

Review

Advances in Numerical Simulation of Coupled Wellbore Fluid Flow and Heat Transfer During Drilling and Well Construction: Models, CFD, Validation, and AI-Assisted Deployment

Zijian Li ^{1,2}, Bo Zhang ², Liping Jiang ², Liqun Xu ^{1,2}, Tai Luo ^{1,2}, Bin Tang ^{1,2}, Yi Cheng ^{1,2}, Xianping Cao ^{1,2}, Gao Li ^{3,4,*}, Hongtao Li ^{3,4,*} , Xu Yang ³  and Stephen Butt ⁵ 

¹ Chengdu North Petroleum Exploration and Development Technology Co., Ltd., Chengdu 610051, China; zl5082@mun.ca (Z.L.)

² China ZhenHua Oil Co., Ltd., Beijing 100037, China

³ Petroleum Engineering School, Southwest Petroleum University, Chengdu 610500, China

⁴ State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu 610500, China

⁵ Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, NL A1B 1T0, Canada

* Correspondence: ligao@swpu.edu.cn (G.L.); lihongtao053@aliyun.com (H.L.)

Highlights

What are the main findings?

- Five model families structure wellbore thermal–hydraulic simulation.
- Consistent state-variable coupling can improve pressure-window prediction.
- Field-facing evidence links model outputs to ECD, BHP, SBP, and cementing-control variables.

What are the implications of the main findings?

- Coupling strategies range from sequential and fully coupled solvers to data-assimilated updating.
- Validation benchmarks are needed for HPHT, MPD, gas kick, and cementing.
- Physics-constrained AI can support real-time hydraulic advisory workflows.

Abstract

Wellbore fluid flow and heat transfer are strongly coupled during drilling and well construction, where temperature, pressure, rheology, gas behavior, transient operations, and cementing displacement jointly affect pressure-window control and wellbore safety. This review synthesizes advances in coupled wellbore thermal–hydraulic numerical simulation, emphasizing governing equations, discretization strategies, coupling algorithms, rheology and turbulence closures, verification and validation, computational efficiency, uncertainty quantification, and AI-assisted deployment. A bibliometric-guided critical review was conducted using an 841-record Web of Science corpus, 79 screened technical records, 86 screened OnePetro field-facing records, and representative prior reviews. CiteSpace was used to identify knowledge structure and thematic evolution, while screened records were coded by governing physics, numerical method, closure assumption, model output, validation evidence, and deployment relevance. The literature is organized into five model families: wellbore temperature and heat transfer; annular non-Newtonian flow, rheology, turbulence, and CFD; pressure-window and transient hydraulics; cementing displacement and well-construction flow; and AI-assisted calibration and deployment. The synthesis



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shows that field-deployable simulation requires consistent state variables, transparent closure hierarchies, benchmark validation, uncertainty reporting, CFD-to-well-scale transfer, reduced-order implementation, and physics-constrained AI updating.

Keywords: numerical simulation; computational fluid dynamics; heat transfer modeling; turbulence modeling; multiphysics flow; non-Newtonian fluid; wellbore thermal–hydraulic simulation; model validation; uncertainty quantification; AI-assisted simulation

1. Introduction

Wellbore thermal–hydraulic behavior is a central control on safe drilling and well construction. During circulation, shut-in, tripping, gas influx, managed-pressure drilling (MPD), and cementing, temperature and pressure evolve together in a confined annular system. These changes affect drilling-fluid density, viscosity, yield stress, gas solubility, multiphase behavior, frictional pressure loss, equivalent circulating density (ECD), bottom-hole pressure (BHP), and surface backpressure (SBP). In deepwater, high-pressure/high-temperature (HPHT), ultra-deep, extended-reach, and narrow-pressure-window wells, small errors in thermal or hydraulic prediction can alter mud-weight interpretation, pressure-margin control, kick/loss diagnosis, tripping limits, and cement-placement decisions [1–6].

The physical coupling is direct. Wellbore temperature is governed by axial fluid convection, radial heat transfer with the formation, heat exchange through drillstring, casing, cement, and annular fluids, and the operating history of circulation and shut-in periods. The resulting temperature field modifies density, rheology, gas solubility, and cement-slurry properties. Annular rheology and geometry then determine pressure loss and local velocity distribution. These hydraulic outputs enter ECD and BHP calculations, which are used to maintain the well within pore-pressure and fracture-pressure limits. Under gas kick, oil-based mud, CO₂ invasion, or other multiphase conditions, gas solubility, compressibility, slip, and phase transitions further complicate the coupling. During tripping, pipe motion and pump transitions create surge and swab pressures. During cementing, mud, spacer, and cement slurry form a multi-fluid displacement system where displacement quality and pressure response must be managed together [7–12].

Numerical simulation is the primary technical approach for analyzing these coupled processes. Analytical and semi-analytical models remain useful for wellbore heat transfer and pressure estimation when geometry and boundary conditions can be simplified. One-dimensional transient simulators support well-scale ECD, BHP, MPD, gas-kick, surge/swab, and cementing calculations. Computational fluid dynamics (CFD) provides local interpretation of eccentric annuli, non-Newtonian flow, wall shear, secondary flow, turbulence or transition behavior, and interface deformation. Data assimilation, surrogate modeling, physics-informed learning, and digital-twin workflows are increasingly used to accelerate, calibrate, and update physics-based simulations. These methods are especially relevant when field decisions require timely estimates of pressure margin, kick/loss tendency, tripping envelope, or cementing pressure response [13–16].

Figure 1 summarizes the conceptual framing used in this review. The framework treats wellbore thermal–hydraulic simulation as a connected state-variable problem. Temperature, rheology, pressure loss, ECD, BHP, SBP, gas behavior, surge/swab pressure, cementing response, and updated model states are interpreted as linked variables across drilling and well-construction operations. The framework links wellbore temperature and heat transfer, temperature-dependent density and rheology, annular non-Newtonian flow, ECD/BHP

and pressure-window response, gas kick and transient hydraulics, cementing displacement, and AI-assisted calibration or deployment. The key bridge variables include temperature profile, pressure loss, ECD, BHP, SBP, surge/swab pressure, displacement efficiency, and updated operational states.

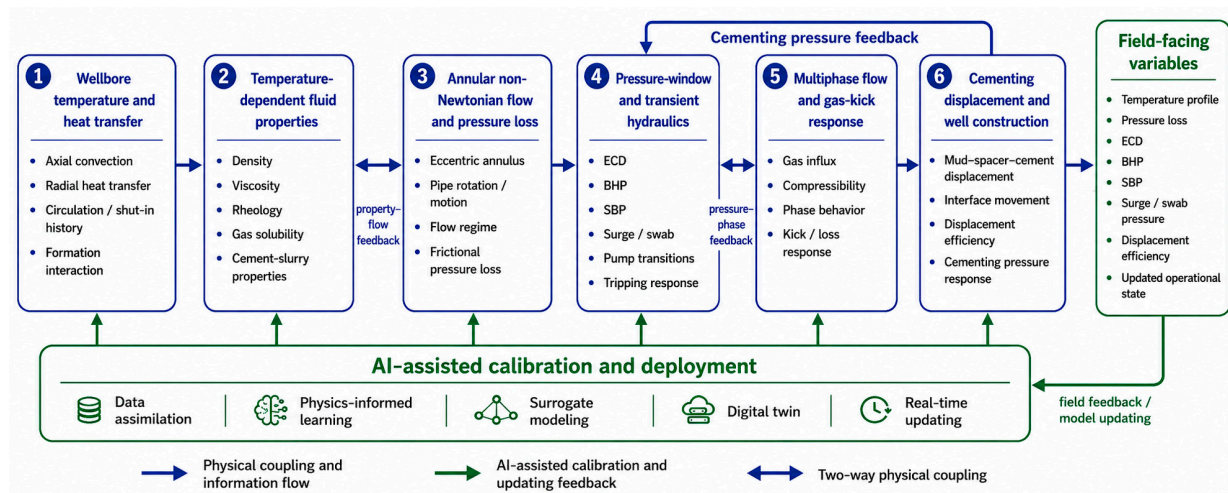


Figure 1. Conceptual framework of coupled wellbore thermal-hydraulic numerical simulation during drilling and well construction. Blue arrows indicate physical coupling and information flow among temperature, temperature-dependent properties, annular pressure loss, transient hydraulics, multiphase gas-kick response, cementing displacement, and field-facing variables. Blue double-headed arrows mark key two-way physical couplings, and green arrows show field-feedback and AI-assisted model-updating pathways.

Several review streams provide important foundations for this topic. Reviews on drilling-fluid rheology and thixotropic flow clarify how non-Newtonian behavior affects pressure loss and transport in wells and pipelines [17,18]. Reviews on hole cleaning and cuttings transport synthesize annular solids transport, rheology, field practices, and real-time applications [19]. Gas-kick and managed-pressure-drilling reviews summarize transient multiphase modeling, early kick detection, inversion, and control logic [20,21]. Intelligent drilling and drilling-systems reviews discuss automation, optimization, digital workflows, and AI-assisted prediction in broader drilling applications [22,23]. Reviews on AI in drilling-fluid engineering and cement-sheath integrity provide useful context for data-driven modeling and downstream well-integrity analysis [24,25].

These reviews define the neighboring knowledge base of the present study. A focused synthesis is still needed for numerical simulation of wellbore thermal-hydraulic processes during drilling and well construction. The current literature contains mature component studies on temperature prediction, annular hydraulics, ECD/BHP, MPD, gas kick, surge/swab pressure, cementing displacement, and AI-assisted updating. The connections among these component models, their closure assumptions, their validation evidence, and their translation into field-facing variables remain dispersed across the petroleum engineering, heat transfer, non-Newtonian fluid mechanics, multiphase flow, CFD, cementing, and digital drilling literature. Table 1 positions the present review relative to representative prior reviews.

Table 1. Positioning of the present review relative to representative prior reviews.

Review Stream	Representative Prior Reviews	Main Contribution of Prior Reviews	Added Perspective of the Present Review
Drilling-fluid rheology and thixotropic/non-Newtonian flow	Livescu [17]; Qu et al. [18]	Synthesizes drilling-fluid rheology, thixotropy, non-Newtonian behavior, and their effects on wellbore flow, pressure loss, and transport behavior.	Places rheology within a coupled thermal-hydraulic simulation chain by linking temperature-dependent fluid properties, pressure loss, ECD/BHP response, closure selection, and validation needs.
Hole cleaning, cuttings transport, and particle-laden annular flow	Al-Shargabi et al. [19] and related hole-cleaning reviews	Reviews cutting transport mechanisms, annular solids transport, drilling-fluid effects, empirical/mechanistic models, and real-time hole-cleaning applications.	Uses particle-laden annular-flow knowledge where solids loading, bed formation, eccentricity, and pipe rotation affect pressure loss, ECD, turbulence or transition closure, and transient hydraulic response.
Gas kick, well control, and MPD	Sleiti et al. [21]; Chen et al. [20]	Reviews transient gas-kick behavior, multiphase flow, MPD control, early kick detection, inversion, and well-control response.	Integrates gas kick and MPD into a broader non-isothermal pressure-window model family involving temperature, rheology, gas solubility, phase behavior, SBP control, and BHP/ECD prediction.
Drilling systems engineering, intelligent drilling, and digital workflows	Epelle and Gerogiorgis [22]; Li et al. [23]	Summarizes drilling-system modeling, automation, optimization, intelligent drilling technologies, and digital decision-support workflows.	Narrows the synthesis to wellbore thermal-hydraulic numerical simulation and compares model families in terms of governing equations, coupling strategies, validation evidence, computational cost, and deployment potential.
AI and data-driven drilling applications	Agwu et al. [24] and related AI-drilling reviews	Reviews machine learning and data-driven prediction for drilling-fluid engineering, drilling optimization, well-control support, and operational diagnostics.	Positions AI as an acceleration, calibration, state-estimation, uncertainty-screening, and deployment layer for physics-based thermal-hydraulic simulators rather than as a standalone black-box prediction tool.
Cementing, cement sheath, and well-integrity analysis	Wu et al. [25] and related cement-integrity reviews	Reviews cement-sheath integrity, thermo-mechanical loading, cement degradation, analytical models, and well-integrity implications.	Treats cementing displacement as a construction-stage thermal-hydraulic flow problem, linking mud-spacer-cement interface behavior, displacement efficiency, cementing ECD/BHP, SBP, and managed-pressure cementing.
Present review	This study	Provides a numerical-simulation synthesis of coupled wellbore fluid flow and heat-transfer modeling during drilling and well construction, supported by bibliometric mapping and screened technical evidence.	Links WoS-based knowledge-structure mapping with five numerical model families, governing equations, numerical methods, coupling strategies, rheology and turbulence closures, V&V (verification and validation) and UQ (uncertainty quantification), model-output to field-variable mapping, computational efficiency, and AI-assisted deployment.

