity or composition sets up concentration gradients that drive osmotic and chemical interactions with shales, and the temperature gradient across the wall can drive Soret diffusion of dissolved species.

3.5.2 Momentum Transport at and Within the Porous Boundary

Models of flow adjacent to or within the formation range from Darcy's law to the Darcy-Brinkman-Forchheimer equation,

$$\frac{\rho}{\varphi}\frac{\partial \mathbf{u}}{\partial t} = -\nabla p + \mu_{eff}\nabla^2\mathbf{u} - \frac{\mu}{K}\mathbf{u} - \frac{c_F\rho}{\sqrt{K}}|\mathbf{u}|\mathbf{u} \qquad (8)$$

in which φ is porosity, K permeability and c_F the Forchheimer coefficient (Nield and Bejan, 2017) [122]. At the interface between the open wellbore and the formation, the Beavers-Joseph slip condition, $u_s - u_p = (\sqrt{K}/\alpha_{BJ})(\partial u/\partial n)$, or a stress-jump condition based on the Brinkman model, is used (Beavers and Joseph, 1967) [58]. For viscoelastic fluids in porous media the Darcy term is commonly replaced by a modified form that includes a relaxation time, giving a Maxwell-Darcy or Oldroyd-Darcy law; these models predict oscillatory approach to steady flow and modified stability thresholds for thermal convection (Kim *et al*., 2003; Nield and Bejan, 2017) [100, 122]. Similarity-solution studies of flow over porous surfaces, including the entropy analysis of Oluwaseun *et al*. (2023) [190], indicate that larger porous drag decelerates the flow and raises the near-wall temperature, an effect analogous to the thermal penalty of flow through a low-permeability mudcake.

3.5.3 Thermal Coupling and Thermoporoelasticity

Heat exchange between the circulating fluid and the formation controls both the fluid temperature and the near-wellbore stress state. In the classical approach the formation is a conductive solid whose transient temperature response is represented by a dimensionless time function (Ramey's f(t) or its successors), and the fluid-to-formation heat flux enters the energy balance of the annulus (Hasan and Kabir, 2002; Ramey, 1962) [89, 199]. When the formation is permeable, local thermal equilibrium (LTE) between pore fluid and matrix is usually assumed; local thermal non-equilibrium (LTNE) models with a fluid-solid interfacial heat transfer coefficient are needed for rapid transients and high pore velocities (Nield and Bejan, 2017) [122].

Temperature changes at the borehole wall induce thermal stresses and, in low-permeability rocks, thermally driven pore-pressure changes. Cooling the wall by circulation tends to reduce hoop stress and can stabilise the hole against shear failure, while heating increases the risk of breakout; in shales, the undrained thermal pressurisation of pore fluid can be significant (Chen and Ewy, 2005; Li *et al*., 1998) [66, 112]. Thermoporoelastic models that couple these effects with filtrate invasion and chemical osmosis show that the time-dependent stability window depends on the history of fluid temperature at the wall, which in turn depends on the rheology and dissipation processes reviewed above.

3.5.4 Cross-Diffusion and Chemical Effects

Soret and Dufour effects are often neglected in liquids, but they become relevant when large temperature gradients coexist with multicomponent mixtures of very different molecular weight, for example light hydrocarbon or gas influx into an OBM, or concentrated brines in contact with a hot formation (Eckert and Drake, 1972; Nield and Bejan, 2017) [80, 122]. Similarity-solution studies of viscoelastic fluids near porous surfaces generally find that a larger Soret number increases the concentration and thickens the solutal boundary layer, and a larger Dufour number increases the temperature, though the magnitudes reported are sensitive to the assumed parameter values. Chemical reactions, such as polymer degradation at high temperature or acid-gas absorption in the

mud, are modelled through first-order or Arrhenius-type reaction terms in the concentration equation; endothermic or exothermic reactions add a further source term to the energy equation. Thermophoresis, which drives fine particles towards cooler surfaces, is also a plausible mechanism for the migration of fine solids and weighting material towards the cooler formation face during circulation, which would influence internal mudcake formation and near-wellbore damage.

3.6. Solution Methods and Validation

Table 2 summarises the main classes of model encountered in this literature together with their strengths and limitations for drilling applications.

Table 2: Modelling approaches for coupled heat and mass transfer of drilling fluids.

Approach	Typical features	Strengths and limitations
Lumped wellbore thermal models	1D steady or transient energy balances for drillpipe and annulus; Newtonian or Bingham fluid; formation time function	Fast, field-calibrated, suitable for well planning; neglect elasticity, relaxation, local dissipation and detailed filtration
Boundary-layer similarity solutions	Stretching or porous surfaces; UCM, Oldroyd-B, Jeffrey, etc.; Cattaneo-Christov fluxes; Soret, Dufour, radiation	Clear parametric trends and insight; idealised geometry, often unvalidated against drilling-fluid data
Annular and pipe analytical/semi-analytical	Fully developed flow in concentric annuli; Graetz-type problems with dissipation	Directly relevant geometry; usually neglect eccentricity, rotation and entrance effects
CFD with viscoelastic models	Finite-volume or finite-element; log-conformation for high Wi; eccentric annuli with rotation	Captures 3D effects; computationally costly; high-Wi numerical problem; property data scarce
Coupled thermo-hydro-mechanical (THM) models	Thermoporoelasticity, filtration, chemical osmosis around the borehole	Links fluid design to wellbore stability; fluid side usually simplified
Experimental	HPHT rheometry, oscillatory shear, HPHT filtration, flow loops with temperature control	Essential for parameters and validation; few datasets combine rheology, thermal and filtration data at HPHT

Similarity solutions are typically computed with shooting methods, finite-difference collocation (for example bvp4c in MATLAB), the homotopy analysis method or spectral methods. Agreement between methods is generally excellent for the idealised problems posed, but validation against physical experiments is uncommon. Spectral collocation and quasilinearization schemes are efficient and highly accurate for strongly nonlinear coupled systems involving radiation, reaction, slip and non-Newtonian rheology. Unsteady squeezing flows between rotating and oscillating disks (Oluwaseun *et al*., 2024) [191] provide a useful analogue for the time-dependent gaps encountered during pipe reciprocation and surge-swab events. For realistic annular geometries, viscoelastic CFD has matured considerably; the log-conformation representation of the conformation tensor has extended the range of tractable Weissenberg numbers, and open-source solvers such as OpenFOAM-based packages now support the UCM, Oldroyd-B, Giesekus and PTT models with energy coupling (Fattal and Kupferman, 2004) [85]. Field validation of circulating temperature models uses measurement-while-drilling temperature logs and surface return temperatures (Hasan and Kabir, 2002; Kabir *et al*., 1996) [89, 97].

