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Invited review

Integrated wellbore thermal management for deep wellbore cooling: Recent advances, critical challenges, and future perspectives

Mei-Chun Li[1,2]*, Yang Ding[1], Zhengming Xu[3], Jiangshuai Wang[4], Yufei Chen[5], Shaine M. Lalji[6]

[1]*Shandong Key Laboratory of Oil and Gas Field Chemistry, School of Petroleum Engineering, China University of Petroleum (East China), Qingdao 266580, P. R. China*

[2]*State Key Laboratory of Deep Oil and Gas, China University of Petroleum (East China), Qingdao 266580, P. R. China*

[3]*School of Energy Resources, China University of Geosciences (Beijing), Beijing 100083, P. R. China*

[4]*School of Petroleum and Natural Gas Engineering, Changzhou University, Changzhou 213164, P. R. China*

[5]*CNPC Engineering Technology R&D Company Limited, Beijing 102206, P. R. China*

[6]*Department of Petroleum Engineering, NED University of Engineering & Technology, University Road, Karachi 75270, Pakistan*

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Abstract:
Wellbore temperature is a critical factor influencing drilling-fluid performance, downhole tool reliability, and operational safety in deep and ultra-deep drilling. Effective wellbore cooling has therefore become increasingly important for maintaining drilling efficiency and enabling safe operations under high-temperature conditions. This review summarizes recent advances in integrated wellbore thermal management across four interconnected areas, i.e., thermal modelling and prediction, functional thermal-management materials, cooling technologies and equipment, and real-time temperature monitoring and updating. First, the evolution of wellbore thermal modelling from steady-state analyses toward transient, fully coupled, and data-driven predictive frameworks is overviewed. Second, the functional thermal-management materials, especially microencapsulated phase-change materials, porous microspheres, and thermal-conductivity enhancers are examined. Third, cooling technologies and equipment, including surface cooling systems, low-thermal-conductivity drill pipes, downhole insulation chambers, and active refrigeration tools, are assessed. Fourth, real-time downhole temperature monitoring and model updating are reviewed based on fiber-optic sensing, probabilistic data assimilation, and intelligent model correction techniques for adaptive thermal management. Finally, the key challenges and future perspectives, including near-, medium-, and long-term priorities, are discussed.

1. Introduction

With the continuous expansion of oil and gas exploration into deep and ultra-deep formations, wellbore temperature has become one of the most critical factors influencing drilling safety and operational efficiency (Gautam et al., 2022; Sun et al., 2024b, 2025; Xu et al., 2025). Elevated downhole temperatures significantly alter drilling-fluid rheology, accelerate the thermal degradation of chemical additives, reduce the reliability of measurement-while-drilling and logging-while-drilling tools, and increase the risk of wellbore instability and operational failure (Sun et al., 2024a; Wang et al., 2024a; Khan et al., 2025). In extreme cases, excessive temperatures can cause tool malfunction, inaccurate downhole measurements,

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*Corresponding author.
E-mail address: mli@upc.edu.cn (M. -C. Li); b24020007@s.upc.edu.cn (Y. Ding); xuzm@cugb.edu.cn (Z. Xu); wjs125126@163.com (J. Wang); chenyufeidri@cnpc.com.cn (Y. Chen); shaine@neduet.edu.pk (S. M. Lalji).
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and even well-control incidents. Consequently, effective wellbore cooling has become an essential strategy for maintaining drilling-fluid performance, ensuring downhole tool reliability, and enabling safe and efficient drilling under high-temperature conditions (Su et al., 2025; Zhang et al., 2025b).

Importantly, cooling interventions do not simply reduce wellbore temperature but also modify the thermo-hydraulic state of the circulating system. Temperature-dependent changes in drilling-fluid density, viscosity, and phase behavior affect pressure loss, equivalent circulating density, phase holdup, slip velocity, and flow-regime transitions, while unsteady multiphase flow, in turn, alter convective heat transfer and the residence time available for cooling. These effects are particularly relevant when gas, liquid, dispersed solids, or microencapsulated phase-change materials (MPCMs) coexist, as cooling-induced changes in rheology and phase state may modify both flow distribution and heat-transfer efficiency (Li et al., 2025c; Zhuang et al., 2026). As a result, transient multiphase-flow effects should be carefully considered where they directly influence heat transfer, MPCM transport and phase transitions, pressure and flow behavior, or wellbore-formation heat exchange.

Against this background, an integrated wellbore thermal management strategy has been emerging as a comprehensive approach for coordinating multiple thermal-control technologies during deep drilling. Integrated wellbore thermal management refers to the systematic coordination of temperature prediction, thermal regulation, temperature monitoring, and operational optimization to control the thermal environment throughout the drilling process. Rather than relying on individual cooling technologies, this approach integrates predictive wellbore thermal models, functional thermal-management materials, engineered cooling equipment, and real-time temperature sensing into a unified framework that enables informed decision-making and dynamic thermal regulation. In such system, thermal modelling provides the basis for predicting downhole temperature evolution and evaluating cooling strategies (Yang et al., 2022); functional materials regulate heat transfer through thermal insulation and latent-heat storage (Shi et al., 2025); engineered cooling technologies directly mitigate heat accumulation (Deng et al., 2025a); and real-time temperature measurements continuously validate and update thermal predictions to improve operational performance (Nakamoto and Leggett, 2025).

In recent years, significant advances have been achieved in the key technologies underpinning integrated wellbore thermal management. Wellbore thermal modelling has progressed from general analytical and thermo-hydraulic formulations (Hasan and Kabir, 2012; Zhang et al., 2021, 2022) to transient models specifically developed for drilling applications. These models incorporate selected combinations of the evolving time-depth trajectory, operational schedules, pressure- and temperature-dependent drilling-fluid properties, drill string eccentricity and rotation, bit and pipe frictional heat, and formation stratification (Xiao et al., 2022; Mao et al., 2023; Chen et al., 2024a). These models provide a basis for evaluating how the rate of penetration, circulation and shut-in sequences, weight on bit, rotary speed, drilling-fluid flow rate and inlet temperature, mud system, well geometry, and layer-specific rock properties affect downhole temperature. Meanwhile, functional thermal-management materials, particularly MPCMs, porous microspheres, and thermal-conductivity enhancers, have attracted increasing attention because of their abilities to absorb heat through latent-heat storage and reduce heat transfer through thermal insulation, thereby providing new opportunities for enhancing wellbore cooling performance (Zhang et al., 2025a). In parallel, various cooling equipment have been developed to reduce downhole temperatures, including surface fluid cooling systems, low-thermal-conductivity drill pipes, downhole insulation devices, and active refrigeration technologies (Li et al., 2025a; Zhao et al., 2025). Furthermore, rapid advances in distributed fiber-optic sensing, wireless downhole telemetry, data assimilation, and artificial intelligence have greatly improved the capability for real-time temperature monitoring, prediction, and adaptive thermal management (Molenaar et al., 2012; Ugueto C et al., 2016).

Despite these significant developments, existing studies remain largely fragmented across individual research areas, and comprehensive reviews that systematically integrate advances in temperature modelling, functional materials, cooling technologies, and real-time monitoring remain limited (Li et al., 2025b; Ali et al., 2026; Li et al., 2026b). The interactions among these components and their collective contributions to integrated wellbore thermal management have not been comprehensively discussed. In addition, several challenges remain, including limited field-scale validation of emerging cooling materials, insufficient coupling between predictive models and engineering technologies, and the difficulty of achieving accurate real-time thermal prediction and adaptive thermal management under complex downhole conditions (Xie et al., 2025; Zhang et al., 2025b).

This review provides a comprehensive overview of recent advances in integrated wellbore thermal management for deep wellbore cooling (Fig. 1). It first summarizes the development of wellbore temperature modelling and prediction methods, followed by recent progress in functional thermal-management materials, cooling technologies and equipment, and real-time temperature measurement and model updating. Finally, current challenges and future research directions are discussed to provide a systematic understanding of integrated wellbore thermal management and identify promising opportunities for improving thermal regulation, operational safety, and drilling efficiency in deep and ultra-deep wells.