The objective of this review is to synthesize recent advances in coupled wellbore thermal-hydraulic numerical simulation for drilling and well construction. The review emphasizes model development, computational coupling, closure selection, validation evidence, computational usability, predictive capability, and field-facing deployment. A bibliometric-guided critical review design is used to support this synthesis. A merged Web of Science (WoS) bibliometric corpus of 841 records is used to map publication trends, disciplinary base, keyword clusters, burst terms, and intellectual structure. A screened WoS technical layer of 79 records supports the critical review of numerical model families. A screened OnePetro field-facing layer of 86 records is used to interpret how simulation outputs appear in drilling and well-construction variables. Representative prior reviews are used to position the scope and contribution of the present synthesis.

Four research questions guide the review:

RQ1. What is the knowledge structure and thematic evolution of wellbore thermal–hydraulic numerical simulation during drilling and well construction?

RQ2. How are the main numerical model families organized in terms of governing physics, numerical methods, closure assumptions, coupling strategies, validation evidence, computational cost, and predictive outputs?

RQ3. How do field-facing records translate academic model outputs into operational variables such as ECD, BHP, SBP, pump rate, tripping speed, loss/kick detection, and cement-placement control?

RQ4. What research gaps and computational priorities are needed for coupled, validated, uncertainty-aware, computationally usable, and field-deployable thermal–hydraulic numerical simulation?

The review makes four contributions. First, it organizes the literature into five numerical model families and compares their governing equations, numerical methods, closure assumptions, outputs, validation evidence, computational constraints, and relevance for deployment. Second, it translates the bibliometric structure of the 841-record merged WoS corpus into a numerical-simulation framework centered on heat transfer, annular non-Newtonian flow and CFD, pressure-window and transient hydraulics, cementing displacement, and AI-assisted deployment. Third, it maps model outputs from the WoS technical literature to field-facing variables reported in the OnePetro layer, including temperature correction, pressure loss, ECD, BHP, SBP, pump rate, tripping envelope, loss/kick indicators, cementing response, and real-time updating. Fourth, it develops a computational roadmap for coupled, validated, uncertainty-aware, computationally usable, and AI-assisted thermal–hydraulic numerical simulation during drilling and well construction.

This review treats well drilling and well construction as an application domain for coupled thermal–hydraulic numerical simulation. The primary focus is the mathematical formulation, numerical discretization, coupling strategy, closure hierarchy, verification and validation, computational cost, predictive capability, and deployability of simulation models. Operational quantities such as equivalent circulating density, bottomhole pressure, surface backpressure, kick indicators, tripping limits, and cementing pressure response are interpreted as model outputs, boundary-control variables, calibration targets, or validation variables within the coupled numerical-simulation framework.

The remainder of the paper is organized as follows. Section 2 describes the review design, data sources, corpus construction, preprocessing, CiteSpace settings, technical coding, and synthesis strategy. Section 3 presents the bibliometric results and translates the mapped themes into the critical review structure. Section 4 reviews the five numerical model families and compares their governing physics, closure assumptions, outputs, validation evidence, and field-use constraints. Section 5 synthesizes the WoS and OnePetro evidence by mapping model outputs to field-facing variables. Section 6 identifies research gaps and develops a numerical-simulation roadmap. Section 7 concludes the review and summarizes the main contribution.

2. Review Design, Data Sources, and Methods

2.1. Review Design and Evidence Architecture

The review is carried out on coupled wellbore thermal–hydraulic numerical simulation during drilling and well construction using a bibliometric-guided critical review design. Bibliometric mapping describes corpus-level knowledge structure, thematic evolution, and research fronts. Technical coding compares governing equations, numerical methods, coupling strategies, closure assumptions, validation evidence, uncertainty treatment, computational usability, and field-deployment relevance.

The review used four main evidence groups, with core, extended, and contextual subdivisions shown in Figure 2. The merged Web of Science (WoS) bibliometric corpus supported science mapping and thematic analysis. The screened WoS technical records supported the model-family synthesis. Representative prior reviews positioned the scope of this review relative to neighboring review streams. The OnePetro field-facing records helped connect model outputs with operational variables, including ECD, BHP, SBP, pump rate, tripping speed, loss/kick detection, cementing schedule, and cement-placement decisions.

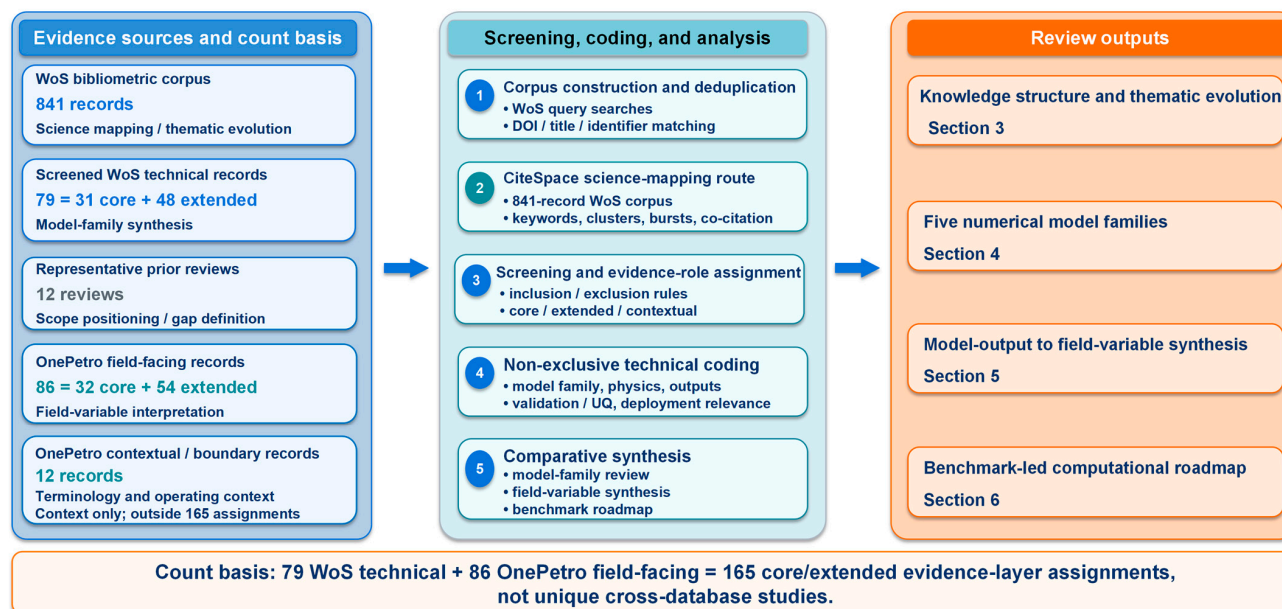


Figure 2. Evidence architecture and review workflow. The workflow links the 841-record WoS bibliometric corpus, 79 screened WoS technical records, representative prior reviews, and 86 screened OnePetro field-facing records to bibliometric mapping, model-family synthesis, model-output to field-variable interpretation, and roadmap development. The 79 WoS technical records and 86 OnePetro field-facing records are reported as 165 core/extended evidence-layer assignments rather than 165 cross-database unique studies.

Records were counted by evidence layer. The 79 WoS technical records and 86 OnePetro field-facing records represent 165 core/extended evidence-layer assignments. Related studies may appear in both databases, especially when a technical development is reported in both conference and journal forms. The two evidence layers support different parts of the synthesis: WoS records mainly support archival model analysis, while OnePetro records mainly support field-facing interpretation.

This evidence structure connects the bibliometric map of the field to the technical evolution of numerical model families and to the use of model outputs for field-facing variables. The resulting synthesis supports the development of a numerical-simulation roadmap for coupled, calibrated, uncertainty-aware, and field-deployable thermal–hydraulic modeling.

2.2. Database Search and Corpus Construction

The WoS corpus was constructed with a modular search strategy. A high-precision seed search captured coupled thermal–hydraulic numerical modeling during oil and gas well drilling. Additional searches covered wellbore heat transfer, ECD/BHP and MPD hydraulics, gas kick and well control, non-Newtonian annular flow, rheology and turbulence, cementing displacement, AI-assisted modeling, surrogate modeling, data assimilation, and complex-well applications. The full WoS search strings are listed in Supplementary File S1.

The WoS searches covered records from 1990 to 31 May 2026 and were finalized on 8 June 2026. The final exports were restricted to English-language articles and reviews in the WoS Core Collection. Records from the modular searches were merged and deduplicated using WoS accession number, DOI, normalized title, and publication year. The resulting WoS bibliometric corpus contained 841 records.

A separate screening step identified the WoS technical records used for model-family synthesis. We retained WoS records in the technical layer when they met three conditions: they addressed a drilling or well-construction thermal–hydraulic problem; they provided usable information on model formulation, governing equations, closure assumptions, numerical method, validation evidence, uncertainty treatment, or deployment relevance; and they contributed to at least one of the five model families reviewed in Section 4. We removed records that focused on reservoir-only production simulation, surface or pipeline flow assurance without wellbore-construction relevance, unrelated heat-transfer systems, purely operational reports without model content, or studies with insufficient technical information for model synthesis. This screening produced 31 WoS core technical records and 48 WoS extended technical records. The screening rubric and record-level assignments are provided in Supplementary File S2.

OnePetro was searched as a field-facing evidence source. The searches covered five directions: wellbore temperature and heat transfer; ECD/BHP, MPD, and well control; surge/swab and tripping hydraulics; cementing displacement and managed-pressure cementing; and AI-assisted modeling, data assimilation, and digital-twin workflows. The searches covered records published from 1990 to 31 May 2026 and were finalized on 8 June 2026. The search strings and retrieval notes for the OnePetro literature search are listed in Supplementary File S1.

The five OnePetro searches yielded 807 records. After overlap checking by DOI, normalized title, and OnePetro identifier, 771 candidate records remained. We retained OnePetro records in the field-facing layer when they provided traceable technical content on field measurements, operating constraints, calibration targets, deployment workflows, operational decision variables, or case-based interpretation relevant to wellbore thermal–hydraulic simulation. We removed records that provided only generic operational background, a commercial description without technical traceability, a reservoir-only interpretation, an equipment discussion without relevance to modeling, or insufficient information for field-variable synthesis. The retained OnePetro evidence included 32 core and 54 extended field-facing records, with a further 12 contextual or boundary records.

Core records directly supported the critical synthesis through model formulation, numerical implementation, closure treatment, validation evidence, uncertainty treatment, calibration relevance, or deployment information. Extended records supported the synthesis through related mechanisms, boundary conditions, partial validation datasets, adjacent model families, or implementation constraints. Contextual or boundary records were used to define terminology, operating context, or adjacent engineering scope. Model-family coding was non-exclusive, so a record could contribute to more than one technical theme when its content supported multiple model families. Table 2 summarizes the evidence layers used in the review.

Table 2. Evidence layers and their use in the review.

Evidence Layer	Records	Main Use in the Review
Merged WoS bibliometric corpus	841	CiteSpace-based science mapping; publication trends; source, country, institution, author, keyword, cluster, burst, cited-source, and reference co-citation analysis
WoS core technical records	31	Primary archival evidence for model families, governing physics, numerical methods, closures, validation, and uncertainty treatment
WoS extended technical records	48	Supporting evidence for model evolution, closure assumptions, partial validation, related mechanisms, and boundary interpretation
Representative prior reviews	12	Scope positioning, comparison with neighboring review streams, and gap definition
OnePetro core field-facing records	32	Primary field-facing evidence for model-to-variable interpretation, calibration, operational constraints, and deployment discussion
OnePetro extended field-facing records	54	Supporting evidence for field cases, operating envelopes, real-time use, and implementation constraints
OnePetro contextual or boundary records	12	Terminology, field context, operating boundaries, and adjacent engineering scope

Note. The 79 WoS technical records and 86 OnePetro field-facing records are counted as 165 core/extended evidence-layer assignments rather than 165 cross-database unique studies. Related studies, conference-to-journal extensions, or records describing the same technical development may occur in both WoS and OnePetro. WoS records mainly support bibliometric mapping and archival model synthesis, while OnePetro records mainly support field-facing interpretation of operational variables, calibration targets, and deployment constraints.

2.3. Data Preprocessing and CiteSpace Mapping

Data standardization was performed prior to the bibliometric analysis. Source-title variants, abbreviations, and journal-title changes were checked to reduce fragmentation in source statistics. *Journal of Petroleum Science and Engineering* and *JPSE* were standardized under *Geoenery Science and Engineering*, while *Journal of Natural Gas Science and Engineering* was standardized under *Gas Science and Engineering*. Common variants of *SPE Journal*, *SPE Drilling & Completion*, *Applied Thermal Engineering*, *International Journal of Heat and Mass Transfer*, and *Journal of Non-Newtonian Fluid Mechanics* were also checked.