Developments in general thermofluid engineering are also transferable. Advances in thermofluid simulation for heat transfer optimisation in compact devices (Adewoyin *et al*., 2020b) [15] and AI-based optimisation of multiphysics fluid dynamics (Adewoyin *et al*., 2024) [18] show how coupled flow and heat transfer solvers can be embedded in design loops, while simulation-based heat-flow analytics and thermodynamic efficiency analysis of air-conditioning and HVAC systems (Ogunnowo *et al*., 2021a; Sunday *et al*., 2019) [166, 214] illustrate practical energy-balance formulations for circulating fluids. On the structural side, reliability-centred design using finite element analysis and DFMEA (Ogunnowo *et al*., 2023a) [168] and topology optimisation (Ogunnowo *et al*., 2024c) [173] provide tools for designing downhole tools and flow components that experience the thermal and pressure loads predicted by the transport models.

3.7. Operational, Integrity and Sustainability Context

The coupled transport phenomena reviewed above do not act in isolation from field operations. Predicted fluid temperatures, pressures and filtration rates feed into equipment integrity, monitoring, safety management, environmental performance and supply-chain decisions. This subsection summarises the adjacent engineering literature that connects drilling-fluid thermo-hydraulics to these operational concerns.

3.7.1 Real-Time Monitoring, Digital Twins and Predictive Maintenance

Accurate thermal models of the circulating system are most valuable when they are coupled to real-time data. Predictive maintenance and condition monitoring are now well established in critical power and energy infrastructure (Adaramola *et al*., 2018; Sunday *et al*., 2020) [2, 217], with vibration-based monitoring of rotating machinery (Omoegun *et al*., 2023) [194], sensor-based fault detection in thermal systems (Sunday and Omoegun, 2022) [215] and preventive maintenance programme design for energy systems (Yeboah *et al*., 2024) [224] providing mature templates for mud pumps, top drives and surface fluid-handling equipment. Multi-algorithm optimisation of induction motor losses and weight (Amayo, 2017; Amayo and Popoola, 2017; Amayo *et al*., 2015) [27, 31, 32] is relevant to the electric drives of mud pumps and top drives, whose duty cycle is set by circulating pressure and therefore by fluid rheology at temperature.

Digital twins extend this approach by pairing a physics-based model with live measurements. Applications include real-time monitoring of mechanical systems (Ogunnowo *et al*., 2024a) [169], predictive maintenance of renewable energy assets (Komi and Adeniji, 2023; Shittu and Shittu, 2024) [106, 203] and fault detection in smart substations (Shittu *et al*., 2023) [208]. A drilling-fluid digital twin would combine the coupled heat and mass transfer equations of Section 3.2 with downhole and surface temperature, pressure and flow data to update rheological and thermal parameters during circulation. Related work on CMMS-based maintenance optimisation

(Obetta *et al*., 2023) [137], reliability-centred and condition-based maintenance of offshore equipment (Obetta, 2020; Obetta and Ninduwezuor-Ehiobu, 2018) [131, 132], systems-engineering frameworks for deepwater mechanical reliability (Makut *et al*., 2022a) [115], data-driven lifecycle performance management of infrastructure (Adelanwa *et al*., 2023) [10] and lifecycle reliability assessment integrated with building information modelling (Makut *et al*., 2024) [118] indicates how such a twin could be integrated into asset management.

Reliability engineering and failure analysis of complex systems (Gideon *et al*., 2019) [87], non-destructive testing for predictive failure analysis (Ogunnowo *et al*., 2020, 2024b) [165, 172], provide the statistical and diagnostic foundations. Interpretable machine learning for early failure prediction (Komi and Adamolekun, 2021) [103], together with simulation of large-scale maintenance-free wireless sensing (Asiedu and Quainoo, 2023) [47], is relevant to the design of downhole and surface sensor networks with limited power budgets.

The machine-learning layer itself requires care. Context-aware data curation for model training (Oyesiji *et al*., 2024) [197] addresses the data-quality issues that also limit physics-informed surrogates for drilling fluids. Comparative reviews of predictive forecasting (Unamma *et al*., 2018) [222] and deep-learning forecasting of energy yield and load (Ezeugwa *et al*., 2023; Komi, 2021, 2023) [81, 101, 102] show how forecasts can be operationalised, while work on distributed control architectures (Komi and Adamolekun, 2022) [104] and edge intelligence for resilient control (Komi and Ganiu, 2023) [108] is relevant to deploying such models at the rig site.

3.7.2 Process Safety, Human Factors and Heat Exposure

High fluid temperatures and pressures raise both process-safety and occupational risks. Frameworks for operational integrity in high-risk drilling (Nwangwu *et al*., 2018) [127] and reviews of safety management systems in oil and gas maintenance projects (Obogo *et al*., 2020c) [141] emphasise that well-control margins, which depend on fluid density and rheology at temperature, must be managed alongside productivity targets. Process safety management and management of change in mature production operations (Makut *et al*., 2022b) [119], integration of HAZOP and reliability analysis into energy infrastructure design (Asibor *et al*., 2023) [43], risk-based process engineering for natural gas systems (Asibor and Isong, 2019) [41] and process-safety models that include human factors in offshore pipeline commissioning (Oduro, 2023) [164] provide structured methods for analysing fluid-related hazards such as kicks, losses and thermal expansion of trapped fluids.