2. Wellbore temperature modelling

Wellbore temperature modelling provides the foundation for integrated wellbore thermal management by predicting downhole thermal evolution and quantifying associated thermal risks. These predictions support the design and deployment of cooling materials, technologies, and equipment under the complex operating conditions encountered in deep and ultra-deep wells. Accurate prediction of wellbore temperature requires more than selecting an appropriate governing equation. A practical modelling framework must integrate model hierarchy, heat-transfer correlations, well geometry, cooling

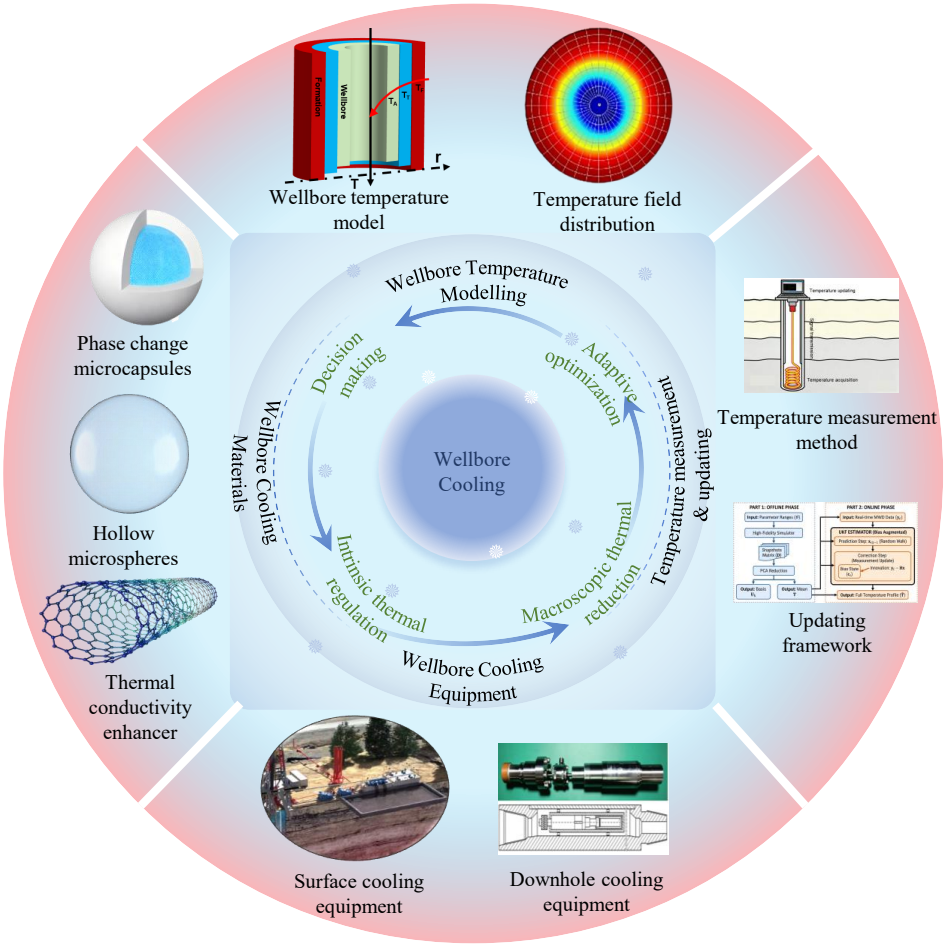


Fig. 1. Integrated wellbore thermal management for deep wellbore cooling. Modelling predicts downhole temperatures and guides cooling decisions; materials and equipment regulate heat transfer, while sensing and data assimilation update predictions to enable adaptive, integrated thermal management.

interventions, validation strategies, uncertainty quantification, and real-time model updating. Fig. 2 summarizes these key components, which are reviewed below as the foundation for integrated thermal-management decision-making and transparent engineering reporting.

2.1 Model hierarchy and governing assumptions

Wellbore temperature modelling is often portrayed as a sequence of progressively more accurate models that solve essentially the same problem (Wei et al., 2026). However, this interpretation is overly simplistic, particularly in the context of deep-well cooling. As shown in Table S1, the literature encompasses several distinct classes of models, each designed for different engineering objectives, including analytical models for rapid screening, one-dimensional transient simulators for predicting whole-well thermal evolution, multidimensional computational fluid dynamics (CFD) models for resolving local heat-transfer mechanisms, and reduced-order or data-assimilative models for real-time prediction and control. These models are complementary rather than interchangeable. Analytical line-source solutions provide rapid order-of-magnitude estimates and transparent benchmarks when their assumptions, such as homogeneous or layer-averaged formation properties and simplified geometries, boundary conditions, and drilling histories, are reasonably satisfied. However, their computational efficiency does not guarantee high predictive fidelity. Chekhonin et al. (2025) reported an approximately 11% average relative difference in the time-depth trajectory, corresponding to errors of up to 3% in reconstructed formation temperature and 20% in geothermal gradient. By comparison, a ±30% uncertainty in rock thermal properties produced errors of up to 2.5% and 9.3%, respectively. Analytical solutions are therefore better suited to preliminary sensitivity analysis, benchmarking, and numerical-code verification than to stand-alone high-fidelity prediction of formation-controlled temperature fields. In contrast, detailed three-dimensional CFD models can capture these local flow and heat-transfer processes with high fidelity but are generally too computationally expensive for long-duration drilling simulations or real-time optimization. Consequently, effective wellbore thermal management requires a hierarchical modelling strategy in which the simplest model capable of representing the governing physical mechanisms is selected for each engineering task, while information is transferred consistently across different model scales (Kabir

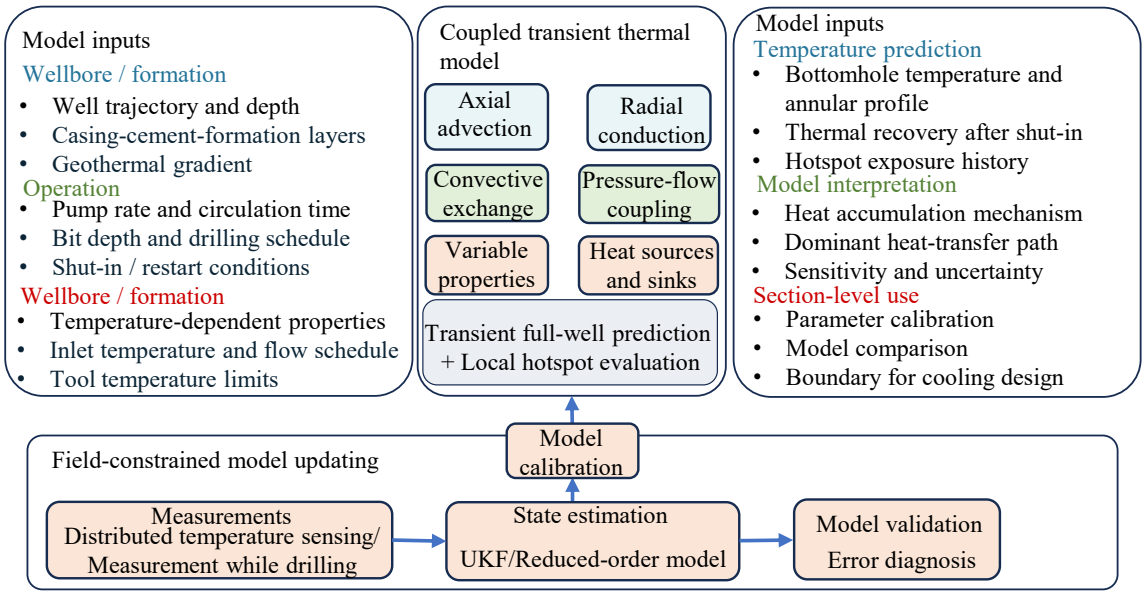


Fig. 2. Framework of wellbore temperature modelling for closed-loop cooling design, real-time updating, and adaptive thermal-management decisions.

et al., 1996; Yao et al., 2025).

Classical analytical models remain valuable for identifying dominant thermal resistances and providing benchmark solutions for model verification. Ramey (1962) represented the wellbore as a line heat source coupled with transient radial heat conduction in the formation, while Raymond (1969) extended this framework to circulating drilling fluids and demonstrated that circulation substantially alters wellbore and formation temperature distribution. Holmes and Swift (1970) developed coupled drill pipe-annulus temperature models that account for depth, flow rate, well geometry, drilling-fluid properties, and formation conditions, while Keller et al. (1973) introduced transient formulations supported by circulating-mud experiments. Wooley (1980) further generalized the analysis to include drilling circulation, fluid injection, production, and shut-in operations within a unified framework. These models remain useful for preliminary design, sensitivity analysis, and numerical-model verification. However, their assumptions, including axisymmetric geometry, cross-sectional temperature averaging, prescribed fluid properties, simplified axial conduction, idealized boundary conditions, and empirical heat-transfer coefficients, limit their applicability under complex downhole conditions (Dang et al., 2025). When these assumptions are violated, agreement with a single measured bottomhole temperature does not guarantee accurate prediction of the complete axial temperature distribution or local heat fluxes.