Keyword variants were merged where they referred to the same technical concept. Examples include bottomhole pressure and bottomhole pressure, wellbore temperature and wellbore temperature, computational fluid dynamics and CFD, managed pressure drilling and MPD, equivalent circulating density and ECD, and bottomhole pressure and BHP. Country, institution, and source-name variants were also standardized. Author names were interpreted with caution because initials, spelling variants, and common surnames can affect author-level networks. Author and institution results were therefore used to identify research lines and collaboration patterns.

CiteSpace 7.0.R0 was used to analyze the merged WoS bibliometric corpus of 841 records. CiteSpace supports the detection of co-occurrence structures, co-citation relationships, thematic clusters, burst terms, and emerging research fronts in the scientific literature [26,27]. The time span was set from 1990 to 2026, with 2026 records covering publications available up to 31 May 2026. One year was used per time slice.

Node selection used the g-index with $k = 25$. The pruning strategy combined Pathfinder, pruning sliced networks, and pruning the merged network. The analyzed node types included authors, institutions, countries or regions, keywords, cited authors, cited sources, and cited references.

Frequency was used to describe node prominence in the corpus. Betweenness centrality was interpreted as a bibliometric bridging indicator. Burst strength was used to

detect rapid growth in attention during specific periods. Keyword co-occurrence, keyword clustering, and timeline visualizations were used to identify conceptual structures and thematic evolution. Reference co-citation and burst detection were used to identify influential knowledge bases and emerging fronts. Cited-source analysis was used to clarify the disciplinary base of the field, including petroleum engineering, heat transfer, non-Newtonian fluid mechanics, multiphase flow, chemical engineering, computational mechanics, and applied mathematical modeling.

Cluster labels were generated using the log-likelihood ratio (LLR) algorithm, with latent semantic indexing (LSI) and mutual information (MI) labels used as auxiliary references. The original labels were checked against representative keywords, cluster members, cited references, and timeline positions. Because the merged corpus intentionally covered adjacent thermal, hydraulic, drilling, cementing, and deployment-oriented topics, some automatic labels contained boundary terms from thermal recovery, geothermal wells, injection problems, or general transport phenomena. The final cluster descriptions reported in Section 3 were therefore manually refined for readability and engineering meaning. This refinement changed the wording of the labels but preserved the cluster membership and the bibliometric evidence behind them.

2.4. Technical Coding and Synthesis Strategy

The screened WoS and OnePetro records were coded with a non-exclusive model-family matrix. The coding fields included evidence source, evidence role, technical module, model family, governing physics, numerical method, closure type, field or laboratory context, main input variables, main output variables, validation evidence, uncertainty treatment, computational cost, field calibratability, and deployment relevance. The coding matrix is provided in Supplementary File S2.

The critical review was organized into five model families: wellbore temperature and heat-transfer models; annular non-Newtonian flow, rheology, turbulence, and CFD; pressure-window and transient wellbore hydraulics; cementing displacement and well-construction thermal-hydraulic flow; and AI-assisted numerical simulation. These families connect the main bibliometric themes with the state variables used in drilling and well-construction models.

For each model family, the review compared governing physical processes, numerical or analytical solution approaches, coupling strategies, closure assumptions, required inputs, output variables, validation evidence, uncertainty treatment, computational requirements, and field-use relevance. Typical outputs included wellbore temperature, pressure loss, ECD, BHP, gas-kick response, surge/swab pressure, cement displacement efficiency, interface position, residual mud, SBP, and updated operational variables.

WoS records mainly supported archival model comparison, including governing-equation formulation, numerical methods, closure assumptions, verification and validation, and uncertainty-related discussions. OnePetro records mainly supported field-facing interpretation, including operational constraints, calibration targets, deployment pathways, and case-based implementation. Conference and OnePetro records were used in the critical synthesis when they provided traceable technical content, field conditions, operational observations, calibration information, or deployment details relevant to the review questions. Extended comparison tables and benchmark specifications are provided in Supplementary File S3.

2.5. Boundary Control

Adjacent topics were addressed based on their contribution to the wellbore thermal-hydraulic numerical simulation. Cuttings transport and hole cleaning were retained when

they informed particle-laden annular hydraulics, pressure loss, ECD, or transient hydraulic response. Cement-sheath integrity was used as a downstream context when it was linked to thermal or hydraulic loading, while the main synthesis focused on cementing displacement, mud removal, spacer/cement flow, and managed-pressure cementing. Topics outside the scope of wellbore drilling and well-construction modeling, including production optimization, reservoir simulation, ground-source heat exchangers, manufacturing drilling, and unrelated heat-transfer systems, were excluded from the technical synthesis.

3. Bibliometric Results: Knowledge Structure and Thematic Evolution of Wellbore Thermal–Hydraulic Numerical Simulation

3.1. Publication Trend and Disciplinary Base

The 841-record merged WoS corpus shows a steady expansion of wellbore thermal–hydraulic numerical simulation from 1990 to 31 May 2026. Figure 3 summarizes the annual trend. The 2026 value represents partial-year coverage, and detailed annual counts are provided in Supplementary File S3.

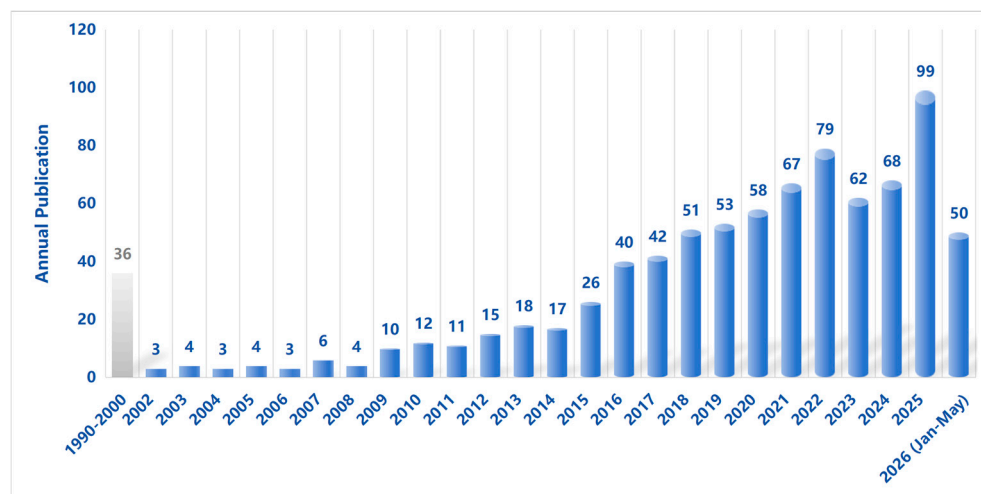


Figure 3. Publication trend and development stages of wellbore thermal–hydraulic numerical simulation based on the 841-record merged WoS corpus. Records from 1990 to 2000 are aggregated as an early-stage baseline, while records from 2001 onward are shown annually. The 2026 value represents publications available up to 31 May 2026. Stage boundaries were defined from changes in publication growth and dominant bibliometric themes.

The publication curve indicates four technical stages. Before 2008, most studies addressed wellbore heat transfer, circulation temperature, annular pressure loss, and early mathematical descriptions of drilling-fluid flow. From 2008 to 2015, temperature–pressure coupling, BHP/ECD prediction, gas kick, and MPD became more visible. From 2016 to 2020, CFD, non-Newtonian annular flow, eccentric annuli, pipe rotation, and transient hydraulics shifted the field toward local flow mechanisms and the development of closures. Since 2021, the literature has expanded toward deepwater and ultra-deep wells, non-isothermal multiphase flow, cementing displacement, surrogate modeling, physics-informed learning, data assimilation, and digital-twin workflows.

The source profile confirms the interdisciplinary base of the field. Petroleum-engineering journals define the main operating variables, including ECD, BHP, SBP, gas-kick response, tripping limits, and cementing pressure. Heat-transfer and fluid-mechanics journals provide the governing equation and numerical method base. Non-Newtonian flow, multiphase flow, chemical engineering, and applied modeling sources contribute to closure models, solver strategies, and uncertainty concepts. Detailed source statistics are provided

in Supplementary File S3. In the main text, these results identify the disciplinary base and the variables that connect the model families.

3.2. Collaboration Patterns and Intellectual Foundations

The collaboration networks show a field shaped by demand in petroleum engineering and cross-disciplinary numerical modeling. High-frequency institutional nodes include petroleum universities, national oil companies, engineering research institutes, and selected international research centers. The country and region network includes major contributions from China and the United States, with recurring contributions from Canada, Brazil, the United Kingdom, Saudi Arabia, Norway, Germany, Iran, Russia, India, Qatar, and other regions. Detailed tables of authors, institutions, and countries or regions are provided in Supplementary File S3.

These patterns provide context for the distribution of evidence. The cited-source structure carries the stronger technical signal. Petroleum-engineering sources define the operational variables and field constraints used in drilling and well construction. Heat-transfer and fluid-mechanics sources support the energy, momentum, and transport equations. Non-Newtonian-flow and multiphase-flow sources support rheology, flow regime, turbulence, slip, and phase behavior closures. Applied modeling and computational sources support discretization, stability, reduced-order modeling, and uncertainty analysis.

The cited-author structure follows the same technical base. Foundational heat-transfer and wellbore-temperature studies support the thermal model family. Drilling hydraulics and non-Newtonian flow studies support annular pressure loss and CFD-informed closure development. MPD, gas-kick, and well-control studies support transient pressure-window modeling. Cementing and well-construction studies extend the same pressure-flow logic to mud-spacer-cement displacement. This evidence base supports the five model families reviewed in Section 4.

3.3. From Keyword Clusters to Model Families

The keyword map identifies the variables that connect the field: temperature, fluid properties, annular pressure loss, ECD/BHP, gas behavior, cementing displacement, and model updating. Figure 4 translates the refined keyword-cluster signals into state-variable links and the five numerical model families used in the critical review. The original CiteSpace keyword co-occurrence network, cluster timeline, cluster IDs, LLR labels, representative terms, and refined engineering labels are provided in Supplementary File S3.

Temperature and heat-transfer clusters define the thermal state of the wellbore. They cover circulation, shut-in response, wellbore–formation heat exchange, formation-temperature interpretation, and temperature-dependent properties. Non-Newtonian flow, eccentric annulus, CFD, annular pressure loss and pipe motion clusters define the annular momentum problem. In this model family, rheology, geometry, wall treatment, turbulence or transition, and pipe motion control pressure loss and ECD correction.

ECD, BHP, MPD, gas kick, surge/swab, tripping, multiphase-flow, and phase-transition clusters define the transient pressure-window problem. These terms connect temperature, rheology, gas solubility, compressibility, pump history, pipe motion, SBP, and well-control boundaries. Cementing-displacement clusters extend the same thermal–hydraulic logic to mud-spacer-cement flow, interface movement, displacement efficiency, and cementing pressure response. AI-related clusters cover surrogate prediction, data assimilation, Kalman filtering, physics-informed learning, fault or kick classification, and digital twin workflows.

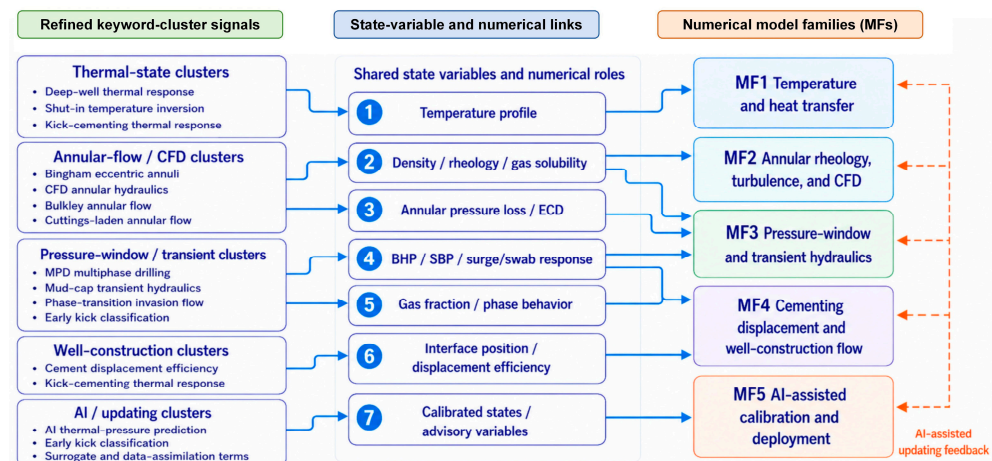


Figure 4. Translation from refined keyword-cluster signals to the five numerical model families used in the critical review. Bibliometric themes were interpreted through engineering-readable state variables and numerical tasks, including temperature prediction, temperature-dependent properties, annular pressure loss, ECD/BHP, multiphase gas-kick response, cementing displacement, and AI-assisted updating. Detailed CiteSpace cluster IDs, LLR labels, representative terms, and timeline outputs are provided in Supplementary File S3.