Data-driven safety risk control has been modelled for large energy infrastructure (Obriki and Arumosoye, 2018) [152], and frameworks exist for emergency response readiness in process facilities (Arumosoye and Obriki, 2023) [39], internal QHSE auditing (Obogo *et al*., 2020a) [139], incident prevention in maintenance environments (Obogo *et al*., 2021b) [145], human error causation (Obriki and Arumosoye, 2020) [154] and prevention-oriented incident investigation (Obriki and Arumosoye, 2024b) [159]. Use of near-miss and hazard observation data (Arumosoye and Obriki, 2019; Obogo *et al*., 2021a) [35, 142], proactive hazard identification from digital safety data streams (Obriki and Arumosoye, 2023) [157], continuous hazard monitoring (Obriki *et al*., 2023a) [160] and workforce safety training (Obriki *et al*., 2022a) [161] are directly applicable to rig-floor operations involving hot drilling fluids.

Human factors and organisation turn a thermal-hydraulic prediction into a safe action. Contractor safety governance and compliance (Arumosoye and Obriki, 2020; Obogo *et al*., 2021c; Obriki and Arumosoye, 2024a) [36, 151, 158], safety governance in large facility operations (Obogo *et al*., 2022) [146], safety risk governance and hazard control in multi-contractor projects (Obogo *et al*., 2019b, 2019c) [149, 150], emergency preparedness and evacuation (Obriki *et al*., 2022b) [162], organisational learning and safety maturity (Arumosoye and Obriki, 2021) [37], safety leadership and culture (Arumosoye and Obriki, 2024; Obogo *et al*., 2023, 2019a) [40, 144, 148], management walkthroughs (Obriki and Arumosoye, 2019) [153], life-preserving safety practices (Obriki and Arumosoye, 2021) [155], recurrence of unsafe behaviour (Obriki and Arumosoye, 2022) [156], and behavioural safety programmes (Obriki *et al*., 2023b) [163] complete this picture, as do risk models for lifting and heavy-equipment operations common during HPHT well construction (Arumosoye and Obriki, 2022; Obogo *et al*., 2020b) [38, 140].

Finally, the same thermal environment that degrades drilling fluids also affects personnel. Integrated heat-stress risk models for industrial operations in extreme environments (Arumosoye and Obriki, 2018) [34] are relevant to crews handling hot returns and working near shale shakers and mud tanks in hot climates.

3.7.3 Materials, Corrosion and Equipment Integrity at High Temperature

Fluid temperature and chemistry govern corrosion and degradation of tubulars, surface equipment and downhole tools. Reviews of corrosion management and material selection for crude oil export equipment in marine environments (Obetta *et al*., 2020) [131], AI-augmented corrosion modelling (Adewoyin *et al*., 2023) [17], predictive corrosion models based on non-destructive testing data (Ogunnowo *et al*., 2024d) [174], green corrosion inhibitors for mild steel in acidic media (Atta *et al*., 2018) [49] and NDT-based corrosion risk assessment for refinery equipment (Atta *et al*., 2020) [52] are directly relevant to managing brine-based and acid-gas-contaminated muds at temperature. Weld inspection standards and NDT for weld integrity in high-capacity plant (Atta *et al*., 2022, 2021) [48, 51] apply to pressure-containing fluid systems.

Material selection for high-temperature service benefits from dynamic mechanical analysis (Adewoyin *et al*., 2020a; Ogunnowo *et al*., 2021b) [14, 170] and from predictive models of microstructural evolution in superalloys (Ogunnowo *et al*., 2022a, 2022b) [167, 171], which are candidate materials for downhole tools exposed to hot circulating fluid. Integrity management of pressure-containing equipment is covered by work on risk-based inspection and fitness-for-service of ageing pressure vessels (Obetta, 2018) [129], reliability of fired heaters and boilers (Obetta, 2019) [130], non-intrusive inspection (Obetta *et al*., 2021) [135], cause-tree failure analysis (Obetta *et al*., 2024) [138], mooring system integrity (Obetta and Ninduwezuor-Ehiobu, 2019) [133], and risk-based design of offshore and floating facilities (Makut *et al*., 2021a, 2021b; Obetta *et al*., 2022) [114, 116, 136]. Analysis of charge transport and recombination losses in thin-film semiconductor devices (Atta *et al*., 2024) [50] illustrates the temperature sensitivity of electronic materials that governs the thermal derating of downhole electronics.

3.7.4 Cyber-Physical Security of Drilling Control Systems

Modern rigs use automated drilling control, managed-pressure systems and real-time hydraulics software that depend on the thermal and rheological models discussed here. These operational technology (OT) systems are exposed to cyber-physical threats. Reviews of ICS and SCADA threat detection in energy networks (Adegbite *et al*., 2023) [7] and AI-augmented threat detection in industrial control systems (Adebayo *et al*., 2023) [4] are relevant, as are frameworks for adversarial machine learning in critical infrastructure (Adebayo *et al*., 2022) [3] and physics-informed ransomware defence in OT (Ojukwu *et al*., 2023) [177]. Architectures for IT and OT convergence in energy networks (Adegbite *et al*., 2022) [6], zero-trust OT (Ahmed *et al*., 2021) [20], secure data exchange for SCADA-controlled systems (Shittu *et al*., 2022) [207], adaptive protection in digital substations (Shittu *et al*., 2024) [203] and AI-driven security operations (Adegbite *et al*., 2024b) [9] describe how data integrity of the measurements feeding a drilling-fluid model can be protected. Security of OT networks under regulatory standards (Adegbite *et al*., 2020) [5] and vulnerability governance for power and utility companies (Adegbite *et al*., 2024a) [8] complete this layer.