During drilling, wellbore temperature is governed by coupled thermo-hydraulic processes and the evolving drilling operation. The rate of penetration determines formation exposure and fluid-formation interaction time, while formation temperature and thermal properties control the magnitude and rate of thermal response. Flow rate and inlet temperature, circulation and shut-in schedules, drill string rotation, and frictional and bit-rock heat generation further affect the energy balance. Accordingly, this review distinguishes thermo-hydraulically coupled models, which resolve flow and temperature fields, from drilling-process-coupled models, which additionally account for evolving depth, operating conditions, formation heterogeneity, and drilling-specific heat sources. Hasan and Kabir (1994) established important foundations, whereas Hasan and Kabir (2012) is treated as a general reference because it does not explicitly simulate drilling advancement. Recent studies have incorporated the rate of penetration, circulation, rotation, drilling fluid properties, heat generation, and formation heterogeneity, demonstrating their important roles in wellbore temperature evolution (Xiao et al., 2022; Mao et al., 2023; Chen et al., 2024a; Chekhonin et al., 2025).

Subsequent developments focused on improving operational realism by incorporating more representative drilling processes. Beirute (1991) introduced alternating circulation and shut-in periods while accounting for thermal history effects. The TEMLOPI model was originally developed for geothermal drilling and later extended to include transient circulation, shut-in conditions, and lost-circulation events (Garcia et al., 1998a, 1998b). Hasan and Kabir (1994) demonstrated that pressure evolution, phase behavior, flow regime transitions, and heat transfer must be solved in a fully coupled manner for two-phase wellbore flow. These advances established the coupled drill string-annulus-tubular-cement-formation framework that underpins most modern engineering simulators (Khan and May, 2016; Dong et al., 2018; Xiao et al., 2026). Nevertheless, increasing model complexity should not be equated with higher predictive accuracy. A common misconception is that incorporating additional conservation equations automatically produces a high-fidelity model. In practice, predictive fidelity depends not only on the governing equations but also on the accuracy of closure relations, boundary conditions, input parameters, and experimental validation.

A model may satisfy energy conservation exactly yet still produce inaccurate temperature predictions if the annular heat-transfer coefficient, inlet thermal history, or drilling-fluid thermophysical properties are poorly characterized. Consequently, rigorous model validation and uncertainty assessment are as essential as mathematical sophistication for developing reliable wellbore temperature models.

2.2 Closure relations, geometry, and multiscale coupling

A cooling-oriented whole-well model typically solves coupled mass, momentum, and energy equations for drill string and annular flow, together with radial heat transfer through the drill pipe, casing, cement, and formation. Heat-source terms may include geothermal influx, viscous and mechanical dissipation, bit and motor heat generation, fluid loss, and heat absorbed or released by cooling interventions. Two-way thermo-hydraulic coupling is essential because temperature- and pressure-dependent fluid properties affect pressure loss, flow behavior, and residence time, which in turn modify convective heat transfer. Cooling may therefore improve tool survivability while increasing viscosity, pressure loss, and equivalent circulating density, making a purely thermal optimum operationally impractical. Yao et al. (2025) demonstrated the importance of explicitly representing layered thermal resistance and well geometry in insulated-drill-pipe models, reporting mean relative errors below 1% against two field wells, although broader independent validation remains necessary.

In many one-dimensional wellbore models, the weakest component is not the axial energy balance but the convective heat-transfer closure employed to estimate wall heat flux. Heat-transfer correlations originally developed for concentric, fully developed, constant-property flows are frequently applied to highly deviated and horizontal wells, where drill string eccentricity, pipe rotation, cuttings-bed formation, non-Newtonian drilling-fluid rheology, and dual-wall heating substantially modify the flow and temperature fields. Gou et al. (2026) addressed part of this limitation by performing 850 three-dimensional CFD simulations covering eccentricities from 0 to 0.8, diameter ratios from 0.3 to 0.7, both laminar and turbulent flow regimes, and simultaneous heating at the inner and outer annular walls. A feedforward neural-network surrogate trained on the CFD database achieved coefficients of determination (R^2) exceeding 0.99 for the demonstrated turbulent cases. When incorporated into a transient one-dimensional wellbore-formation model, the eccentric-annulus closure predicted temperature differences of up to 12.6 °C compared with conventional heat-transfer correlations.

Although these results demonstrate the value of improved closure relations, they should be interpreted cautiously. A high R^2 indicates accurate interpolation within the CFD dataset but does not independently validate the turbulence model, boundary conditions, rheological formulation, or field-scale eccentricity representation. Independent validation against simultaneous measurements of eccentricity, flow rate, and temperature remains essential (Gou et al., 2026). Such surrogate models should therefore be treated as physics-informed closures applicable within their calibrated parameter space and accompanied by uncertainty quantification and out-of-domain assessment. The same scrutiny should apply to empirical heat-transfer correlations, with key assumptions regarding Reynolds number, rheology, geometry, eccentricity, rotation, roughness, thermal boundary conditions, and fluid-property evaluation explicitly reported to ensure reproducibility. Model reliability also depends on input-data quality. Complete datasets may remain unsuitable if they contain inconsistent trajectories, inaccurate time-depth histories, implausible thermophysical properties, or biased measurements. Before calibration, inputs should therefore be checked for units, plausible ranges, provenance, pressure-temperature validity, cross-property consistency, synchronization, and energy balance. Rock and drilling-fluid properties should reflect the actual lithology and fluid composition and their temperature- and pressure-dependent behavior. Chekhonin et al. (2025) quantified how errors in drilling history and rock properties propagate into reconstructed formation temperature and geothermal gradient, demonstrating that both data plausibility and data completeness are essential for reliable model evaluation.

A practical multiscale modelling framework combines whole-well and local high-fidelity models. A transient one-dimensional model should describe the overall well geometry and operating schedule, while CFD or conjugate heat-transfer sub-models can resolve regions where cross-sectional averaging fails, such as eccentric annuli, bit nozzles, downhole motors, and insulated drill-pipe joints (Khan and May, 2016; Dong et al., 2018; Xiao et al., 2026). Local simulations can generate response surfaces, Nusselt-number correlations, or reduced-order models for incorporation into the whole-well simulator. Key variables transferred across scales should include fluid temperature, wall heat flux, pressure, flow rate, eccentricity, rotation, and effective thermal resistance. Importantly, local component temperatures and cumulative thermal exposure may be more relevant to equipment reliability than bulk-fluid temperature alone. The same upscaling principle applies to dispersed cooling particles such as MPCMs. Because MPCMs are much smaller than the annular hydraulic diameter, particle-fluid heat transfer is generally represented through interphase heat-transfer closures and volumetric latent-heat source terms rather than explicitly resolved. The bulk-fluid temperature therefore serves as the primary coupling variable between particle-scale phase-change behavior and whole-well thermal prediction.

2.3 Cooling-aware models and engineering interpretation

Most legacy wellbore temperature models were developed to predict thermal profiles rather than to support the design of active thermal-management systems. Representing a cooling technology simply by reducing the inlet-fluid temperature or adjusting an overall heat-transfer coefficient may be adequate for preliminary screening, but it cannot capture the underlying cooling mechanisms or engineering constraints. A comprehensive review should therefore require each cooling intervention to be represented according to its actual energy-

transfer pathway and operational limitations.

For example, surface cooling systems should account for heat-exchanger duty, approach temperature, flow rate, secondary-loop conditions, parasitic power, and control constraints (Zhang et al., 2025b). Insulated drill pipes require consideration of multilayer conduction, thermal bridging, insulation interval, material degradation, and potentially reduced heat dissipation in shallow sections. Passive thermal-protection chambers should consider transient heat leakage, finite storage capacity, contact resistance, internal heat generation, and end-of-protection criteria (Peng et al., 2023b), whereas active refrigeration systems should incorporate cooling capacity, coefficient of performance, power consumption, heat rejection, dimensional constraints, and reliability. Such models should ultimately provide engineering metrics including required cooling duty, protected depth, allowable tool exposure time, and energy consumption.