These groups form a calculation chain that follows the main state variables. Temperature models define the thermal state. Property models update density, viscosity, yield stress, gas solubility, and slurry behavior. Annular-flow models convert those properties and the well geometry into pressure loss. Transient-hydraulics models use that pressure response to estimate ECD, BHP, SBP, gas-kick behavior, surge/swab response, and pressure-window margins. Cementing models extend the pressure-flow logic to mud-spacer-cement displacement. Calibration, data assimilation, and AI-assisted methods update the state or reduce computational cost as field measurements become available. This chain supports the five model-family structure used in Section 4. Table 3 summarizes how the refined bibliometric signals were translated into the model-family structure, physical/numerical links, and critical-review uses.

Table 3. From refined CiteSpace signals to a critical review structure.

Refined Bibliometric Signal	Model Family	Physical/Numerical Link	Critical Review Use
Wellbore temperature; heat transfer; circulation and shut-in response	Temperature and heat transfer	Energy equation; wellbore–formation exchange; thermal state	Assess boundary conditions, heat-transfer coefficients, calibration, and uncertainty propagation
Non-Newtonian fluid; eccentric annulus; CFD; annular pressure loss	Annular flow, rheology, turbulence, and CFD	Momentum closure; rheology; wall treatment; pipe motion	Compare closure fidelity, near-wall limits, CFD-to-well-scale transfer, and pressure-loss uncertainty
ECD; BHP; MPD; gas kick; surge/swab; tripping; multiphase flow	Pressure-window and transient hydraulics	Transient mass-momentum balance; gas behavior; compressibility; boundary control	Compare drift-flux, mixture, two-fluid, VOF, and Level Set assumptions
Cementing displacement; residual mud; interface movement; displacement efficiency	Cementing displacement and well-construction flow	Mud-spacer-cement displacement; interface tracking; pressure response	Evaluate displacement quality, pressure control, and indirect post-job validation
Surrogate modeling; data assimilation; machine-learning prediction; Kalman updating; digital-twin terms	AI-assisted calibration and deployment	Acceleration; parameter updating; state estimation; advisory output	Compare ROM, surrogate ML, PINN, neural operator, Kalman/data assimilation, and digital-twin use

3.4. Burst Terms and Critical-Review Transition

Burst terms add timing to the cluster interpretation. The first shift is from component-level temperature or pressure calculations toward coupled temperature–pressure models. The second shift is from one-dimensional hydraulics toward CFD-informed closure development for eccentric annuli, non-Newtonian flow, pipe rotation, turbulence or transition, and particle-affected pressure loss. The third shift is from offline simulation toward field-facing prediction, including MPD control, gas-kick response, managed-pressure cementing, real-time calibration, surrogate modeling, and digital-twin workflows.

These shifts expose the main technical gaps. Temperature models still depend on heat-transfer coefficients, formation properties, inlet temperature history, and field calibration data. Annular CFD provides local flow detail, yet turbulence closure, wall treatment, near-wall non-Newtonian behavior, accuracy for eccentric narrow gaps, and CFD-to-well-scale transfer still limit its direct field use. Transient pressure-window models depend on multiphase formulations, slip closures, gas solubility, phase transitions, and boundary-control assumptions. Cementing models need stronger links between local interface movement and well-scale pressure response. AI-assisted models reduce computational costs and enable updates, while their reliability depends on training-domain coverage, sensor quality, uncertainty reporting, and independent validation. These links set up the model-family appraisal in Section 4. Each family is examined in terms of governing physics, numerical methods, closure assumptions, validation evidence, dominant sources of uncertainty, and field-use limits.

4. Critical Review of Numerical Model Families

Section 3 translated the bibliometric signals into five connected model families: wellbore temperature and heat-transfer models; annular non-Newtonian flow, rheology, turbulence, and CFD models; pressure-window and transient wellbore hydraulics models; cementing-displacement and well-construction flow models; and AI-assisted numerical simulation methods. This section reviews these families in terms of their governing physics, numerical methods, closure assumptions, model outputs, validation evidence, computational constraints, and field-use limits.

The model families share a common calculation chain. The temperature field changes density, viscosity, yield stress, gas solubility, and slurry behavior. Annular-flow models translate these properties into pressure loss, wall shear, velocity distribution, and ECD response. Pressure-window and transient-hydraulics models then connect ECD, BHP, SBP, gas influx, surge/swab pressure, tripping response, pump transitions, and other time-dependent operating changes. Cementing-displacement models extend the same thermal–hydraulic logic into mud-spacer-cement flow. AI-assisted methods support model acceleration, calibration, state estimation, uncertainty screening, and field updating. Figure 5 summarizes the model-family map used in this section. The map links the five model families with representative outputs and field-facing variables.

4.1. General Mathematical and Numerical Structure of Coupled Wellbore Thermal–Hydraulic Simulation

At the well scale, coupled wellbore thermal–hydraulic simulation is commonly formulated as a cross-section-averaged multiphysics problem, whereas local CFD resolves three-dimensional annular-flow and interface structures. The main state variables include pressure, temperature, velocity or flow rate, density, viscosity, yield stress, gas fraction, phase state, solids or cuttings concentration where relevant, and cementing-interface position during well construction. These variables evolve along the wellbore and change with operating history, boundary control, and thermal exchange with the surrounding formation.

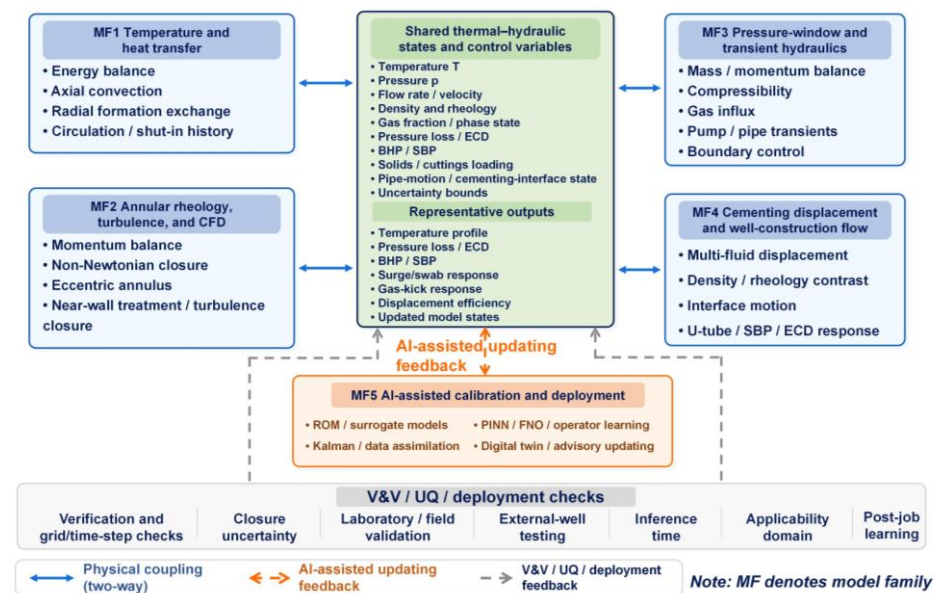


Figure 5. Coupled thermal-hydraulic model-family map for drilling and well construction. The map links the five numerical model families with shared state variables, representative outputs, and field-facing variables. Blue arrows indicate the coupled physical/state-variable chain, while feedback links show how pressure response, multiphase behavior, cementing pressure, and AI-assisted updating interact across model families.

At the well scale, most drilling-oriented simulators are built around one-dimensional mass, momentum, and energy balances. In schematic form, the mass balance tracks compressible or incompressible flow along the wellbore; the momentum balance relates the pressure gradient to gravity, acceleration, wall friction, pipe motion, and local losses; and the energy balance links axial convection to radial heat exchange between the wellbore and the formation. Additional property relations and closure models are required for density, viscosity, rheology, gas solubility, phase behavior, slip, friction factor, turbulence or transition, and cementing-interface movement [1–3,28,29].

The coupling path is often implemented sequentially for computational convenience, although the underlying thermal, hydraulic, rheological, and multiphase feedbacks are inherently two-way. Temperature affects density, viscosity, yield stress, gas solubility, and cement-slurry properties. These properties determine frictional pressure loss, velocity distribution, flow regime, and equivalent circulating density. Pressure and temperature jointly affect gas expansion, multiphase behavior, phase transition, and kick response. During MPD, the surface backpressure boundary modifies the bottomhole pressure target. During tripping, pipe motion changes the surge and swab response. During cementing, density and rheology contrasts between mud, spacer, and cement control both displacement efficiency and pressure response [5,6,8,10,12].

Different numerical methods are used depending on the scale and purpose of the model. Analytical and semi-analytical methods are useful for simplified heat-transfer and pressure-response problems. Finite-difference method (FDM), finite-volume method (FVM), and finite-element method (FEM) approaches support transient temperature and pressure calculations and multiphase-flow calculations. CFD is used to resolve local annular flow, eccentricity, pipe rotation, wall shear, turbulence or transition behavior, particle-laden flow, and cementing-interface deformation. Reduced-order models (ROMs), surrogate models, Kalman filtering, data assimilation, and physics-informed learning are increasingly used to accelerate, calibrate, and update physics-based models [13,15,16,30,31].

This general structure provides the numerical basis for the five model families reviewed below. Although these families differ in governing equations, closure assumptions,

spatial scale, computational cost, validation evidence, and deployment potential, they share the need for consistent state variables, transparent coupling, reliable verification and validation, and explicit uncertainty reporting.

The main coupling task is to keep these state variables consistent as the model moves from energy balance to pressure response, multiphase behavior, cementing displacement, and field updating. Inconsistent state transfer creates a major numerical risk. A temperature field can be passed explicitly to a rheology model, updated iteratively with pressure loss, or solved in a tighter coupled scheme. Slow formation heat transfer and fast hydraulic transients also require different time scales. Field-usable models, therefore, need clear coupling variables, stable time-step control, transparent closure assumptions, and validation targets that match the intended decision.

Table 4 summarizes the numerical-method dimensions of the five model families reviewed in this section. The comparison links each model family with its governing equations, discretization or solver strategy, coupling treatment, and main verification or validation focus. This table provides a common numerical simulation framework before the following subsections examine each model family in more detail.

Table 4. Numerical-method dimensions of wellbore thermal–hydraulic model families.

Model Family	Governing Focus	Solver/Method	Coupling Role	Verification/Validation Focus
Temperature and heat transfer	Energy balance; axial convection; radial wellbore–formation exchange	Analytical/semi-analytical solutions; FDM, FVM, FEM	Feed density, rheology, gas behavior, and pressure loss	Analytical limits; outlet/downhole temperature; circulation and shut-in calibration
Annular flow, rheology, turbulence, and CFD	Annular momentum; non-Newtonian rheology; transition/turbulence	Hydraulic correlations; 1D models; Reynolds-averaged Navier–Stokes (RANS) CFD; high-fidelity benchmarks	Converts fluid properties and geometry into pressure loss and ECD	Flow-loop data; rheology data; pressure-drop error; mesh/time-step sensitivity
Pressure-window and transient hydraulics	Mass and momentum balances; compressibility; gas influx; boundary control	1D transient solvers; multiphase simulators; pressure-wave models	Couples temperature, rheology, pipe motion, pump history, SBP, and BHP/ECD	Field pressure data; MPD records; transient-response comparison
Cementing displacement and well-construction flow	Multi-fluid displacement; density/rheology contrast; interface motion	1D cementing hydraulics; transient simulators; interface-resolving CFD	Links displacement quality with ECD/BHP, U-tube response, and SBP	Displacement tests; pressure records; CFD comparison; post-job evidence
AI-assisted calibration and deployment	Data-driven or hybrid approximation of thermal–hydraulic states	ROMs; surrogate ML; PINNs; Kalman/data assimilation; digital twins	Updates states, parameters, closures, and advisory variables	External-well tests; interval coverage; inference time; domain-shift checks

Table 5 complements Table 4 by appraising the same model families through main assumptions, dominant uncertainties, validation gaps, and field-deployment limitations. Together, Tables 4 and 5 define the numerical and critical-review basis for Sections 4.2–4.6 and for the WoS–OnePetro synthesis in Section 5.

Table 5. Comparison of numerical model families for wellbore thermal–hydraulic simulation.