3.7.5 Environmental Management, Produced Water and Emissions

Drilling and production generate fluid waste streams whose composition reflects the thermal history of the mud. Lifecycle risk assessment of offshore produced water (Falegan and Aniebonam, 2022) [82], physicochemical and biological treatment strategies (Falegan and Aniebonam, 2023) [83], and decentralised treatment for remote assets (Falegan and Aniebonam, 2024) [84] are relevant to the handling of spent water-based muds and filtrate-contaminated produced water. Sustainable environmental practice in safety management (Obogo *et al*., 2024a) [143], environmental compliance in infrastructure projects (Obogo *et al*., 2024b) [147], automated ESG reporting in energy projects (Abioye *et al*., 2023) [1] and predictive monitoring of emissions and infrastructure risk (Okojie *et al*., 2023) [178] provide the management context.

Subsurface contamination is a particular concern where drilling fluids or filtrate migrate beyond the near-wellbore region. Data-driven prediction of subsurface contamination pathways (Azeez and Badmus, 2018) [55], spatially explicit modelling of contaminant migration in data-limited settings (Lamidi and Olamide, 2018) [110], and vapour intrusion risk assessment (Azeez and Badmus, 2024b) [54] link the porous-media transport models of Section 3.5 to environmental outcomes. Geostatistical soil assessment (Kianguebene-Koussingounina *et al*., 2023) [99] and remote-sensing interpretation of hydrothermal alteration (Dagodzo, 2018c) [72] are complementary tools for baseline characterisation near drilling sites, particularly in geothermal provinces.

Emissions management is the other half of the environmental picture. Flare-gas recovery technologies (Asibor and Isong, 2020) [42], methane emission reduction in petroleum production (Asibor and Olisakwe, 2022) [45] and vapour recovery and gas gathering optimisation (Makut and Olisakwe, 2022) [115] address gas released during drilling and well testing. Improved GHG inventory and carbon accounting methods (Azeez and Badmus, 2024a; Lamidi, 2023) [53, 109] and GHG disclosure obligations for energy enterprises (Ominyi and Anichukwueze, 2022) [192] determine how these emissions are reported.

3.7.6 Supply Chain, Project Delivery and Pipeline Monitoring

HPHT wells require specialised fluid additives, high-temperature polymers and weighting materials whose availability affects fluid design. Supply-chain risk management for EPC and gas processing projects (Agbabiaka *et al*., 2019) [19], strategic sourcing of fuel and equipment for energy operations (Asibor *et al*., 2019) [41], dual sourcing under price volatility (Asibor *et al*., 2021) [46], resilience during disruptions (Babayemi *et al*., 2020; Ogunwole *et al*., 2021) [56, 176], digital supply-chain governance (Okonkwo *et al*., 2024a, 2024b) [179, 180], predictive procurement for operational uptime (Okonkwo *et al*., 2024c) [181], materials readiness (Okonkwo *et al*., 2021a) [184], asset lifecycle and inventory visibility (Okonkwo *et al*., 2023b) [186], regulatory-compliant procurement in high-risk energy environments (Okonkwo *et al*., 2021b) [187], procurement optimisation in oil and gas (Okonkwo *et al*., 2018a) [188] and inventory availability for plant uptime (Okonkwo *et al*., 2018b) [189], along with reviews of procurement strategy and digital supply-chain models (Okonkwo *et al*., 2024d, 2024e, 2023a) [182, 183, 185], automation and digital twins for procurement (Akinlade *et al*., 2024) [21] and supply-chain resilience and end-to-end visibility (Anene, 2021; Nnabueze *et al*., 2021) [33, 123], are all pertinent to securing HPHT fluid systems.

At the project level, aligning capital budgeting with field development execution (Nwangwu *et al*., 2021) [124], technical due diligence in energy transactions (Nwangwu *et al*., 2023) [126], predictive schedule-risk methods (Zhou *et al*., 2024) [226] and governance of multinational infrastructure projects (Amayo *et al*., 2023, 2024a) [28, 29] shape how well-construction risks, including fluid-related non-productive time, are priced and managed. Automated risk assessment for regulatory deliverables in upstream operations (Uchechi and Ominyi, 2020) [220], statutory compliance in upstream licensing (Ominyi *et al*., 2020; Uchechi *et al*., 2019) [193, 219] and liability management in energy service contracts (Uchechi and Ominyi, 2019) [219] define the regulatory frame.

Once fluids and produced hydrocarbons leave the well, pipelines and corridors must be monitored. UAV-based pipeline and corridor monitoring (Dagodzo and Ahiaeke Patrick, 2020) [73], integration of UAV, LiDAR and GIS in corridor management (Dagodzo and Ahiaeke Patrick, 2021b) [75], GIS for utility asset management (Dagodzo and Ahiaeke Patrick, 2021a) [74], right-of-way encroachment detection (Dagodzo and Ahiaeke Patrick, 2022) [76], drone integration with enterprise GIS (Dagodzo and Ahiaeke Patrick, 2023a) [77], UAV inspection programmes for power infrastructure (Dagodzo, 2018a, 2018b) [70, 71], UAV regulatory frameworks (Dagodzo and Ahiaeke Patrick, 2023b) [78] and deep-learning vegetation classification in corridors (Dagodzo *et al*., 2022) [76] provide remote-sensing tools for this downstream segment.