At the whole-well scale, Wang et al. (2026d) developed a transient multiphase model incorporating particle slip, shell-conduction-controlled thermal lag, phase-change kinetics, and wellbore-formation heat transfer. The model predicted bottomhole temperature reductions of up to 21.3 °C under baseline conditions and 29.7 °C after multi-objective optimization. However, these predictions have not been directly validated by MPCM flow-loop or field experiments. Although the thermo-hydraulic solver was benchmarked against classical solutions and data from 20 wells, this does not validate the MPCM phase-change module, particle integrity, dispersion stability, rheological effects, or predicted cooling magnitude. The results should therefore be regarded as mechanistic design predictions requiring high-pressure high-temperature (HPHT) flow-loop and field-scale validation (Liu et al., 2025a; Wang et al., 2026d).

A key challenge is bridging particle-scale heat transfer and whole-well predictions. Current models generally employ homogenized closure relations rather than explicitly resolving individual particles. Wang et al. (2026d), for example, represents particle-fluid heat exchange using a Nusselt-number correlation coupled with shell thermal resistance and phase-change kinetics, with latent-heat absorption introduced as a distributed volumetric heat sink. The validity of this upscaling depends on the relative timescales of particle thermal relaxation, shell conduction, phase transition, and fluid residence. Significant thermal lag can reduce latent-heat utilization and lead to overprediction of cooling. Therefore, these closures should be subjected to sensitivity analysis, uncertainty propagation, and HPHT flow-loop validation, particularly under non-Newtonian and eccentric-annulus conditions where particle-scale heat-transfer data remain limited.

Although these findings are promising, they remain predominantly model-based and should therefore be interpreted cautiously. The underlying thermo-hydraulic solver was validated against the Holmes-Swift and Keller models, as well as field measurements from 20 deep wells, with reported relative errors below 10% (Wang et al., 2026d). However, the authors also acknowledged that publicly available datasets for MPCM circulation under field conditions are currently unavailable. Consequently, the coupled multiphase phase-change module has not yet been independently validated under high-pressure, high-temperature drilling conditions. This distinction should be made explicit in the present review. Validation of the baseline heat-transfer model supports the credibility of the wellbore thermal framework but does not directly verify the predicted cooling performance of MPCMs, particle integrity, long-term dispersion stability, rheological effects, nozzle transport, or surface regeneration efficiency. The next stage of validation should therefore include pressurized flow-loop experiments with controlled thermal loading to measure particle phase fraction, interphase slip, pressure loss, and cyclic durability, followed by pilot-scale field trials incorporating distributed temperature measurements and particle-recovery analyses.

Accordingly, cooling-system design should be formulated as a constrained, uncertainty-aware optimization problem rather than a simple temperature-minimization exercise (Chen et al., 2025b). Typical design objectives include limiting peak tool temperature, minimizing the duration of thermal exposure above critical thresholds, reducing surface energy consumption, and lowering material or equipment costs. These objectives must be balanced against practical constraints, including pump capacity, equivalent circulating density, solids loading, material compatibility, bottomhole assembly space, electrical power availability, and operational continuity. For MPCM-based cooling systems, phase-change temperature, latent heat, shell thickness, particle concentration, particle-size distribution, interphase slip, and thermal cycling stability should be optimized simultaneously rather than independently (Wang et al., 2026d). Likewise, for insulated drill pipe, thermal conductivity, insulation thickness, joint configuration, installation length, and placement depth should be considered as coupled design variables (Yao et al., 2025). Ultimately, a robust cooling strategy is one that maintains an adequate thermal safety margin across realistic uncertainties in formation properties, drilling-fluid characteristics, well geometry, and operational schedules. The lowest predicted bottomhole temperature under a single calibrated scenario does not necessarily represent the optimal solution for field deployment.

2.4 Uncertainty characterization, calibration, validation, and real-time updating

Uncertainty characterization should precede parameter calibration and model validation. Major uncertainties can be grouped into four categories: Operational inputs, including the time-depth trajectory, flow rate, inlet temperature, and circulation schedule; formation properties, including geothermal gradient, thermal conductivity, and volumetric heat capacity; measurement uncertainty; and structural uncertainty arising from omitted physics or inappropriate closure relations. Chekhonin et al. (2025) demonstrated that an approximately 11% discrepancy in drilling-depth trajectory produced errors of up to 3% in reconstructed formation temperature and 20% in geothermal gradient, whereas ±30% uncertainty in rock thermal properties produced errors of 2.5% and 9.3%, respectively. Chen et al. (2024a) further reported bottomhole-temperature sensitivities of 5.4, 2.6, 13, and 22 °C to HPHT fluid properties, drill string eccentricity, rotation, and rock-

breaking heat, respectively. These study-specific results highlight the importance of quantifying uncertainty rather than treating model inputs as deterministic.

Calibration should therefore follow sensitivity and parameter-identifiability analyses. Plausible parameter ranges or probability distributions should be established from measurement accuracy, laboratory and field data, and literature-supported bounds, followed by uncertainty propagation using sampling-based or Bayesian approaches. Calibration and validation datasets should remain independent, with fitted parameters, uncertainty intervals, and prediction intervals reported for key outputs such as bottomhole temperature, peak tool temperature, cooling capacity, and threshold-exceedance probability. Wang et al. (2026a) demonstrated that conventional parameter tuning under structural model mismatch yielded a root-mean-square error of 16.63 K, whereas probabilistic state updating with an explicit bias term reduced it to 1.01 K, emphasizing that parameter tuning should not be applied to compensate for structural model deficiencies.

Validation should then proceed hierarchically. First, mathematical and numerical verification should assess conservation, grid and time-step independence, limiting cases, and analytical benchmarks (Ramey, 1962; Raymond, 1969; Holmes and Swift, 1970). Second, individual closure relations and component models should be validated, including pressure-loss and heat-transfer correlations, insulation properties, MPCM phase-transition behavior, heat-exchanger performance, and refrigeration capacity. Third, system-level predictions should be compared with measured temperatures under multiple operating conditions, including circulation, shut-in, restart, and flow-rate changes (Beirute, 1991; Garcia et al., 1998a, 1998b). Finally, intervention-specific field validation should compare thermal performance before and after cooling implementation. Reporting should include sensor locations, measurement uncertainty, initial conditions, calibration and validation periods, and statistical measures of both bias and transient errors; a single endpoint percentage error is insufficient for time-dependent thermal-management applications.

Within this hierarchy, model fidelity should ultimately be evaluated against the intended engineering application rather than model complexity or R^2 alone. Relevant criteria include numerical reliability, predictive accuracy against measured temperatures, and independent validation with adequate thermal safety margins (Table S2). The proposed 1% numerical criterion should be regarded as preliminary screening thresholds, whereas acceptable temperature and timing errors should be defined before calibration according to measurement uncertainty and engineering objectives.

Real-time model updating can further reduce discrepancies between pre-drilling assumptions and evolving downhole conditions by assimilating temperature observations into physics-based models (Naderi et al., 2024; Wang et al., 2026a). However, the updating framework should explicitly distinguish among measurement noise, uncertain physical parameters, and structural model bias, because parameter tuning alone may compensate for structural model deficiencies by driving parameter estimates toward physically unrealistic values (Götte and Timmermann, 2023; Wang et al., 2026a). Surrogate or reduced-order models applied to accelerate repeated simulations should also document their training domain, boundary-condition representation, conservation error, extrapolation limits, and update latency. Extrapolation to substantially different operating conditions should be avoided unless additional verification has been performed (Xie et al., 2025). Most importantly, the operational objective should be defined before deployment; otherwise, real-time prediction may remain primarily a monitoring function rather than becoming part of a closed-loop thermal-management system (Naderi et al., 2024; Wang et al., 2026a).

2.5 Remaining challenges and future perspectives

Overall, advances in wellbore temperature modelling should no longer be judged primarily by the addition of increasingly complex governing equations. Instead, the key criterion is whether a model accurately resolves the physical mechanisms governing the engineering decision, employs defensible closure relations and boundary conditions, and has been validated at the scale for which it is intended. Classical analytical models provide transparent benchmark solutions; transient whole-well simulators capture operational history; CFD-informed closure relations resolve local geometric effects such as eccentric annuli; multiphase models represent the transport and release of latent heat by MPCMs; and reduced-order models combined with data assimilation enable real-time prediction and correction. These modelling approaches should be regarded as complementary components of an integrated modelling framework rather than successive replacements for one another.