Model Family	Main Assumptions	Dominant Uncertainties	Validation Gap	Field-Deployment Limitation
Temperature and heat transfer	Cross-section-averaged energy balance; prescribed inlet temperature, geothermal gradient, heat-transfer coefficients, and well structure	Heat-transfer coefficient; formation thermal properties; circulation/shut-in history; temperature-dependent fluid properties	Often calibrated to limited BHT, outlet-temperature, or tool-temperature data; axial annular profile remains weakly constrained	Thermal error propagates into density, rheology, gas behavior, ECD/BHP, and cementing pressure
Annular flow, rheology, turbulence, and CFD	Rheological law represents drilling mud; eccentricity, pipe motion, and wall treatment can be parameterized	Downhole rheology; thixotropy; transition regime; wall functions; narrow-gap near-wall behavior; solids loading	Flow-loop and CFD validation often differ from field geometry, pipe motion, thermal state, and cuttings loading	Full CFD is too costly for routine advisory use; well-scale models need validated closures or correction factors
Pressure-window and transient hydraulics	1D transient mass–momentum framework; gas behavior, slip, compressibility, pipe motion, and SBP are closed	Gas solubility and breakout; slip closure; influx/loss rate; pump history; boundary conditions; sensor lag	Sparse downhole pressure data and uncertain influx/loss diagnosis limit independent validation	Real-time use requires stable solvers, synchronized field data, and uncertainty bounds on pressure margin
Cementing displacement and well-construction flow	Mud–spacer–cement flow represented by interface tracking or displacement-efficiency closure; pressure and displacement are coupled	Rheological contrast; density hierarchy; eccentricity; losses; U-tube effect; temperature-dependent slurry behavior	Post-job evidence is indirect; pressure records and cement logs do not resolve local interface history	Models must balance displacement quality with ECD/BHP and loss-risk control
AI-assisted calibration and deployment	Training or simulator data cover the operating envelope; physical constraints reduce extrapolation risk	Training-domain coverage; sensor quality; data leakage; model drift; extrapolation; uncertainty model	Many studies lack external-well tests, complete-operation tests, and interval-coverage reporting	Best used for acceleration, calibration, screening, and advisory support; control use needs conservative safeguards

4.2. Wellbore Temperature, Heat Transfer, and Temperature-Dependent Properties

Wellbore temperature modeling is the thermal foundation of the coupled model chain. During drilling, the circulating fluid exchanges heat with the drillstring, annulus, casing, cement, and surrounding formation. The temperature field changes with circulation history, inlet mud temperature, geothermal gradient, well depth, flow rate, wellbore structure, and shut-in duration. These changes affect density, viscosity, yield stress, gas solubility, hydrate risk, cement hydration, and pressure prediction.

Classical wellbore heat-transfer models established the basis for this work. Early studies by Ramey, Raymond, and Hasan and Kabir treated the wellbore as a heat-transfer system involving axial convection inside the wellbore and radial heat conduction into the formation [1–3]. These models remain important because they provide interpretable relationships among circulation time, formation temperature, fluid flow, and wellbore thermal response. Later drilling-oriented models extended this foundation to circulation, shut-in, kick, and complex wellbore configurations. Recent drilling-oriented studies extend classical heat-transfer formulations to transient bottomhole temperature, circulation and shut-in response, kick conditions, drillstring and casing effects, and steady or transient analytical temperature modeling [8,10,32–34].

These studies share a common physical structure. The governing problem includes an energy equation for the circulating fluid, heat exchange between the drillstring and

the annulus, heat transfer across the casing and cement, and transient heat conduction into the formation. Analytical and semi-analytical methods are useful when the geometry and boundary conditions can be simplified. Finite-difference, finite-volume, and finite-element approaches provide greater flexibility for variable flow rates, wellbore structures, multiphase conditions, and changing boundary conditions.

Temperature-dependent properties are central to thermal-hydraulic coupling. A temperature model becomes more useful when its output is passed to density, viscosity, and rheology calculations. In deep, ultra-deep, and HPHT wells, moderate temperature errors can affect density correction, pressure loss, gas expansion, and mud-weight interpretation. Recent ultra-deep-well and insulated-drill-pipe studies further show how dynamic temperature modeling and thermal-control measures affect pressure prediction and temperature stability [35–37]. Field-calibration studies using drilling microchip data and unscented Kalman filtering show how measurements can update thermal states or model parameters during drilling [16,38]. Similar calibration logic is also used in hydraulic and digital-twin workflows, where temperature is treated as a state variable that supports the full model chain.

Temperature models provide the thermal state variables for the rest of the model chain. Their field value increases when temperature outputs are coupled with density correction, rheology, pressure loss, gas behavior, ECD/BHP calculation, and model updating [39].

4.3. Annular Non-Newtonian Flow, Rheology, Turbulence, and CFD

Annular-flow models convert temperature-dependent fluid properties and well geometry into pressure loss, wall shear, velocity distribution, and ECD response. Their main assumption is the rheological closure. Bingham, Power-law, Herschel–Bulkley, and Yield-power-law (YPL) models support practical hydraulics, while temperature- and pressure-dependent formulations better represent HPHT and deepwater behavior. Recent Yield-Power Law studies show that thermal and pressure effects can shift frictional pressure loss enough to alter pressure-margin interpretation [40,41].

CFD adds local information that one-dimensional hydraulics cannot resolve. It can show narrow-gap shear, wide-gap recirculation, rotation-induced secondary flow, and local pressure-gradient changes in eccentric annuli. Recent high-fidelity and eccentric-annulus studies show why average pressure-drop agreement is an incomplete validation target: local wall shear, secondary flow, and near-wall gradients can differ even when the global pressure loss appears acceptable [42–44].

Turbulence closure remains a major source of numerical uncertainty. Standard $k-\epsilon$ models are inexpensive and robust, which makes them useful for engineering CFD and closure screening. Their wall-function assumptions can break down in eccentric narrow gaps with non-Newtonian shear, pipe rotation, and strong velocity asymmetry. $k-\omega$ SST models usually improve near-wall behavior and adverse-pressure-gradient treatment, although they require stronger mesh control and careful handling of effective viscosity. Reynolds stress models (RSMs) represent anisotropy and secondary flow more explicitly, which is useful in eccentric and rotating annuli, but they are more expensive and sensitive to pressure-strain and near-wall closures. Large-eddy simulation (LES), direct numerical simulation (DNS), and lattice Boltzmann method (LBM) studies provide mechanism-level evidence and can support the development of closures. Their cost and input requirements limit routine field-scale use [43,45].

Wall treatment deserves separate attention. Equilibrium wall functions assume near-wall behavior that rarely holds for yield-stress or strongly shear-thinning drilling fluids in a narrow eccentric gap. Near-wall resolution, y^+ control, mesh sensitivity, rheology fitting, pipe-motion assumptions, and validation targets should be reported together. For field

deployment, CFD is most useful when it produces validated friction multipliers, eccentricity corrections, rotation effects, or reduced-order closures for well-scale transient models.

Particle-laden annular hydraulics intersects with this model family when cuttings concentration changes mixture density, apparent viscosity, frictional pressure loss, and ECD. Such evidence should be used where solids loading affects pressure loss, ECD, turbulence, or closure-transfer interpretation, while detailed hole-cleaning mechanics fall outside the central scope of this thermal–hydraulic review.

4.4. Pressure-Window and Transient Wellbore Hydraulics

Pressure-window models connect pressure loss, hydrostatic head, temperature-dependent properties, gas behavior, pump history, pipe motion, and surface backpressure. Their main outputs are ECD, BHP, SBP, surge/swab pressure, gas-kick response, and operating envelopes. Recent mud-weight-window modeling shows that thermal effects can alter pressure-margin estimates in deepwater and deep drilling, so heat-transfer uncertainty should be incorporated into ECD/BHP and pressure-window calculations [46].

Multiphase formulation controls the credibility of gas-influx and pressure-window prediction. Drift-flux models solve mixture balances and close gas holdup through slip or distribution-parameter relations. They are efficient for fast kick screening, MPD advisory calculations, and real-time BHP estimation. Their accuracy depends on gas solubility, slip closure, flow-regime treatment, and pressure- and temperature-dependent properties. Mixture models occupy a similar well-scale role and reduce cost, although they lose detail when phase slip, gas breakout, or rapid regime transition controls the pressure response [5,12,47,48].

Two-fluid models solve separate mass and momentum balances for gas and liquid phases. They provide stronger physical resolution for interphase momentum transfer, counter-current tendencies, compressibility, and regime change. They also require interfacial drag, wall friction, mass transfer, and closure-stability assumptions. These closures often dominate prediction uncertainty during gas influx, especially in oil-based mud, where gas dissolution and breakout depend on pressure and temperature [5,21].

VOF and Level Set methods mainly resolve local interface motion. VOF can capture large gas–liquid, mud-spacer, or mud-cement interfaces and preserve phase volume well. Level Set methods provide smoother interface geometry and curvature representation, with mass-conservation treatment as a key numerical concern. These methods support studies of local mechanisms, benchmark cases, and closure development. Full-well real-time pressure-window prediction usually requires reduced-well-scale formulations that can run stably in the presence of field data, sensor lag, uncertain influx rate, and changing boundary conditions [49].

4.5. Cementing Displacement and Well-Construction Thermal–Hydraulic Flow

Cementing displacement is a scale-bridging problem. Local interface-resolving models can show mud removal, spacer effectiveness, density-driven interface movement, eccentric-annulus bypassing, casing movement, and residual mud. Recent VOF-based and displacement-efficiency studies provide stronger evidence for this local physics, especially in irregular annuli and non-Newtonian or foamed cement systems [49,50]. Well-scale cementing hydraulics supports pump scheduling, ECD/BHP control, U-tube response, surface-backpressure planning, and loss-risk assessment.

The two scales require different validation targets. Interface-resolving CFD should be evaluated by interface movement, residual mud, displacement efficiency, and sensitivity to rheological contrast, density hierarchy, eccentricity, and mesh treatment. Well-scale hydraulics should be evaluated by pressure response, volume balance, pump schedule, and

pressure-window control. Post-job validation is indirect because pressure records, returns, volumes, cement-bond logs, and temperature logs do not fully resolve the annular interface.

Managed-pressure cementing adds a pressure–displacement tradeoff. The model must keep BHP within the pressure window while preserving displacement energy and interface stability. A defensible cementing model should therefore report both hydraulic response and displacement-quality evidence. Pressure agreement alone gives incomplete evidence of mud removal.

4.6. AI-Assisted Numerical Simulation, Calibration, and Deployment

AI-assisted methods should be evaluated by their numerical role. ROMs, including proper orthogonal decomposition (POD)—and dynamic mode decomposition (DMD)—type approaches, project high-fidelity solutions onto lower-dimensional bases. They are useful when the operating envelope is bounded and the dominant response modes are stable. Their accuracy can degrade under gas influx, severe nonlinearity, geometric changes, or fluid property shifts outside the training range.

Surrogate ML models approximate simulator outputs or field variables such as ECD, BHP, temperature, pressure loss, and kick indicators at low online cost. Recent field data studies demonstrate their value for ECD prediction and drilling fluid management, especially when surface data are available at high frequency [51,52]. Their limitation is training-domain dependence. External-well testing, complete-operation testing, sensor-quality screening, and uncertainty reporting are needed before such models can support field advisory decisions.

Physics-informed neural networks (PINNs) add governing-equation residuals, boundary conditions, or physical penalties to the training objective. This is attractive for sparse pressure or temperature data and for real-time thermal estimation [15]. Training can become difficult for stiff transient problems, multiphase discontinuities, strong advection, and changing boundary conditions. Fourier neural operators (FNOs) and related neural operators learn mappings between input functions and output fields, such as from a circulation schedule to a temperature profile or from boundary-control history to pressure response. They are promising for repeated PDE-solver acceleration, while drilling-specific field validation remains limited.

Kalman filtering, ensemble Kalman filtering, unscented Kalman filtering, and related data assimilation methods are directly relevant to drilling because they update states or parameters as measurements arrive. Recent model-based updating and event-detection studies show how data assimilation can connect physics-based simulators with real-time drilling signals [16,53]. Adjacent high-temperature examples also support method-level interpretation by addressing downhole temperature prediction and data-driven calibration, but drilling use still requires validation under rig-state, mud-system, and pressure-window constraints [54]. The update quality depends on model-error assumptions, measurement-error structure, sensor synchronization, and the choice of updated states.

A field-facing digital-twin workflow combines these methods. A physics-based simulator provides the prior state. Sensor data updates uncertain parameters and states. Surrogates or ROMs reduce online costs. Uncertainty bounds are propagated to ECD, BHP, kick/loss indicators, tripping limits, and cementing-control variables. The workflow should report the training domain, field-data quality, update frequency, physical constraints, uncertainty output, independent test evidence, and failure modes.

These model families generate the variables examined in the field-facing synthesis, including temperature, pressure loss, ECD, BHP, SBP, gas-kick response, surge/swab pressure, displacement efficiency, and updated model states.