3.7.7 Energy Transition: Geothermal, Carbon Storage and Hydrogen

Many of the highest-temperature wells now being drilled are geothermal, and carbon capture and storage introduces CO_2-rich, reactive fluids. Strategies for CO_2 utilisation to revitalise mature oil fields (Ijiga *et al*., 2023a) [92], direct air capture technologies (Liadi *et al*., 2024) [113], and hydrogen integration in national grids (Shittu *et al*., 2019) [204] define new wellbore environments in which the coupled heat and mass transfer framework applies. The power systems that

geothermal and hybrid projects connect to are reviewed in work on smart-grid architectures for high renewable penetration (Adenuga, 2022) [12], battery storage in hot and weak-grid regions (Komi and Ganiu, 2022) [107], co-optimisation of solar microgrids (Komi and Adeniji, 2020) [105], hybrid solar-diesel microgrids (Ijiga *et al*., 2023b) [93], portfolio optimisation of solar, wind and storage (Ilesanmi *et al*., 2024) [94], load distribution in hybrid solar installations (Sunday and Omoegun, 2018, 2019) [213, 214], power electronics efficiency (Adenuga, 2023) [13], voltage control and grounding design in distribution networks (Adeniji *et al*., 2020; Oshevire *et al*., 2017) [11, 195], peer-to-peer renewable energy trading (Shittu *et al*., 2021) [206] and project management of solar deployments (Amayo *et al*., 2024b; Yeboah and Ike, 2020) [30, 225]. Alternative fuels for rig power (Bello *et al*., 2023) [59] and the wider impacts of large-scale renewable integration (Joseph and Uzondu, 2024) [96] round out the context in which future high-temperature drilling will take place.

3.8. Conceptual Model

3.8.1 Structure of the Model

The synthesis in Section 3 shows that the three focal mechanisms are connected to one another and to fluid rheology through temperature, and that their combined effect is expressed in operational outcomes rather than in any single transport coefficient. Figure 1 consolidates these findings into a conceptual model. Two sets of inputs, the operating conditions imposed by the rig (flow rate, annular geometry and eccentricity, pipe rotation, and the sequence of circulating and static periods) and the formation state (geothermal gradient, permeability, porosity, in-situ stress and pore fluid), act on a viscoelastic drilling fluid whose relaxation time, viscosity, yield stress, thermal conductivity and diffusivity all depend on temperature and pressure (Sections 3.1 and 3.2).

The fluid properties govern the three mechanisms: thermal and solutal relaxation (Section 3.3), viscous dissipation (Section 3.4) and porous formation interactions (Section 3.5). Their combined effect determines the coupled outcomes of practical interest: circulating and bottomhole temperature, equivalent circulating density and pressure margins, fluid loss and formation damage, wellbore stability, degradation of additives, thermal exposure of downhole tools and the composition of spent fluid. Three feedback loops close the system. Dissipative heating raises fluid temperature and lowers viscosity; the temperature history at the borehole wall, set by formation heat exchange and filtration, conditions transient relaxation and thermoporoelastic effects; and cumulative thermal exposure degrades the fluid itself, changing its rheology over successive circulations. The whole system is embedded in an operational context of monitoring, safety, integrity, security, environmental and supply-chain management (Section 3.7), which supplies data to the model and acts on its predictions.

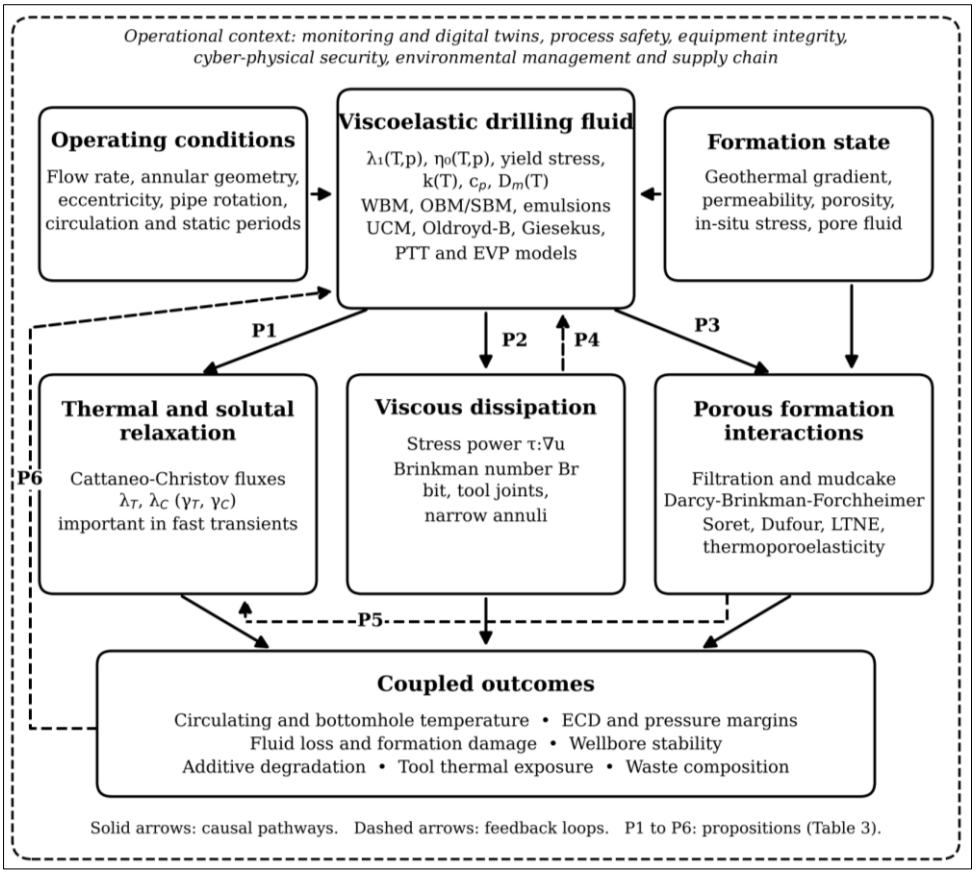


Fig 1: Conceptual model of coupled heat and mass transfer in viscoelastic drilling fluids under high-temperature wellbore conditions. Solid arrows denote causal pathways and dashed arrows denote feedback loops; P1 to P6 refer to the propositions in Table 3.

3.8.2 Propositions

Six propositions follow from the model. P1 to P3 concern the individual mechanisms, and P4 to P6 concern the feedback loops. Each is stated in a form that can be tested, and Table 3 summarises the supporting evidence and a suggested test for each.