To improve the comparability, reproducibility, and long-term value of future studies, authors should comprehensively report wellbore and drill string geometry; well trajectory, eccentricity, drill string rotation, and wall roughness; initial and time-dependent boundary conditions; drilling-fluid property correlations and rheological models; heat-transfer and formation-response closure relations, together with their ranges of validity; numerical discretization, convergence, and conservation assessments; calibration and independent validation datasets; sensor uncertainty and time synchronization; parameter and structural uncertainty analyses; the physical representation and operational constraints of each cooling technology; and decision-oriented performance metrics accompanied by confidence intervals.

Finally, the strength of any engineering claim should be commensurate with the supporting evidence. Validation of a baseline thermal model does not constitute validation of a novel cooling material; high accuracy of a CFD-based surrogate does not substitute for field verification; and agreement with a measured outlet temperature does not necessarily guarantee an accurate downhole temperature distribution. Adhering to these principles would establish a rigorous methodological foundation for evaluating the cooling materials and technologies reviewed in Sections 3 and 4, thereby transforming wellbore temperature modelling from a descriptive simulation tool into an auditable component of integrated wellbore thermal

management.

3. Wellbore cooling materials

Wellbore cooling materials play a pivotal role in downhole thermal management because they directly regulate heat transfer through their intrinsic thermophysical properties, enabling localized heat absorption and thermal insulation within the wellbore. Unlike conventional surface-cooling technologies, these materials provide *in-situ* thermal regulation under the complex thermal environments encountered in deep and ultra-deep wells (Yang et al., 2025). The principal classes of wellbore cooling materials include MPCMs, porous insulation materials, and thermal-conductivity enhancers, all of which actively regulate downhole heat transfer through distinct thermophysical mechanisms, thereby enabling effective control of wellbore temperature (Li et al., 2025b).

3.1 MPCMs

Phase-change materials (PCMs) store and release thermal energy through reversible phase transitions, offering high energy-storage density and near-constant temperature during phase change (Hou et al., 2024; Liu et al., 2025b; Dong et al., 2026). These characteristics render PCMs particularly attractive for wellbore thermal management (Gao et al., 2024; Li et al., 2024; Deng et al., 2025b). However, the direct application of PCMs in drilling fluids is hindered by two major challenges, i.e., leakage during the phase transition and limited long-term durability under harsh downhole conditions, both of which significantly increase operational costs. Microencapsulation provides an effective solution by encapsulating PCMs within organic or inorganic shells, thereby preventing leakage while preserving the desirable thermal properties of the core material (Chen et al., 2024b; Cheng et al., 2025; Wu et al., 2025a).

Common PCMs include paraffin waxes, fatty acids, and binary eutectic salts, whereas shell materials typically consist of polymers or inorganic materials (Chang et al., 2022; Wu and Chang, 2025). Representative fabrication techniques include *in-situ* polymerization, interfacial polymerization, sol-gel synthesis, and spray drying (Liu et al., 2025e; Wang et al., 2025a). For example, Zhao et al. (2026a) developed urea@silicon dioxide (SiO_2) MPCMs with a phase-change temperature of 133.4 °C and latent heat of 181.9 J/g. A 10 wt% loading of MPCMs reduced the bottomhole temperature by approximately 17 °C, but this cooling effect largely disappeared after 15 min due to the saturation of the phase-change process.

As ultra-deep-well temperatures increasingly exceed 200 °C, MPCMs with high phase-change temperatures are particularly important (Chen et al., 2025c). To address this challenge, Zhao et al. (2026b) developed lithium nitrate@SiO_2 MPCMs (Fig. 3(a)) with a phase-change temperature of 249.4 °C and latent heat of 140.86 J/g. At 8 wt% and 260 °C, they delayed fluid heating by 61 min and produced a maximum temperature reduction of 52 °C (Fig. 3(b)). Alternatively, Guo et al. (2024) reported sodium nitrate/potassium nitrate@SiO_2 MPCMs with a phase-change temperature of 216 °C and 61 J/g latent heat, retaining 96.7% of their initial latent heat after 50 cycles. However, at 10 wt% and 220 °C, they reduced fluid temperature by only 2.1 °C.

Notably, reported cooling magnitudes diverge considerably across studies, even for microcapsules at comparable additive mass fractions (Table S3) owing to differences in both material properties and testing protocols. Key material factors include latent-heat density and phase-change temperature, which should be matched to the operating temperature to maximize heat absorption and avoid premature phase transition or insufficient thermal driving force. Dosage, particle size, shell thickness, and encapsulation quality further affect heat-transfer area, phase-change utilization, leakage resistance, and cycling stability. Comparisons are also complicated by the lack of standardized MPCM testing protocols. Studies differ in baseline temperature, heating rate, thermal boundary conditions, circulation rate, test geometry, additive concentration, test duration, and cooling-performance metrics, making direct comparison of reported cooling magnitudes difficult.

The mechanical integrity of MPCMs under flow-induced loading is critical for long-term reliability. During high-rate circulation, microcapsules experience hydrodynamic shear and repeated impacts with drill pipes, cuttings, and suspended solids, with particularly severe stresses near bit nozzles. Shell fatigue, cracking, or fracture may release the PCM core and cause three major problems, including altered drilling-fluid rheology and filtration behavior, increased suspended solids and degraded hole cleaning, and accumulation around nozzles or downhole components, potentially causing plugging and tool malfunction. However, quantitative data on MPCM breakage under drilling-relevant shear and impact conditions remain scarce (Guo et al., 2024). Mechanical vulnerability depends on shell composition, thickness, structure, and defects. Polymeric shells may undergo deformation and fatigue, whereas rigid SiO_2 shells may suffer brittle fracture under localized loading (Su et al., 2025). Therefore, realistic flow-loop testing under representative pressure, temperature, flow rate, solids loading, and nozzle conditions is needed to quantify capsule breakage and its effects on rheology and filtration performance.

The economic feasibility of MPCM-based cooling at field scale remains insufficiently studied, as well. In deep and ultra-deep wells, lost circulation and breakage can require substantial replenishment of functional additives, making cost dependent not only on MPCM price and dosage but also on cycling stability, mechanical survivability, latent-heat retention, and recovery efficiency. Poor durability, high dosage, limited recovery, or mechanical breakage could substantially increase material consumption and operating costs with drilling depth and duration. Future studies should therefore report MPCM cost, dosage, thermal and mechanical retention, recovery efficiency, and recyclability alongside cooling performance to enable quantitative assessment of field-scale economic and operational viability (Zhao et al., 2026a).

3.2 Porous insulating materials

Porous insulation materials possess well-developed internal pore structures that effectively suppress both solid-state and gaseous heat conduction, resulting in exceptionally low