5. WoS–OnePetro Comparative Synthesis: From Numerical Model Outputs to Field-Facing Variables

Section 4 reviewed the main numerical model families and their governing physics, closure assumptions, numerical methods, outputs, and field-use constraints. This section examines how those outputs appear in field-facing drilling and well-construction records. The screened OnePetro records provide the operational counterpart to the WoS technical records, showing how simulation outputs are used for planning, monitoring, control, and post-job interpretation. The synthesis is organized around field-facing variables that can be measured, constrained, updated, or adjusted during operations. These variables include pressure-window variables, thermal and rheological calibration variables, cementing-displacement variables, and model-updating variables. Figure 6 summarizes the mapping from numerical model families to field-facing use.

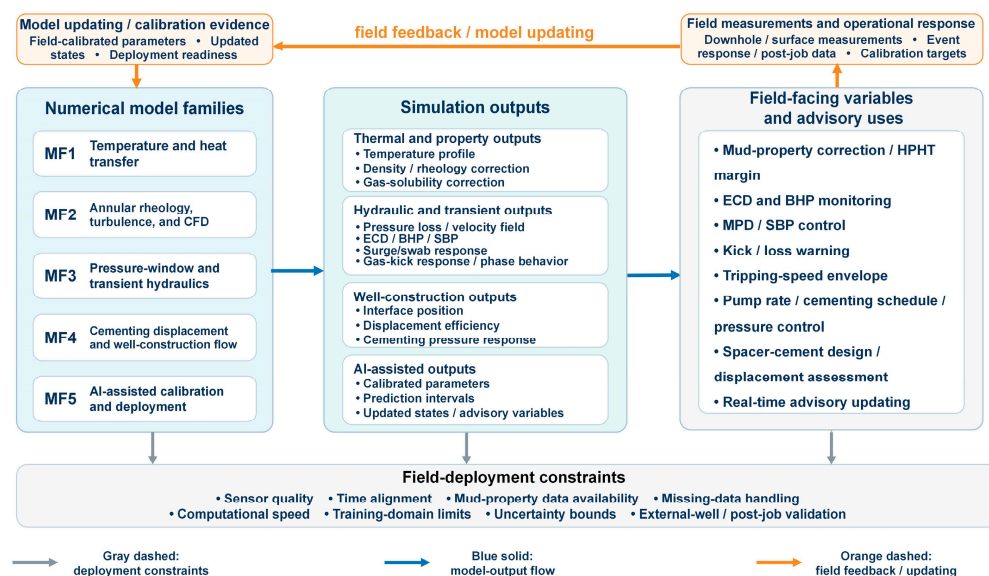


Figure 6. Mapping from numerical model families to simulation outputs, field-facing variables, and model-updating pathways. The diagram links WoS-supported model families with representative outputs such as temperature, pressure loss, ECD, BHP, SBP, surge/swab pressure, gas-kick response, displacement efficiency, and updated model states. Field-facing variables and operational responses provide feedback for calibration, data assimilation, digital-twin updating, and advisory use.

5.1. Model-Output to Field-Variable Mapping

The five model families reviewed in Section 4 generate outputs that differ in field visibility and operational use. Wellbore temperature and heat-transfer models provide temperature profiles and thermal corrections to fluid properties. Annular non-Newtonian flow and CFD models provide pressure-loss and flow-regime information. Pressure-window and transient-hydraulics models provide ECD, BHP, SBP, gas-kick response, surge/swab pressure, and operating envelopes. Cementing models provide interface position, residual mud, displacement efficiency, cementing pressure response, and pump-schedule constraints. AI-assisted methods provide updated states, calibrated parameters, uncertainty ranges, and advisory variables. Table 6 provides an organizing map for the comparative synthesis by linking the model outputs reviewed in Section 4 to the operational variables and roadmap needs developed in Section 6.

Table 6. Model-output to field-variable mapping for the WoS–OnePetro comparative synthesis.

Model Family	Representative Model Outputs	Field-Facing Variables	Typical Field-Facing Evidence	Main Use in Section 5
Wellbore temperature and heat transfer	Temperature profile, bottomhole circulating temperature, shut-in temperature, thermal correction to density and rheology	Mud-property correction, HPHT margin, temperature calibration, thermal input for pressure models	Temperature measurements, circulation-temperature calibration, HPHT planning records	Thermal calibration and model updating
Annular non-Newtonian flow, rheology, turbulence, and CFD	Frictional pressure loss, velocity profile, wall shear, ECD correction, flow-regime interpretation	Pump rate, rheology characterization, hydraulic-model calibration, ECD margin	Rheology characterization, YPL-based hydraulics, pressure-loss interpretation	Rheology and pressure-loss correction
Pressure-window and transient wellbore hydraulics	ECD, BHP, surge/swab pressure, pressure-wave response, gas-kick response, SBP, tripping-speed envelope	Mud weight, pump rate, SBP/choke control, loss/kick indicators, tripping speed, well-control response	MPD design, HPHT ECD estimation, automated MPD, transient hydraulics, well-control workflows	Pressure-window and transient-operation synthesis
Cementing displacement and well-construction flow	Displacement efficiency, interface position, residual mud, cementing ECD/BHP, pump schedule, SBP	Spacer/cement design, cement volume, mud displacement, loss control, managed-pressure cementing	Cementing displacement practices, real-time cementing monitoring, managed-pressure cementing records	Cementing and well-construction synthesis
AI-assisted calibration and deployment	Updated states, calibrated parameters, fast ECD/BHP prediction, kick warning, uncertainty range, advisory variables	Real-time model updating, digital twin, BHP estimation, kick detection, advisory support	Digital hydraulic workflows, machine-learning-assisted BHP estimation, gas-kick identification, Kalman-filter calibration	Field-facing interpretation and deployment synthesis

The mapping shows that field-facing use is concentrated on variables that directly relate to pressure control, model calibration, cement placement, or operational updates. The following subsections discuss these links by evidence group.

5.2. Pressure-Window and Transient-Operation Variables

Pressure-window variables form the strongest connection between numerical simulation and field use. ECD, BHP, mud weight, pump rate, SBP, tripping speed, gas-kick indicators, and loss indicators define the working margin between pore pressure and fracture pressure during circulation, MPD, well control, tripping, and other transient operations.

Technical modeling studies provide the physical basis for these variables. Non-isothermal gas-kick models link temperature, pressure, gas solubility, phase behavior, and well-control response [5,12]. Models of thixotropic or compressible drilling fluids show how fluid behavior affects kick detection and pressure response [47]. CO₂ invasion and phase-transition models add a compositional and thermodynamic layer to the interpretation of pressure windows [11,55]. Temperature–pressure models for narrow drilling-fluid density windows extend this logic to mud-weight selection and safe drilling margins [48].

The field-facing records show how these outputs are incorporated into operating workflows. Field-facing MPD and HPHT records translate these outputs into BHP targets, ECD margins, SBP schedules, choke response, pump-rate limits, operating-window identification, and post-well pressure interpretation [56–61]. These records treat simulation

outputs as pressure-control variables, especially BHP target, ECD margin, SBP schedule, choke response, and pump-rate limit.

Transient hydraulics adds the time-dependent part of this field problem. Surge/swab and tripping models show how pipe motion, pump transitions, non-Newtonian rheology, and wellbore compressibility affect BHP and ECD [62,63]. Field-facing studies on transient ECD and surge/swab behavior connect these outputs to tripping-speed envelopes and pump start/stop procedures [64,65]. Pressure-wave propagation studies also help interpret dynamic pressure response in the wellbore [66].

The evidence from WoS and OnePetro is consistent. The WoS technical records emphasize governing equations, closure assumptions, and multiphase-flow structure. The OnePetro records translate those outputs into BHP targets, ECD margins, SBP schedules, tripping limits, and kick/loss indicators. This makes pressure-window modeling the most direct bridge between numerical simulation and field decision support.

5.3. Thermal Calibration, Rheology Characterization, and Real-Time Updating

Thermal calibration, rheology characterization, and real-time updating form the calibration layer of field-facing thermal-hydraulic simulation. Temperature and rheology influence pressure loss, ECD, BHP, gas behavior, and cementing hydraulics. Field records, therefore, often connect thermal or rheological outputs to measured pressure, flow, and downhole condition indicators.

Temperature-calibration studies show that downhole measurements, drilling microchip data, Kalman-filter-based updating, and physics-informed heat-transfer models can reduce uncertainty in circulation-temperature estimates and improve thermal-state correction [15,16,38,67]. Real-time updating studies extend the same logic to ML-supported ECD prediction, physics-based BHP estimation, gas-kick identification, dynamic hydraulic modeling, and digital-twin workflows with transient hydraulics and real-time rheology [13,14,68–70].

Calibration has a direct field value. Updated temperature profiles improve density and rheology correction. Rheology characterization improves pressure-loss and ECD prediction. Real-time updating improves BHP estimation, loss/kick detection, and advisory support. These steps reduce the gap between pre-job numerical simulation and rig-site decision variables.

5.4. Cementing and Well-Construction Variables

Cementing records provide a field-facing counterpart to the displacement and well-construction model family. The main variables are pump rate, cement volume, spacer design, mud weight, displacement efficiency, residual mud, cementing ECD/BHP, loss risk, and SBP. These variables connect multi-fluid displacement physics with well-construction decisions.

The WoS technical records provide the basis for displacement and pressure modeling. Technical cementing records connect displacement efficiency, casing movement, density contrast, pad-fluid sequencing, eccentric annuli, shale-gas horizontal-well displacement, transient temperature–pressure coupling, and cementing-quality interpretation [6,7,9,71–73]. The OnePetro field-facing records show how the same model outputs are applied in cementing practice. Field-facing cementing records apply these outputs to displacement practice, real-time primary-cementing monitoring, mud/cement displacement in eccentric annuli, managed-pressure cementing, cementing-interface ECD modeling, and adjustment of mud weight, pump rate, and SBP under narrow-pressure-window conditions [74–80].

The cementing evidence connects two scales of the same problem. Interface-resolving models explain local mud removal, displacement efficiency, and channeling tendency.

Well-scale hydraulic simulators support pump scheduling, ECD/BHP estimation, and pressure control. Field-facing cementing decisions need both types of information. This scale connection is carried forward into the roadmap in Section 6.

5.5. Field-Facing Interpretation and Implications for the Roadmap

The WoS–OnePetro comparison shows that field-facing use concentrates on variables that can be measured, constrained, updated, or adjusted during operations. Pressure-window variables have the clearest field connection because ECD, BHP, SBP, mud weight, pump rate, tripping speed, and kick/loss indicators can be monitored or controlled during drilling. Temperature and rheology support these decisions through calibration and property correction. Cementing-displacement outputs remain harder to observe directly, so field interpretation often combines pressure response, pumped volume, returns, displacement-efficiency proxies, and post-job evaluation.

This pattern leads to a narrower roadmap. Field-deployable simulation needs consistent coupled state variables, closure choices with stated validity limits, validation and uncertainty reporting, CFD-to-well-scale transfer, computationally efficient reduced-order implementation, and physics-constrained model updating. Section 6 develops these priorities into numerical simulation tasks.

5.6. Field-Deployment Constraints for Advisory Use

The OnePetro records identify the operational variables, calibration targets, sensor constraints, computational speed requirements and deployment pathways that are used in field-facing applications. WoS technical records remain the main basis for governing equations, numerical methods, closures, validation, and uncertainty treatment.

Field deployment depends on model fidelity, sensor quality, and time-aligned operating data. Surface measurements such as standpipe pressure (SPP), pump rate, flow-in/flow-out, pit volume, mud density, and periodic rheology tests are accessible but uneven in quality. They include sensor drift, missing intervals, manual reporting errors, time delays, and synchronization errors among rig state, mud-property measurements, and downhole tools. Downhole pressure and temperature measurements, including pressure-while-drilling (PWD) data, provide stronger calibration targets for ECD, BHP, and thermal correction, but they may be intermittent, depth-lagged, tool-limited, or unavailable during high-risk operations. Field-updating and temperature-control studies highlight the value of sensor-quality screening, time alignment, and operational-state definition before calibration begins [53,81].

Computational speed sets another deployment boundary. Pre-job studies can use detailed parameter sweeps, high-resolution CFD, interface-resolving displacement models, or ensemble uncertainty runs. Rig-site advisory workflows need faster estimates of BHP, ECD, SBP requirement, tripping envelope, kick/loss warning, or cementing pressure response. High-fidelity annular CFD and LBM-type studies support closure development and benchmark generation. Online advisory use usually relies on one-dimensional transient solvers, reduced-order closures, tabulated CFD corrections, or physics-constrained surrogate models [43–45].

Training data also constrain AI-assisted deployment. Field datasets are often proprietary, unevenly labeled, and concentrated within specific well types, mud systems, sensor packages, and operating practices. Random pointwise train/test splits can overstate reliability when adjacent time samples from the same well appear in both subsets. External-well or external-field testing gives a stronger measure of transferability. Field-data ECD and event-detection studies show the value of ML-supported prediction, but deployment depends on training-domain control, sensor coverage, missing-data treatment, inference time,

and uncertainty coverage [51–53]. Advisory outputs, therefore, need uncertainty-bounded operating ranges for mud-weight margin, pump-rate envelope, SBP or choke response, tripping-speed limit, kick/loss warning confidence, and cementing schedule.