Table 3: Propositions derived from the conceptual model.

No.	Proposition	Main evidence	Suggested test
P1	Thermal and solutal relaxation measurably alter wall heat and mass transfer only when the relaxation numbers γ_T and γ_C are not small, that is, in rapid transients such as circulation restart, thermal shock at the wall or pulsed flow; in steady circulation, Fourier and Fick laws are adequate.	Section 3.3	Transient thermal-pulse experiments on gelled muds; comparison of Fourier and Cattaneo-Christov predictions against downhole temperature during circulation restart.
P2	Viscous dissipation becomes a first-order heat source where the Brinkman number is not small, raising local temperature and lowering effective viscosity and ECD; for viscoelastic fluids only the dissipated part of the stress power contributes.	Section 3.4	Temperature-controlled flow-loop tests in narrow and eccentric annuli; CFD comparing full stress power with thermodynamically consistent dissipation.
P3	Filtration rate and mudcake properties depend on fluid temperature through filtrate viscosity, polymer degradation and cake permeability, while the filtrate transports heat and solutes that modify near-wellbore temperature and stress.	Section 3.5	Dynamic HPHT filtration tests with temperature measurement inside the core; coupled flow, heat and solute modelling of invasion.
P4	Dissipative heating feeds back on rheology through temperature thinning, giving a self-limiting coupling whose strength increases with the temperature sensitivity of viscosity (activation energy) and with the Brinkman number.	Sections 3.1 and 3.4	Coupled simulations with Arrhenius-type properties; sensitivity analysis on activation energy and flow rate.
P5	The temperature history at the borehole wall, set by formation heat exchange and filtration, controls transient relaxation effects and thermoporoelastic stresses, linking fluid thermal behaviour to wellbore stability.	Sections 3.3 and 3.5	Coupled thermo-hydro-mechanical simulations driven by realistic transient wall temperature; laboratory thick-walled cylinder tests with thermal cycling.
P6	Cumulative thermal exposure degrades polymers and additives, altering rheology and filtration control over successive circulations and determining the composition of spent fluid.	Sections 3.1 and 3.7.5	Cyclic hot-rolling and ageing tests with rheology and composition tracked over cycles; field sampling of returns over a well section.

Taken together, the propositions imply that the three mechanisms should not be modelled in isolation. A prediction of circulating temperature that ignores dissipation will be biased low in high-shear sections; a prediction of fluid loss that ignores temperature-dependent cake permeability will be biased in a direction that depends on the fluid chemistry; and a stability analysis that ignores the wall temperature history will mis-state the time-dependent mud-weight window.

3.9. Discussion

3.9.1 When Does Each Mechanism Matter?

A recurring difficulty in the literature is that each mechanism is studied in isolation and its importance is asserted rather than established for drilling conditions. Table 4 consolidates the synthesis into an indicative regime map that links each mechanism to its controlling dimensionless group, the conditions under which it becomes significant, the wellbore locations where those conditions arise, and its main practical consequence. The thresholds are indicative orders of magnitude drawn from the trends reported in Section 3, not universal criteria, and should be refined as HPHT property data become available.

Table 4: Indicative regime map for the coupled mechanisms in high-temperature drilling.

Mechanism	Controlling group	Indicative condition for significance	Typical wellbore locations	Main consequence
Thermal and solutal relaxation	$\gamma_T = \lambda_T U/L$, $\gamma_C = \lambda_C U/L$	Event time comparable to the effective relaxation time	Circulation restart after static periods; thermal shock at the wall; pulsed flow	Transient wall heat and mass flux; local temperature overshoot
Viscous dissipation	Brinkman number, Br	Br of order 0.1 or larger	Bit nozzles; tool joints; narrow, eccentric or slim-hole annuli	Local heating; lower viscosity and ECD; higher tool temperature
Fluid elasticity	Weissenberg or Deborah number	Wi of order 1 or larger	High-shear annular flow; contractions; start-up of gelled mud	Normal stresses; stress overshoot; altered velocity and dissipation fields
Porous slip and invasion	Darcy number, Da; Forchheimer number	Permeable, fractured or vuggy formations; high overbalance	Open-hole reservoir sections; loss zones	Filtrate invasion; wall slip; heat carried into the formation
Cross-diffusion	Soret and Dufour numbers	Large temperature gradients with multicomponent fluids	Gas or light-hydrocarbon influx into OBM; concentrated brines at a hot wall	Solute redistribution; minor additional heat flux
Formation thermal coupling	Formation Fourier number; LTNE parameters	Early times after a change in circulation; high pore velocity	Open-hole intervals during trips, connections and kicks	Thermal stress and pore-pressure change at the wall

Read against Table 4, the evidence suggests a clear ranking for most field situations. Temperature-dependent rheology and formation heat exchange are always first-order; viscous dissipation is first-order locally and in narrow-clearance or high-rate operations; porous interactions are first-order in permeable open-hole sections; and thermal relaxation and cross-diffusion are second-order except in specific transients or fluid systems. This ranking partly answers RQ2 and is consistent with the success of classical circulating-temperature models, which capture the first-order terms, and with their known weaknesses in high-shear and highly transient conditions (Hasan and Kabir, 2002; Kabir *et al*., 1996) [89, 97].

3.9.2 Points of Convergence and Tension in the Literature

Several findings are consistent across the reviewed studies. Temperature dependence of viscosity and relaxation time couples the momentum and energy equations even in forced convection; dissipation becomes important in proportion to the Brinkman number; and lower formation permeability or higher porous drag decelerates near-wall flow and raises near-wall temperature (Nield and Bejan, 2017; Oluwaseun *et al*., 2023) [122, 190]. Across similarity-solution studies, thermal relaxation steepens temperature profiles and raises wall heat transfer rates relative to the Fourier prediction (Han *et al*., 2014; Straughan, 2010) [88, 211].