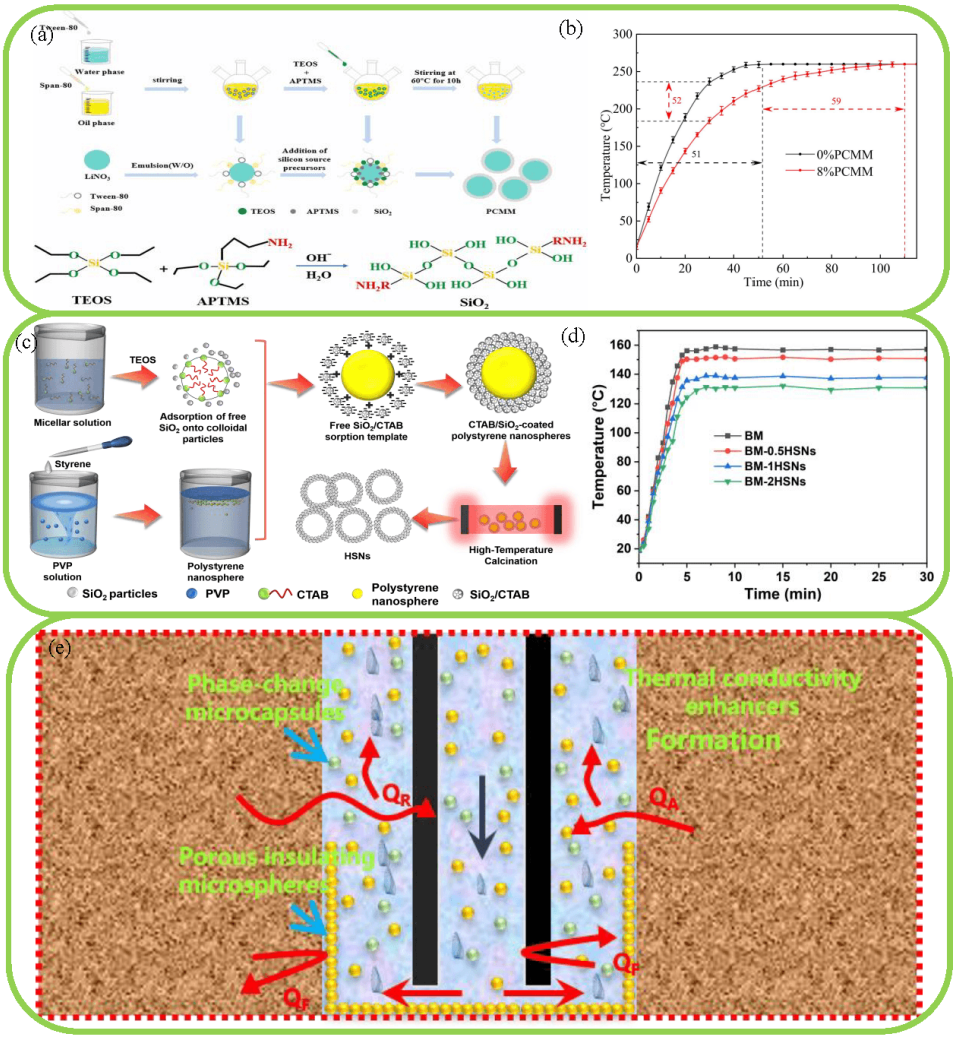


Fig. 3. Preparation and thermal insulation performance of wellbore cooling materials. (a) MPCMs with a lithium nitrate core and a SiO_2 shell fabricated via interfacial polymerization (Zhao et al., 2026b), (b) Temperature-rise curves of drilling fluid containing 8 wt% MPCMs (Zhao et al., 2026b), (c) Hollow silica nanospheres prepared via sacrificial template method (Wang et al., 2026c), (d) Temperature-rise curves of mud cakes containing hollow silica nanospheres (Wang et al., 2026c), and (e) Schematic diagram of "latent-heat absorption-wellbore thermal insulation-drilling fluid thermal dissipation" cooling system.

thermal conductivity (Cha et al., 2023; Wang et al., 2024b). In recent years, these porous microspheres have been proposed as a means of forming a thermal-insulation layer on the wellbore wall, thereby reducing heat transfer from the surrounding formation to the circulating drilling fluid and lowering downhole temperatures (Han et al., 2025; Wang et al., 2026b). During drilling-fluid circulation, porous microspheres are co-deposited with bentonite particles to form an insulating filter cake that mitigates geothermal heat influx from the surrounding high-temperature formation (Alosail et al., 2026).

Porous microspheres for downhole thermal insulation must combine ultralow thermal conductivity, durable adhesion to the wellbore wall, and sufficient mechanical strength to withstand high pressure, pressure fluctuations, and erosive drilling fluids (Ding et al., 2026). Compared with conventional insulation materials, silica-based porous microspheres offer enclosed cavities that suppress heat transfer while their spherical shells distribute external stresses, providing a favorable combination of thermal insulation and mechanical stability (Ding et al., 2023a, 2023b). For example, Zhang et al. (2025a) developed polymer-coated silica aerogel particles with a thermal conductivity of 0.061 W/m·K. At 2 wt%, the polymer-coated silica aerogel particles reduced the thermal conductivity of bentonite drilling fluid from 0.619 to 0.562 W/m·K and that of the filter cake from 4.14 to 2.742 W/m·K, while remaining stable above 210 °C. Using a different strategy, Wang et al. (2026c) developed hollow silica nanospheres whose hollow cavities and thin silica shells suppress gas-phase and solid-phase heat transfer. The hollow silica nanospheres dispersed well in drilling fluids and reduced the filter-cake cold-side temperature by approximately 27 °C, demonstrating strong thermal-insulation performance (Figs. 3(c) and 3(d)).

Despite these encouraging results, current porous insulation materials rely mainly on co-deposition with filter cakes and therefore cannot form continuous thermal barriers in sections with limited filtration. Surface functionalization of porous

microspheres could overcome this limitation by promoting direct adsorption onto wellbore walls through electrostatic or zwitterionic interactions. For example, porous microspheres coated with a zwitterionic polymer have been developed, which formed stable insulating layers, reduced filter-cake thermal conductivity, and enhanced rock-particle adhesion in water-based drilling fluids (Wang et al., 2025b). Surface modification also affects drilling-fluid rheology, i.e., unmodified negatively charged microspheres can weaken clay-particle networks through electrostatic repulsion, whereas positively charged polymer-modified microspheres can promote clay adsorption. However, their mechanical durability, thermal and chemical stability, and resistance to pore plugging under HPHT conditions remain insufficiently understood.

Future research should therefore focus on multifunctional surface engineering to simultaneously enhance mechanical strength, thermal insulation, and interfacial adhesion. Polymer coatings or grafting can repair shell defects and improve pressure resistance, while controlled surface structures may increase interfacial porosity and anchoring sites (Liu et al., 2024). Zwitterionic or other functional groups could further promote electrostatic and hydrogen-bonding interactions with wellbore rock. Such integrated modification may enable durable thermal-insulation layers independent of filter-cake formation. In addition, pore preservation must be addressed because colmatation by fine solids can progressively block the internal pore network and degrade insulation performance under practical drilling conditions.

3.3 Thermal-conductivity enhancers

In contrast to the latent-heat storage of MPCMs and the thermal-barrier effect of porous microspheres, thermal-conductivity enhancers promote heat dissipation by increasing the effective thermal conductivity of drilling fluids, thereby facilitating heat transport from the bottomhole region toward the wellhead. Conventional water-based and oil-based drilling fluids typically have relatively low thermal conductivities of approximately 0.5-0.7 W/m·K and 0.15-0.25 W/m·K, respectively. Elevated temperatures can further alter these properties through changes in molecular interactions, colloidal structure, and additive stability, particularly through hydrogen-bond disruption, clay aggregation, and thermal or oxidative degradation (William et al., 2014; Aftab et al., 2017). Incorporating highly conductive nanomaterials therefore offers a promising approach to enhance heat transport and wellbore cooling.

In recent years, zero-, one-, and two-dimensional nanomaterials have been widely investigated for this purpose. Their enhancement mechanisms involve both conductive and convective heat transfer. Highly conductive nanomaterials provide additional heat-transfer pathways and reduce the effective transport distance within the low-conductivity base fluid, while interfacial interactions can modify solid-liquid thermal resistance (Yan et al., 2026). Especially, one- and two-dimensional nanomaterials can form interconnected thermal-conduction networks at appropriate concentrations and dispersion states (Zhu et al., 2019). Meanwhile, Brownian motion, shear-induced orientation, and thermophoretic migration can modify microscale fluid motion and thermal boundary layers, further affecting heat transfer (Suganthi and Rajan, 2017).

However, enhancement performance is highly sensitive to downhole conditions. Shear can disrupt particle networks while improving dispersion and altering the orientation of anisotropic nanomaterials (Liang, 2007). Pressure may affect interparticle contact and interfacial thermal resistance, while polymers, bentonite, and other additives can modify nanoparticle interactions, dispersion, and suspension stability. Therefore, optimizing thermal-conductivity enhancers requires simultaneous consideration of temperature, pressure, shear rate, nanomaterial morphology and concentration, dispersion stability, and chemical compatibility to achieve stable heat-transfer enhancement under deep and ultra-deep drilling conditions.

3.4 Remaining challenges and future perspectives

Overall, these three classes of cooling materials regulate downhole heat transfer through distinct but complementary mechanisms. MPCMs absorb excess heat through latent-heat storage, porous microspheres suppress geothermal heat influx through thermal insulation, and thermal-conductivity enhancers accelerate heat transport toward the wellhead. Together, they offer a promising approach to maintaining drilling-fluid performance and protecting downhole tools under extreme thermal conditions. However, field-scale applications remain unreported. MPCMs are mainly limited by insufficient latent-heat density and high cost, whereas porous microspheres face challenges in mechanical strength, thermal conductivity, and interfacial adhesion. Thermal-conductivity enhancers must also maintain stable dispersion and compatibility with drilling-fluid components under high temperature, pressure, and shear conditions.