6. Research Gaps, Future Perspectives, and Computational Roadmap for Field-Deployable Numerical Simulation

Sections 3–5 provide the evidence base for the computational roadmap, and show how the field has moved from component models toward coupled, calibrated, and field-facing simulation. Section 3 identifies the knowledge structure, Section 4 appraises the five numerical model families, and Section 5 links model outputs with operating variables. The remaining gaps concern coupling, validation, simplification, updating, and field use under data constraints.

6.1. Coupled Thermal–Hydraulic State Variables and Numerical Coupling

A field-deployable coupled model starts from a defined state vector and a clear transfer rule among thermal, hydraulic, multiphase, and well-construction modules. The minimum state vector includes temperature, pressure, density, rheological parameters, phase state or gas fraction where relevant, flow rate, pressure loss, ECD, BHP, SBP, pipe-motion state, and cementing-interface or displacement state. Temperature changes density, viscosity, yield stress, gel strength, gas solubility, and cement-slurry properties. These updated properties then change frictional pressure loss, ECD, BHP, surge/swab response, gas expansion or dissolution, and cementing pressure. Pressure and temperature also control gas compressibility, phase transition, solubility in oil-based mud, and pressure–volume–temperature (PVT) response, which feed back into pressure-window prediction [40,41,46].

Coupling strength changes with the operating scenario. Routine circulation often tolerates sequential updating when temperature-dependent properties change slowly relative to hydraulic response. HPHT drilling, deepwater operations, gas kicks, narrow-pressure-window drilling, and managed-pressure cementing create tighter feedback loops among pressure, temperature, phase state, and fluid properties. An explicit update calculates density, rheology, solubility, or friction factor from the previous thermal or hydraulic state and then advances the pressure calculation. This approach is efficient and easy to implement. An implicit or iterative sequential update solves the thermal and hydraulic states until the property changes and the pressure response becomes mutually consistent. The added cost is justified when small pressure errors alter the mud-weight window, choke response, kick interpretation, or cementing pressure margin [6,46,48]. Different coupling strategies are needed because thermal, hydraulic, multiphase, cementing, and updating modules operate at different scales and time resolutions. Table 7 summarizes the main coupling strategies relevant to field-deployable simulation.

The choice of coupling strategy should match the operating scenario, the strength of thermal–hydraulic feedback, and the required response time. The main numerical difficulty comes from mixed time scales. Radial heat conduction in the formation and wellbore elements evolves over minutes to hours. Hydraulic pressure transients, pump start/stop events, surge/swab response, choke movement, pipe acceleration, and gas expansion can evolve over seconds or less. A single global time step often wastes computational effort during quasi-steady periods and misses rapid pressure events during transitions. Operator splitting can update the energy equation and hydraulic equation in separate substeps. Subcycling can solve fast pressure transients within a larger thermal time step. Adaptive time-stepping can reduce the step size during pump transitions, gas influx, pipe acceleration, choke movement, or cementing density-interface changes, and then increase it during stable circulation or shut-in periods [63].

Table 7. Coupling strategies for wellbore thermal–hydraulic numerical simulation.

Coupling Strategy	Numerical Treatment	Typical Use	Strength	Main Limitation
One-way sequential coupling	Temperature is solved first, followed by density, rheology, pressure loss, and ECD/BHP calculation	Fast planning calculations and simplified well-scale simulation	Computationally efficient and easy to implement	Weak feedback from hydraulics to thermal and property states
Iterative sequential coupling	Thermal and hydraulic modules are solved repeatedly until state variables converge	Deep, HPHT, and narrow-pressure-window wells	Improves consistency among temperature, properties, and pressure	Higher computational cost and convergence sensitivity
Fully coupled solution	Mass, momentum, energy, and phase-behavior equations are solved in a shared system	Gas kick, transient multiphase flow, MPD, and strongly coupled operations	Captures strong thermal–hydraulic feedback	More demanding stability, time stepping, and solver requirements
CFD-to-1D closure transfer	CFD is used to generate correction factors or closures for well-scale simulators	Eccentric annuli, drillpipe rotation, turbulence, cuttings loading, cementing interfaces	Retains local-flow physics in field-scale models	Scale-transfer uncertainty and limited validity range
Data-assimilated coupling	Measurements update model states, parameters, or closure factors during operation	Real-time hydraulics, digital twins, BHP estimation, kick warning, cementing advisory workflows	Improves field calibration and predictive updating	Sensitive to sensor quality, data drift, and model-transfer limits

Operational convergence checks combine solver residuals with field-facing variables. A coupled simulation needs mass-balance residuals, energy-balance residuals, BHP/ECD residuals, property-update tolerance, and phase-state consistency. Temperature calibration needs outlet or downhole temperature residuals and updated density /rheology consistency. Gas-kick calculations need gas volume, phase fraction, solubility, and pressure-response consistency. Cementing calculations need pump pressure, interface position, density distribution, and displacement-pressure residuals. These criteria reduce ambiguity between a mathematically converged solution and a prediction that can support pressure-window or cementing decisions.

6.2. Closure Selection and Uncertainty

Closure selection remains a key source of uncertainty across the model chain. Wellbore thermal–hydraulic simulation depends on closures for non-Newtonian rheology, flow-regime transition, turbulence, gas slip, phase behavior, pipe-motion effects, and cementing interfaces. These closures strongly influence whether a calculation can support decisions on field pressure, kick, tripping, or cementing.

Rheology is the first closure layer. Drilling fluids may be represented by Bingham, Power-law, Herschel–Bulkley, or Yield-power-law models. More detailed descriptions include thixotropy, temperature- and pressure-dependent viscosities, and solid-loading effects. The rheology of a field mud affects the Reynolds number, friction factor, velocity profile, wall shear, pressure loss, and ECD. Studies on transport phenomena, drilling-fluid rheology, and YPL-based hydraulics provide the foundation for this layer [4,28–30].

Flow-regime and turbulence closures form the second layer. Non-Newtonian annular flow may be laminar, transitional, or turbulent, and the transition can change with temperature, pipe rotation, eccentricity, and flow rate. CFD studies provide detailed insight into eccentric annuli, wall shear, secondary flow, and local pressure gradients [31,82]. One-dimensional turbulent non-Newtonian models remain important for field-scale hydraulics because they can be used in real-time workflows [83].

Multiphase flow introduces additional closure choices. Gas solubility, gas slip, compressibility, CO₂ behavior, and phase transition affect gas-kick simulation and MPD response, especially in oil-based mud, HPHT wells, deepwater systems, and narrow pressure windows [11,12,47,55]. Cementing introduces interface closures that govern mud–spacer–cement displacement, density contrast, rheological contrast, eccentricity, and U-tube-related pressure response [6,7,9].

A useful closure hierarchy would help organize these choices. Fast engineering closures can support pre-job and real-time well-scale calculations. CFD-derived closures can provide correction factors for eccentricity, pipe rotation, turbulence, particle loading, and interface behavior. Field-calibrated corrections can update the model when measured pressure, temperature, rheology, or flow response differs from the planned state. This hierarchy would make closure selection more transparent and would support uncertainty reporting.

6.3. Verification, Validation, Calibration, and Uncertainty Quantification Under Field Constraints

V&V and UQ remain difficult because the most safety-critical operating regimes provide the least complete data. HPHT flow-loop tests and downhole tests require pressure-rated and temperature-rated facilities, specialized sensors, and strict safety controls. Full-scale gas-kick data are limited because deliberate field-scale influx is unsafe, and actual kicks are controlled events with incomplete boundary information. Narrow-pressure-window records contain valuable pressure data, but they often include missing flow-out intervals, delayed pit-volume response, changing mud properties, rig-state transitions, and proprietary MPD or choke-control settings. Service-company datasets may also contain control logic, calibrated parameters, and sensor-processing steps that cannot be fully disclosed. These data restrictions limit reproducibility even when pressure and temperature trends are reported. The validation problem can be organized by the type of model, the available data, the measured variable, and the uncertainty source. Table 8 translates this requirement into a practical validation and uncertainty-quantification hierarchy.

This hierarchy separates code verification, calibration, validation, and transfer testing, so model credibility can be judged against the intended field use rather than against a single generic error metric. Cementing validation has a separate observability problem. Direct observation of mud-spacer-cement interface motion in the wellbore is normally unavailable. Pump pressure, returns, losses, pumped volumes, density schedule, and post-job cement evaluation provide indirect evidence. These data do not uniquely identify local mud removal, channeling, bypassing, or interface deformation. Post-job logs also depend on tool physics, interpretation method, and time after placement. Cementing-displacement models therefore require a tiered validation path: laboratory displacement tests for local mechanisms, CFD or semi-local simulations for interface behavior, well-scale hydraulic comparisons for pressure response, and post-job evaluations for placement plausibility [49,50].

Uncertainty reporting should separate inputs, closures, model form, numerics, measurements, and operating boundaries. Input uncertainty includes well geometry, trajectory, geothermal gradient, inlet temperature, mud density, rheological parameters, PVT data, gas solubility, pump schedule, tripping speed, SBP, and cement/spacer properties. Empirical log-derived corrections, including the Larionov shale-volume correction and related gamma-ray index–shale-volume transforms, should also be treated as input-property uncertainty when shale volume, lithology, or other log-derived formation properties enter pore-pressure interpretation, fracture-gradient estimation, mud-weight-window limits, formation thermal-property assignment, or field calibration of thermal–hydraulic models [84]. Closure uncertainty comes from friction-factor correlations, turbulence closures, wall functions, slip relations, phase-behavior models, heat-transfer coefficients, gel-strength

evolution, and cementing-interface rules. Model-form uncertainty enters through one-dimensional averaging, drift-flux or two-fluid assumptions, interface-capturing choices, and CFD-to-well-scale transfer. Numerical uncertainty comes from mesh resolution, time-step size, discretization, nonlinear iteration, and operator splitting. Measurement and operating-boundary uncertainty includes drift, calibration bias, missing data, time lag, depth mismatch, unreported rig events, mud-property changes, losses, gains, and changes in choke or MPD control logic.

Table 8. Practical validation and uncertainty-quantification framework for field-deployable wellbore thermal–hydraulic simulation.

Task	Required Data	Metrics	Uncertainty Focus	Field Use
Code and solution verification	Equations; simplified geometry; fixed boundary conditions; mesh/time-step sequences	Conservation error; residual convergence; grid/time-step sensitivity	Discretization; time step; nonlinear iteration; operator splitting	Confirms implementation before calibration
HPHT circulation-temperature validation	Well geometry; geothermal gradient; inlet temperature; pump/shut-in history; outlet or downhole temperature	Temperature error; transient-lag error; interval coverage	Heat-transfer coefficient; thermal properties; sensor drift	Supports thermal correction of density, rheology, gas behavior, and cementing
Eccentric-annulus flow validation	Diameter ratio; eccentricity; pipe rotation; flow rate; rheology; pressure drop; velocity data, if available	Pressure-drop error; friction-factor error; velocity-profile agreement	Rheology closure; turbulence model; wall treatment; mesh	Supports CFD-to-well-scale pressure-loss correction
Field ECD/BHP calibration and validation	Mud weight; rheology; pump rate; SPP; PWD/BHP; SBP; flow-in/out; rig state	BHP/ECD error; transient peak error; pressure-margin classification	Sensor bias; pump efficiency; friction factor; temperature-property correction	Supports real-time pressure-margin advisory
Non-isothermal gas-kick validation	Influx timing; pit gain; flow-in/out; choke/SBP; PVT; solubility; pressure/temperature history	Kick-volume error; gas-front timing; detection delay; BHP error	Slip closure; solubility; compressibility; sensor delay	Supports kick/loss warning and well-control simulation
Surge/swab validation	Pipe speed/acceleration; pump state; mud rheology; geometry; PWD/BHP	Peak-pressure error; timing error; safe-speed envelope agreement	Pipe-motion record; gel strength; compressibility; sensor lag	Supports tripping-speed limits

Calibration and validation need separate reporting. Calibration uses field data to update uncertain parameters or states, such as heat-transfer coefficient, friction factor, rheological correction, gas-behavior parameter, or pressure offset. Validation tests model prediction against independent data from another interval, event, well, or field. This distinction matters for AI-assisted models and digital twins. A model trained or calibrated on one well needs external-well testing when transferability is claimed. Useful UQ outputs include prediction intervals for temperature, ECD, BHP, SBP, surge/swab peaks, kick/loss warning, and cementing pressure. Interval coverage needs to be compared with measured data where available. Detailed benchmark geometries, boundary conditions, fluid inputs, measured outputs, and uncertainty variables are provided in Supplementary File S3.