Three tensions stand out. The first concerns the physical relevance of thermal relaxation. The mathematical literature reports robust parametric trends, but measured relaxation times for simple liquids are extremely short, and the longer effective values suggested for structured media remain contested (Joseph and Preziosi, 1989; Kaminski, 1990; Straughan, 2011) [95, 98, 212]. The magnitude of relaxation effects in real drilling fluids is therefore an open empirical question rather than an established result. The second concerns the formulation of dissipation. Much of the literature inserts the full stress power as a heat source, whereas thermodynamically consistent treatments separate stored elastic energy from dissipated energy (Leonov, 1976; Bird *et al*., 1987) [61, 111]; the difference is negligible in steady shear but can matter in start-up and pulsating flows. The third concerns geometry and parameters. Most coupled heat and mass transfer studies use stretching-sheet, disk or channel geometries with assumed property values, while drilling occurs in long, eccentric, rotating annuli with fluids whose properties are poorly characterised at HPHT conditions.

A further tension lies between the transport literature and the operational literature reviewed in Section 3.7. The operational studies are rich in frameworks for monitoring, integrity, safety and environmental management, but they rarely represent fluid temperature, rheology or filtration explicitly, and much of this literature is conceptual rather than empirically validated. Conversely, transport studies rarely connect their predictions to operational decisions. The conceptual model in Section 3.8 is intended as a bridge between the two.

3.9.3 Bridging Transport Modelling and Field Practice

The most promising route to closing this gap is to embed coupled transport models in data-driven operational systems. A drilling-fluid digital twin would combine the governing equations of Section 3.2 with downhole and surface measurements to estimate, in real time, the parameters identified in Figure 1: relaxation time, zero-shear viscosity and its activation energy, thermal conductivity and mudcake permeability. Such a twin would provide the predictive layer for hydraulics management, tool thermal protection, early detection of fluid degradation and wellbore stability control, and its outputs would feed the safety and integrity frameworks discussed in Section 3.7 (Nwangwu *et al*., 2018) [127]. Its credibility, however, depends on validation data and on the integrity of the measurement chain, which points back to the data and security issues identified in the synthesis.

3.9.4 Answers to the Research Questions

With respect to RQ1, the review finds that thermal relaxation steepens thermal and solutal boundary layers and raises wall transfer rates in idealised flows; viscous dissipation adds a positive heat source that raises near-wall temperature and alters the direction of wall heat flux in some regimes; and porous interactions control filtrate invasion, slip, near-wall heating and thermoporoelastic stress. With respect to RQ2, the mechanisms interact through temperature-dependent rheology and through the temperature history at the borehole wall, and their relative importance follows the regime map in Table 4. With respect to RQ3, the coupled processes affect fluid design, hydraulics, tool reliability, wellbore stability, safety and environmental outcomes, and the main knowledge gaps concern HPHT property data, realistic geometries, consistent thermodynamic formulations and two-way coupling with the formation; these are developed in Sections 3.10 and 3.12.

3.10. Implications

3.10.1 Implications for Drilling-Fluid Design and Well Engineering

For fluid designers, the review implies that specifying HPHT fluids by plastic viscosity, yield point and fluid loss at a single test temperature is insufficient. Fluids should be characterised by temperature- and pressure-dependent viscoelastic properties (relaxation time, storage and loss moduli and their activation energies) together with thermal conductivity and heat capacity, so that coupled models can be parameterised (Alderman *et al*., 1988; Rommetveit and Bjørkevoll, 1997) [25, 201]. For well engineers, the Brinkman number provides a simple screening criterion for dissipation hotspots during hydraulics design, particularly for slim-hole, casing-while-drilling and managed-pressure operations. Filtration testing should move towards dynamic conditions with realistic temperature gradients across the cake, and wellbore stability analyses should use the predicted wall temperature history rather than a single static temperature (Chen and Ewy, 2005) [66].

3.10.2 Implications for Modelling and Research Practice

For modellers, three practices follow. Frame-invariant relaxation laws should be used only where the relaxation numbers justify them, and the values assumed should be stated and bounded. Dissipation terms should be thermodynamically consistent with the constitutive model. Studies should report the dimensionless groups of Table 1 and Table 4 so that results can be compared and placed on the regime map. More broadly, the field would benefit from a shift away from further parametric similarity solutions towards validated annular simulations coupled to formation heat transfer and filtration, and from shared benchmark problems with experimental data.

3.10.3 Implications for Digital Operations, Safety and Integrity

For operators, coupled thermal-hydraulic models are a natural core for digital twins, predictive maintenance of pumps and downhole tools, and alarm logic for abnormal temperature or pressure trends. Because these models influence well-control decisions, their inputs and outputs must be governed with the same rigour as other safety-critical data, including protection of the measurement chain against cyber-physical threats and integration with process-safety and management-of-change procedures (Section 3.7).

3.10.4 Implications for Environmental Management and the Energy Transition

Because thermal degradation alters the composition of spent fluids and cuttings, environmental assessment of HPHT drilling waste should account for the thermal history of the fluid rather than its fresh formulation alone, drawing on data pipelines that link environmental measurement to risk prediction (Aladegba and Ayinde, 2024; Aladegba *et al*., 2021) [23, 24]. The same coupled framework applies, with higher temperatures and reactive chemistries, to geothermal, carbon-storage and hydrogen-related wells, which are likely to account for a growing share of high-temperature drilling.

3.11. Limitations

Several limitations of this review should be acknowledged. First, it is an integrative narrative review rather than a systematic review with meta-analysis. Although explicit inclusion criteria and thematic coding were applied, the selection and weighting of sources involve judgement, and no quantitative pooling of results was possible because the studies differ in geometry, constitutive model and parameter values.

Second, coverage is limited to English-language sources published up to the end of 2024. Relevant work in other languages, in proprietary industry reports, or published after this date is not captured.