Future development should adopt a demand-driven strategy guided by wellbore thermal modelling and cooling-system requirements. Thermal models can define material targets for phase-change temperature, latent-heat density, thermal conductivity, response rate, and mechanical durability, while cooling systems determine injection, circulation, residence-time, and thermal-loading conditions. Accordingly, MPCMs should feature high latent-heat density and tunable phase-change temperatures; porous microspheres should combine ultralow thermal conductivity, reinforced shells, and strong wellbore adhesion; and thermal-conductivity enhancers should provide high conductivity, stable dispersion, and physicochemical compatibility without compromising rheology, suspension stability, or filtration. Ultimately, integrating these materials with thermal modelling, cooling technologies, and real-time temperature monitoring could establish a coupled "latent-heat absorption-wellbore insulation-thermal dissipation" system (Fig. 3(e)) for more efficient deep- and ultra-deep-well thermal management.

4. Wellbore cooling equipment

Wellbore cooling equipment constitutes the macroscopic thermal-control component of an integrated wellbore thermal-

management system. Through surface cooling, thermal insulation, and localized refrigeration, these technologies mitigate excessive heat accumulation, protect temperature-sensitive drilling fluids and downhole tools, and improve operational safety and drilling efficiency (Zhang et al., 2026). Wellbore cooling equipment can generally be classified into two categories according to its thermal-management function. The first category provides whole-wellbore thermal regulation by reducing the inlet temperature of the drilling fluid and/or suppressing its temperature rise during circulation. Representative technologies include surface drilling-fluid cooling systems and low-thermal-conductivity drill pipe and casing. The second category focuses on localized thermal protection of temperature-sensitive downhole components and primarily includes downhole thermal-insulation chambers and active refrigeration systems.

4.1 Surface drilling-fluid cooling systems

Surface drilling-fluid cooling systems typically employ plate or shell-and-tube heat exchangers, using spray water, air, or circulating seawater as secondary cooling media to remove heat from high-temperature drilling fluids. As one of the most mature thermal-management technologies currently available, surface cooling remains attractive because of its relatively low cost, operational simplicity, and high heat-transfer efficiency. Its engineering maturity is reflected by the availability of commercial systems from established suppliers such as National Oilwell Varco and Drill Cool Systems.

For example, the Freshwater Geo-Cooler developed by Drill Cool is marketed as a mud-cooling system for HPHT and geothermal drilling applications (Fig. 4(a)), with a nominal mud-handling capacity of approximately 50.5 L/s (Cool, 2026). Similarly, National Oilwell Varco offers the TUNDRA MAX Onshore Mud Chiller and TUNDRA Offshore Mud Cooler. The latter is designed for drilling-fluid flow rates of up to 56.78 L/s, inlet temperatures of up to 85 °C, and outlet temperatures as low as 22.17 °C under specified operating conditions (NOV, 2026). These commercial systems demonstrate the technological maturity and practical feasibility of surface drilling-fluid cooling.

However, such engineering maturity should not be interpreted as evidence of universal downhole effectiveness. Both theoretical analyses and field experience indicate that the bottomhole cooling benefit obtained solely through inlet-temperature reduction decreases substantially with increasing true vertical depth (Guenot and Maury, 1995; Li et al., 2026a). During circulation, the cooled drilling fluid is progressively reheated by viscous dissipation and continuous geothermal heat transfer from the surrounding formation. The deeper the well, the greater the cumulative thermal load imposed on the circulating fluid, thereby diminishing the fraction of the initial surface-cooling benefit that remains at the bottom hole. Consequently, surface cooling is more appropriately regarded as an efficient and economically attractive front-end thermal-conditioning strategy rather than a stand-alone solution for thermal management in ultra-deep wells. Its effectiveness can be further enhanced when integrated with downhole insulation, thermal-storage materials, or localized cooling technologies.

4.2 Low thermal conductivity drill pipe

Low-thermal-conductivity drill pipe is a specialized drill string component designed to suppress radial heat transfer between the circulating drilling fluid and the surrounding formation (Wang et al., 2021; Zhang et al., 2025d). Its typical architecture consists of an inner tube, an outer tube, and an intermediate thermal-insulation layer containing low-thermal-conductivity materials such as aerogels, ceramic fibers, or hollow microspheres. This multilayer structure can substantially reduce the effective thermal conductivity of the drill pipe compared with conventional steel drill pipe (Ali et al., 2026).

During drilling, heat is continuously transferred from the high-temperature formation toward the wellbore and circulating drilling fluid. The insulation layer within the drill pipe introduces an additional radial thermal resistance and thereby reduces heat transfer between the drilling fluid and the surrounding formation (Xi et al., 2026). As a result, the drilling fluid retains a lower temperature for a longer period during circulation and can deliver a greater thermal margin to the bottom hole, ultimately reducing the bottomhole circulating temperature (Li et al., 2023; Xiao et al., 2024). Unlike surface cooling, which primarily modifies the initial thermal condition of the circulating fluid, thermally insulating drill pipe directly modifies the heat-transfer pathway along the wellbore and therefore offers a passive means of maintaining the cooling benefit during circulation.

The potential of low-thermal-conductivity drill pipe has been demonstrated through theoretical modelling, laboratory experiments, and field-scale testing (Xiao et al., 2022). For example, the insulated drill pipe developed by Eavor has an equivalent thermal conductivity of approximately 1.30 W/m·K, and field trials have reported a maximum bottomhole temperature reduction of approximately 42 °C, demonstrating considerable engineering potential (Figs. 4(b) and 4(c)) (Vetsak et al., 2024). Similarly, Yao et al. (2025) developed a wellbore heat-transfer model for ultra-deep wells equipped with insulated drill pipe and predicted a temperature reduction of approximately 15 °C. Their results further indicated that the cooling effect became more pronounced as the insulated section was positioned closer to the bottom hole. These findings highlight the importance of both insulation performance and the spatial placement of the insulated section in determining the overall thermal benefit.

Low-thermal-conductivity drill pipe offers several practical advantages, including a relatively simple structural concept, no requirement for external power input, and continuous passive thermal regulation during drilling. These characteristics make it an attractive strategy for deep and ultra-deep wells, particularly where continuous downhole power or active refrigeration is difficult to implement. However, several technical challenges currently limit its large-scale deployment. First, the utilization of high-performance insulation materials and multilayer composite structures substantially increases manufacturing costs compared with conventional drill pipe. Second, the extreme downhole environment, characterized by high tem-