6.4. CFD-to-Well-Scale Bridging and Computational Efficiency

Computational efficiency is a deployment constraint across all model families. Three-dimensional CFD, multiphase CFD, particle-laden annular flow, eccentric-annulus simulations, and cementing-interface models can provide detailed local physics, but their mesh resolution, time-step requirements, and nonlinear closures make direct real-time use difficult. Well-scale one-dimensional transient simulators are more suitable for field workflows because they can run across the full wellbore, follow operating history, accept

field inputs, and provide variables such as ECD, BHP, SBP, surge/swab pressure, and cementing pressure response.

Scale bridging is therefore needed to connect local mechanisms with well-scale operational variables. CFD and interface-resolving models can explain velocity profiles, wall shear, local pressure gradients, recirculation, eccentricity effects, rotation-induced flow, particle-laden behavior, and deformation of the cementing interface. These local results can be transferred into well-scale simulators through ROMs, surrogate models, tabulated correction factors, and closure-transfer rules. Relevant correction factors may describe eccentricity, pipe rotation, turbulence or transition, cuttings loading, and displacement-interface behavior.

Several studies illustrate the value of local simulation for closure development. CFD-based annular-flow studies resolve eccentricity, orbital pipe motion, local velocity fields, and non-Newtonian pressure response [30,31,82]. Cementing studies use local or semi-local models to interpret displacement mechanisms and interface behavior [6,7,77]. The field-facing records in Section 5 show why these local mechanisms must eventually be translated into well-scale variables used in MPD, HPHT drilling, transient hydraulics, and managed-pressure cementing workflows [14,57,74,78].

High-performance and parallel computing are relevant when detailed CFD, multi-phase simulation, parameter sweeps, or uncertainty quantification require large numbers of high-resolution runs. GPU acceleration and parallel solvers can reduce computational cost for local simulations and ensemble calculations. Their main value in field-facing wellbore simulation lies in supporting closure development, benchmark generation, uncertainty analysis, and the generation of training data for reduced-order or AI-assisted models.

Scale transfer also needs validity limits and uncertainty bounds. A correction derived from one geometry, mud system, solids loading, or flow regime has a defined range of applicability. The same principle applies to AI surrogates. Fast models are most useful when their training range, physical constraints, error behavior, and uncertainty response are clear. Surrogate and AI models should therefore be interpreted as acceleration and updating layers that still require physical constraints, validation evidence, and uncertainty reporting.

6.5. Physics-Constrained AI Deployment and Post-Job Learning

Field-transfer testing is the central requirement for AI-assisted deployment. For ECD, BHP, gas-kick warning, temperature prediction, and cementing-pressure support, the operational question is whether the model remains reliable when the well trajectory, mud system, pressure window, sensor package, or operating procedure changes. External-well validation provides the minimum test of transferability. When external datasets cannot be disclosed, the study should still report training-testing separation, excluded operating ranges, sensor-quality rules, missing-data handling, inference time, and event types excluded from calibration [51–53].

Surrogate and operator-learning models can reduce repeated solver cost, but field use requires domain checks, conservation consistency, inference-time reporting, and uncertainty coverage. Surrogates trained on CFD, transient hydraulics, or cementing simulations remain valid within the represented geometry, rheology, phase behavior, and operating envelope. Physics-constrained models need to preserve mass, momentum, energy, pressure-response trends, and boundary-condition consistency. Advisory outputs also need uncertainty intervals for mud-weight adjustment, pump-rate selection, SBP or choke response, tripping-speed limit, kick/loss warning, and cementing schedule.

Post-job learning closes the deployment loop. Measured pressure, temperature, flow, pit-volume, mud-property, and post-job cement-evaluation data update calibration factors, closure choices, uncertainty ranges, and benchmark libraries. This workflow supports

advisory use. The practical target is a controlled loop: pre-job model initialization, field data-quality screening, coupled state updating, uncertainty-bounded advisory output, and post-job recalibration for the next well. Figure 7 summarizes this controlled workflow and the corresponding roadmap from benchmark definition to field advisory deployment and post-job learning.

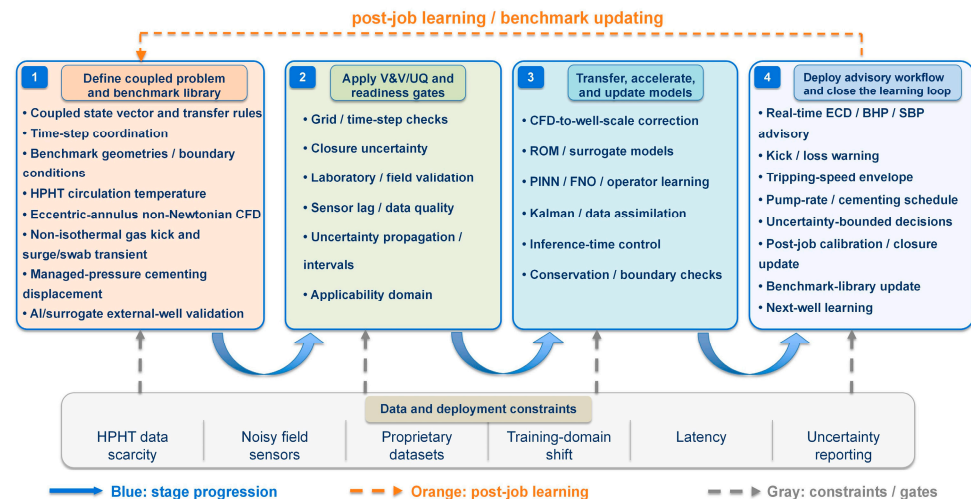


Figure 7. Computational roadmap for field-deployable wellbore thermal-hydraulic numerical simulation. The roadmap connects the main gaps identified in the review with numerical-simulation priorities and field-facing outcomes, including coupled state-variable models, transparent closure hierarchies, benchmark cases, V&V and UQ, CFD-to-well-scale transfer, reduced-order or surrogate implementation, physics-constrained AI deployment, and post-job learning.

The same logic can be converted into benchmark targets for future model comparison and field deployment. Table 9 lists compact benchmark targets, required data, metrics, suitable methods, and implementation uses. Detailed benchmark geometries, boundary conditions, fluid inputs, measured outputs, and uncertainty variables are provided in Supplementary File S3.

Table 9. Benchmark targets and implementation priorities for field-deployable coupled wellbore thermal-hydraulic simulation.

Benchmark Target	Data/Outputs	Metrics	Suitable Method	Implementation Target
HPHT circulation-temperature	Geometry; well structure; geothermal gradient; inlet temperature; pump/shut-in schedule. Outputs: outlet/downhole temperature; BHP/ECD if available	Temperature error; transient-lag error; interval coverage	1D transient thermal-hydraulic solver; Kalman updating; thermal surrogate	Temperature-to-property correction for pressure-window use
Eccentric-annulus non-Newtonian CFD	Diameter ratio; eccentricity; pipe rotation/orbit; flow rate; T-dependent rheology. Outputs: pressure drop; velocity profile; wall shear	Pressure-drop error; friction-factor error; velocity-field agreement; mesh sensitivity	RANS comparison; RSM; LES/LBM for mechanism cases; reduced-order correction	CFD-to-well-scale closure transfer
Non-isothermal gas kick	Influx rate/volume; depth; pump/choke schedule; PVT; gas solubility; temperature field. Outputs: BHP; SBP; pit gain; gas-front timing	Kick-volume error; gas-front timing; BHP error; detection delay	Drift-flux or two-fluid transient solver; data assimilation; ensemble UQ	Pressure-window and well-control advisory testing

Table 9. Cont.

Benchmark Target	Data/Outputs	Metrics	Suitable Method	Implementation Target
Surge/swab transient	Geometry; pipe speed/acceleration; pump state; gel time; rheology. Outputs: transient BHP/PWD; peak surge/swab; recovery time	Peak-pressure error; timing error; safe-speed envelope agreement	1D transient hydraulics; adaptive time stepping; ROM screening	Tripping-speed envelope and transition-pressure control
Managed-pressure cementing displacement	Geometry; eccentricity; mud/spacer/cement schedule; SBP/choke history; returns/losses; post-job evidence. Outputs: pump pressure; BHP/ECD; placement proxy	Pressure-curve error; ECD/BHP error; interface-arrival proxy; placement classification	Well-scale cementing simulator; CFD sub-benchmark; managed-pressure control simulation	Links displacement quality with pressure-window control
AI/surrogate external-well validation	Training wells; external test well; sensor-quality rules; missing-data rules; inference time. Outputs: ECD, BHP, temperature, or kick warning	External-well error; interval coverage; inference time; failure-case rate	Surrogate ML; PINN; FNO/neural operator; Kalman/data assimilation	Field-transfer check for advisory use

The roadmap developed here links bibliometric signals, model-family evidence, and field-facing variables to define simulation priorities for wellbore thermal–hydraulic modeling. The central direction is coupled, validated, computationally usable, uncertainty-aware, and field-deployable numerical simulation.

7. Conclusions

This review synthesized coupled wellbore thermal–hydraulic numerical simulation during drilling and well construction using a bibliometric-guided critical review design. The evidence architecture linked an 841-record WoS bibliometric corpus, screened WoS technical records, representative prior reviews, and screened OnePetro field-facing records. The evidence design separates bibliometric mapping, archival model synthesis, field-facing interpretation, and roadmap development, which clarifies the role of each source layer.

The literature can be organized into five connected model families: wellbore temperature and heat transfer; annular non-Newtonian flow, rheology, turbulence, and CFD; pressure-window and transient wellbore hydraulics; cementing displacement and well-construction flow; and AI-assisted calibration and deployment. The main technical differences among these families lie in their closure assumptions, dominant sources of uncertainty, validation evidence, scale-transfer requirements, and deployment limits. Temperature prediction gains field value when it feeds density, rheology, gas behavior, ECD/BHP, and cementing calculations. Annular CFD improves local-flow interpretation but requires validation for transfer to well-scale simulators. Pressure-window models provide the most direct link to field decisions, whereas cementing models require joint evidence of pressure response and displacement quality. AI-assisted methods are most useful when they accelerate, calibrate, or update physics-based models under clear data-domain and uncertainty constraints.

The field-facing synthesis shows that operational use depends on a limited set of variables that can be measured, constrained, updated, or adjusted: temperature, pressure loss, ECD, BHP, SBP, pump rate, tripping speed, gas-kick or loss indicators, cementing pressure, displacement proxies, and updated model states. OnePetro records help interpret these variables and the deployment constraints associated with them, while peer-reviewed technical records remain the primary source for model formulation, closures,

validation, and uncertainty discussions. Field deployment requires reliable sensor data, time alignment, computational speed, external-well testing for AI-assisted models, and uncertainty-bounded advisory outputs.

Future progress should move toward benchmark-led, uncertainty-aware, and field-deployable simulation. Priority benchmarks include HPHT circulation temperature, eccentric-annulus non-Newtonian CFD, non-isothermal gas kick, surge/swab transients, managed-pressure cementing displacement, and AI or surrogate external-well validation. These benchmarks can support consistent state-variable coupling, closure selection, V&V and UQ, CFD-to-well-scale transfer, reduced-order implementation, physics-constrained updating, and post-job learning across wells.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/pr14142342/s1>. Supplementary File S1: search strategy, preprocessing, and CiteSpace settings; Supplementary File S2: screening rubric, evidence-layer assignment, and coding matrix; Supplementary File S3: detailed bibliometric results, extended comparison tables, and benchmark specifications; Supplementary File S4: CiteSpace alias and merged-term control file; Supplementary File S5: CiteSpace exclusion and noise-term control file.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial intelligence
ANN	Artificial neural network
BHP	Bottomhole pressure
CFD	Computational fluid dynamics
CO ₂	Carbon dioxide
DMD	Dynamic mode decomposition
DNS	Direct numerical simulation
ECD	Equivalent circulating density
ERT	Electrical resistance tomography
FDM	Finite-difference method
FEM	Finite-element method
FNO	Fourier neural operator
FVM	Finite-volume method
GPU	Graphics processing unit
HPHT	High-pressure/high-temperature
LBM	Lattice Boltzmann method
LES	Large-eddy simulation
LLR	Log-likelihood ratio
LSI	Latent semantic indexing
MI	Mutual information
MPD	Managed-pressure drilling
PINN	Physics-informed neural network
POD	Proper orthogonal decomposition
PWD	Pressure while drilling
PVT	Pressure–volume–temperature
RANS	Reynolds-averaged Navier–Stokes
ROM	Reduced-order model
RSM	Reynolds stress model
SBP	Surface backpressure
SPE	Society of Petroleum Engineers
UQ	Uncertainty quantification
V&V	Verification and validation
WoS	Web of Science
YPL	Yield Power Law

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