Third, the evidence base is uneven. The literature on thermal relaxation and coupled boundary-layer transport is dominated by idealised similarity solutions with assumed property values, and HPHT experimental data for real drilling fluids are scarce. Conclusions about the magnitude of relaxation and cross-diffusion effects are therefore qualitative, and the thresholds in Table 4 are indicative.

Fourth, much of the operational, integrity and sustainability literature included in Section 3.7 consists of conceptual frameworks and reviews with limited empirical validation, and its connection to drilling-fluid transport is inferred from the topic of each study rather than demonstrated within it. This part of the synthesis should be read as mapping the context in which transport models are used, not as evidence about the transport processes themselves.

Finally, the conceptual model and propositions are theoretical constructs derived from the synthesis and have not yet been tested. Harmonising notation across sources may also obscure differences between original formulations, and readers applying specific results should consult the primary sources.

3.12. Future Research

Building on the propositions in Section 3.8, the regime map in Section 3.9 and the limitations above, the following research priorities are identified.

- **Property data at HPHT.** Relaxation times, normal-stress coefficients, thermal conductivity, heat capacity and diffusivities of real drilling fluids at temperatures above 150 °C and elevated pressure are rarely reported together. Without such data, parameter values in theoretical studies remain arbitrary. Combined HPHT oscillatory rheometry, transient hot-wire conductivity and diffusion measurements on the same samples are needed.
- **Physical basis of thermal relaxation in muds.** The magnitude of λ_T for structured drilling fluids is not established. Dedicated transient experiments (for example, laser flash or thermal pulse tests on gelled muds) would determine whether Cattaneo-Christov effects matter at field scale or only in micro-scale transients.
- **Thermodynamically consistent dissipation.** Future models should distinguish stored elastic energy from dissipated energy, particularly for start-up of gelled muds and pulsating flows (mud-pulse telemetry, pipe reciprocation).
- **Realistic geometry.** Eccentric annuli, drillpipe rotation, tool joints and washouts strongly affect shear rates and therefore dissipation and heat transfer. Coupling viscoelastic CFD in these geometries with formation heat conduction is still limited.
- **Two-way coupling with the formation.** Few studies integrate rheology-dependent filtration, temperature-dependent cake properties and thermoporoelastic stress around the borehole in one framework. Such models would support integrated fluid design for wellbore strengthening and lost-circulation control.
- **Degradation kinetics.** Polymer and additive degradation should be modelled as a coupled reaction process whose rate depends on the local temperature history, which in turn depends on dissipation and heat exchange.
- **Geothermal and CO_2 storage wells.** Wells for enhanced geothermal systems and CO_2 injection impose higher temperatures, larger thermal cycles and reactive chemistries; these extend the relevance of the coupled framework beyond oil and gas.
- **Data-driven and hybrid models.** Machine-learning surrogates trained on validated physics-based simulations could make coupled models fast enough for real-time hydraulics and temperature management, provided their training spans the HPHT range. Experience from other data-intensive fields underlines that such models depend on well-curated measurement pipelines and transparent validation (Aladegba and Ayinde, 2024) [23].
- **Environmental and health dimensions.** Spent HPHT drilling fluids and cuttings contain degraded polymers, hydrocarbons, heavy metals and thermally altered additives. Data pipelines that link environmental measurement to health prediction (Aladegba and Ayinde, 2024) [23] and exposure-biomarker prevention frameworks (Aladegba *et al*., 2021) [24] could be adapted to assess how high-temperature degradation pathways change the environmental footprint of drilling-fluid waste.

4. Conclusion

Heat and mass transfer in viscoelastic drilling fluids under high-temperature wellbore conditions is a fully coupled problem in which rheology, energy and species transport, and formation response interact. Using an integrative review of 226 sources, this paper has shown that:

- Drilling fluids are measurably viscoelastic, and their viscosity and relaxation time vary strongly with temperature, which couples the momentum and energy equations even in forced convection.
- Cattaneo-Christov thermal and solutal relaxation consistently steepens temperature and concentration profiles and raises wall transfer rates in idealised flows, but its quantitative importance for real muds at field scale is unproven and depends on relaxation times that have not been measured reliably.
- Viscous dissipation is significant wherever the Brinkman number is not small, notably in narrow annuli, bit nozzles and high-rate slim-hole operations, and it feeds back on ECD and on the thermal exposure of downhole tools; for viscoelastic fluids only the dissipated part of the stress power should be counted.
- Interactions with the porous formation (filtration, mudcake dynamics, Darcy-Brinkman-Forchheimer flow, local thermal non-equilibrium, cross-diffusion and thermoporoelastic stress changes) close the coupling loop between fluid design and wellbore stability.
- An integrated conceptual model with six testable propositions links temperature-dependent rheology, the three mechanisms and their feedback loops to operational outcomes, and an indicative regime map identifies where each mechanism is significant.

Bridging the gap between mathematically sophisticated boundary-layer studies and practical wellbore engineering requires better HPHT property data, realistic geometries and explicit two-way coupling with the formation. Progress on these fronts will improve the prediction of circulating temperatures, ECD, fluid loss and borehole stability in the deep, hot wells that increasingly define the frontier of drilling.

Nomenclature

Table 5

Symbol	Description
C	Solute concentration
c_p	Specific heat capacity at constant pressure
c_F	Forchheimer coefficient
D	Rate-of-deformation tensor
D_m	Mass diffusivity
E_a	Activation energy
J, q	Mass flux and heat flux vectors
k	Thermal conductivity
K	Permeability
k_T	Thermal-diffusion ratio
p, T, u	Pressure, temperature, velocity vector
β_T, β_C	Thermal and solutal expansion coefficients
η_0, μ	Zero-shear viscosity, dynamic viscosity
λ_1, λ_2	Relaxation and retardation times of the fluid
λ_T, λ_C	Thermal and solutal flux relaxation times
ρ, φ	Density, porosity
τ	Extra-stress tensor

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