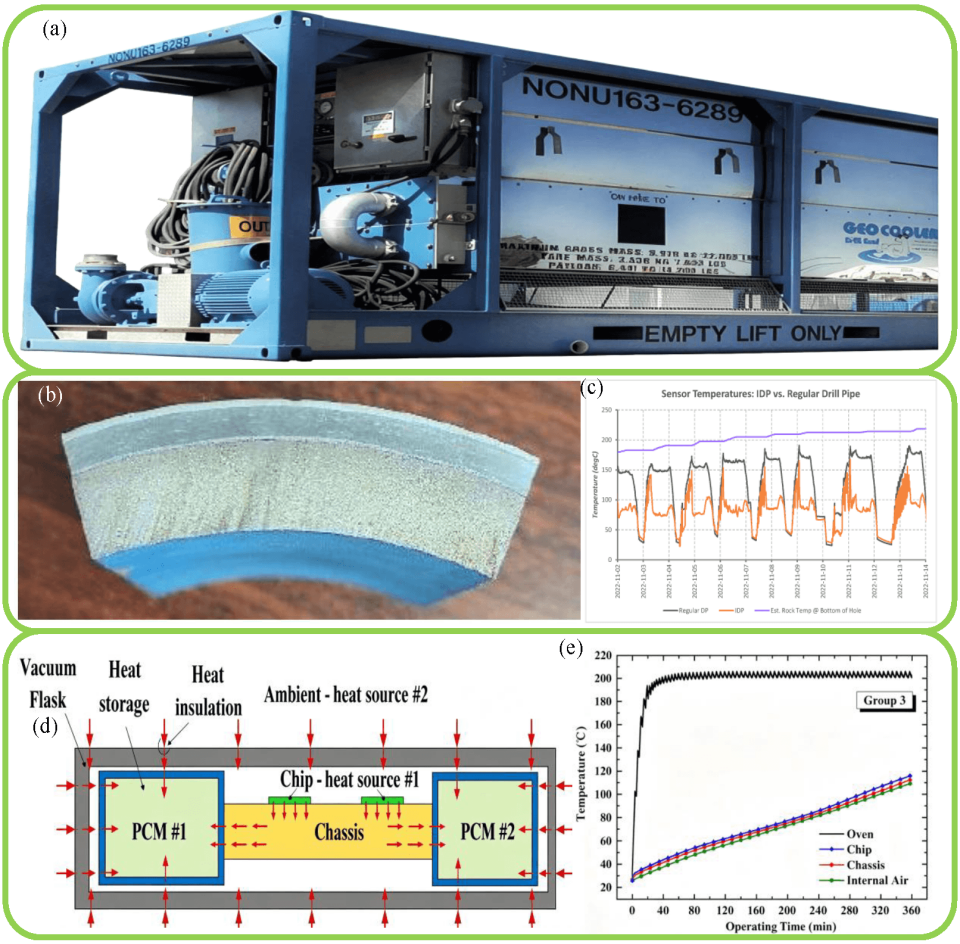


Fig. 4. Wellbore cooling equipment: (a) Drill Cool's Freshwater Geo-Cooler (Cool, 2026), (b) Photograph of a drill pipe with thermal insulation coating (Vetsak et al., 2024), (c) Comparison of thermal insulation performance between insulating drill pipe and conventional drill pipe (Vetsak et al., 2024), (d) Downhole cooling tool combining a vacuum-insulated flask with PCMs (Ma et al., 2016) and (e) Cooling performance of the vacuum flask-PCM system over 6 h (Ma et al., 2016).

perature, high pressure, cyclic mechanical loading, vibration, and abrasive erosion, may progressively degrade the insulation layer and cause cracking, compression, or delamination, thereby reducing its long-term thermal performance. Third, maintaining thermal-insulation continuity across tool joints and other drill string connections remains challenging. These discontinuities can create localized low-resistance heat-transfer pathways, commonly referred to as thermal bridges, which may significantly reduce the effective insulation performance of the entire drill string (Li et al., 2026a). In addition, the mechanical, hydraulic, and thermal compatibility of insulation materials with conventional drill string components must be maintained throughout repeated tripping and drilling cycles.

Therefore, future development of low-thermal-conductivity drill pipe should move beyond simply minimizing the intrinsic thermal conductivity of the insulation material. A more comprehensive design should simultaneously consider thermal resistance, mechanical strength, thermal-bridge suppression, connection design, pressure resistance, manufacturing cost, and long-term durability. In particular, optimized placement of insulated sections based on transient wellbore temperature modelling may provide a more cost-effective strategy than insulating the entire drill string. Coupling spatially optimized insulation with surface drilling-fluid cooling and other downhole thermal-management technologies could further improve the overall cooling efficiency while reducing material requirements and system cost.

4.3 Downhole cooling chambers

Downhole cooling chambers provide localized thermal protection for temperature-sensitive tools through passive insulation, active refrigeration, or a combination of both. They can be broadly classified into passive thermal-insulation chambers and active cooling devices (Wei et al., 2022). Passive systems typically combine vacuum insulation with phase-change heat storage, offering simple and reliable operation without external power, whereas active systems employ refrigeration to provide stronger and more controllable cooling at the cost of greater complexity, power consumption, and heat-rejection requirements (Peng et al., 2023a; Tang et al., 2023; Kang et al., 2025).

Passive thermal-insulation chambers generally consist of inner and outer metallic shells separated by an evacuated

annulus, with a PCM inside and an insulating plug at the opening to reduce thermal bridging (Shang et al., 2017; He et al., 2022). The vacuum suppresses conductive and convective heat transfer, while the PCM absorbs heat through phase transition, maintaining the internal temperature below the tolerance of sensitive electronics. Ma et al. (2016) developed such a system for logging tools at 200 °C and maintained the component temperature below 120 °C for 6 h under a 30 W internal heat load (Figs. 4(d) and 4(e)). However, protection duration is fundamentally limited by the finite PCM heat-storage capacity and gradual insulation degradation. Complete PCM melting reduces further latent-heat absorption, while vacuum degradation and thermal bridging increase heat leakage. These effects generally limit protection at approximately 200 °C to about 6-9 h under reported conditions.

Active cooling devices use externally powered mechanical or thermoelectric refrigeration to maintain a localized low-temperature environment (Wei et al., 2022; Peng et al., 2023a, 2023b; Deng et al., 2025a). They include thermoelectric, Stirling-cycle, and vapor-compression systems (Table S4). Thermoelectric systems are compact and reliable but generally less energy-efficient. Stirling systems offer a favorable balance of compactness and cooling efficiency, and vapor-compression systems provide higher cooling capacity but require more complex mechanical and auxiliary components (Gao et al., 2021; Tang et al., 2023). Regardless of configuration, active systems require continuous energy input and effective heat rejection. For example, a reverse Stirling system provided 2.26 W of cooling at 225 °C while maintaining an instrument compartment near 100 °C (Li et al., 2025a). Battery-powered refrigeration, however, competes with sensing, telemetry, and control for limited downhole power. Hydraulic-energy-driven systems, such as turbine-driven Stirling refrigeration, can reduce the electrical burden but introduce additional pressure losses, conversion inefficiencies, vibration, and mechanical complexity (Gao et al., 2021; Liu et al., 2025c). Thus, refrigeration capacity must be balanced against power consumption, tool endurance, heat rejection, and reliability. Current active systems are therefore more suitable for localized protection of electronics and sensors than for cooling large downhole assemblies such as mud motors.

4.4 Remaining challenges and future perspectives

Overall, existing wellbore cooling technologies have distinct application boundaries. Surface cooling is mature and economical but becomes less effective with depth as the circulating fluid is progressively reheated. Low-thermal-conductivity drill pipe provides continuous passive thermal regulation but is limited by cost, thermal bridging, durability, and service life. Passive downhole insulation chambers effectively protect sensitive electronics but have finite thermal-storage capacity, whereas active refrigeration provides stronger local cooling at the expense of power, space, heat rejection, and system complexity. Thus, no single technology can currently provide comprehensive thermal control across the entire wellbore.

Future temperature control should therefore rely on the coordinated deployment of complementary technologies in conjunction with the high-performance cooling materials discussed in Section 3 (Fig. 5). Such a hierarchical architecture can assign different functions to different technologies, i.e., surface systems remove bulk heat, insulated pipe suppresses heat transfer along the circulation path, cooling materials provide distributed heat absorption or insulation, and localized systems protect critical components. The objective should shift from maximizing individual cooling capacity to minimizing overall thermal exposure while satisfying hydraulic, mechanical, energy, and economic constraints. Importantly, integration does not require deploying every technology throughout the well. Model-guided functional specialization can reduce life-cycle costs by limiting high-cost technologies to thermally critical intervals or components.

5. Real-time temperature measurement and updating

Real-time downhole temperature measurement and dynamic thermal-model updating constitute the information-centric core of an integrated wellbore thermal-management system. While cooling equipment provides macroscopic thermal regulation, the ability to continuously monitor the evolving thermal environment and assimilate observations into predictive models determines the system's intelligence, responsiveness, and robustness. This section first reviews sensing technologies that enable high-fidelity downhole temperature monitoring and then discusses data-assimilation and machine-learning frameworks that transform sparse and noisy measurements into accurate, physics-consistent temperature fields (He et al., 2025). Finally, it outlines a pathway toward integrating real-time temperature updating with cooling-material performance data to achieve adaptive thermal control.

5.1 Fiber Bragg grating sensing for downhole temperature measurement

Among the technologies available for permanent downhole thermal monitoring, Fiber Bragg grating (FBG) sensing has emerged as a promising solution for high-temperature/high-pressure deep-well environments. Its advantages arise primarily from its passive optical architecture: FBG sensors contain no electrical components at the sensing location, are intrinsically immune to electromagnetic interference, and can multiplex multiple sensing points along a single optical fiber to provide quasi-distributed temperature profiles (Yang et al., 2019; Ji et al., 2022; Liu et al., 2022; Liang et al., 2025). These characteristics render FBG arrays attractive for the harsh environments encountered in deep and ultra-deep wells, where conventional electronic sensors may suffer from thermal drift, insulation degradation, or electromagnetic interference associated with drilling and logging operations.

The operating principle of FBG thermometry is based on the temperature-dependent shift of the Bragg wavelength. An FBG consists of a periodic modulation of the refractive index within the core of an optical fiber. Changes in temperature alter the effective refractive index and grating period, resulting

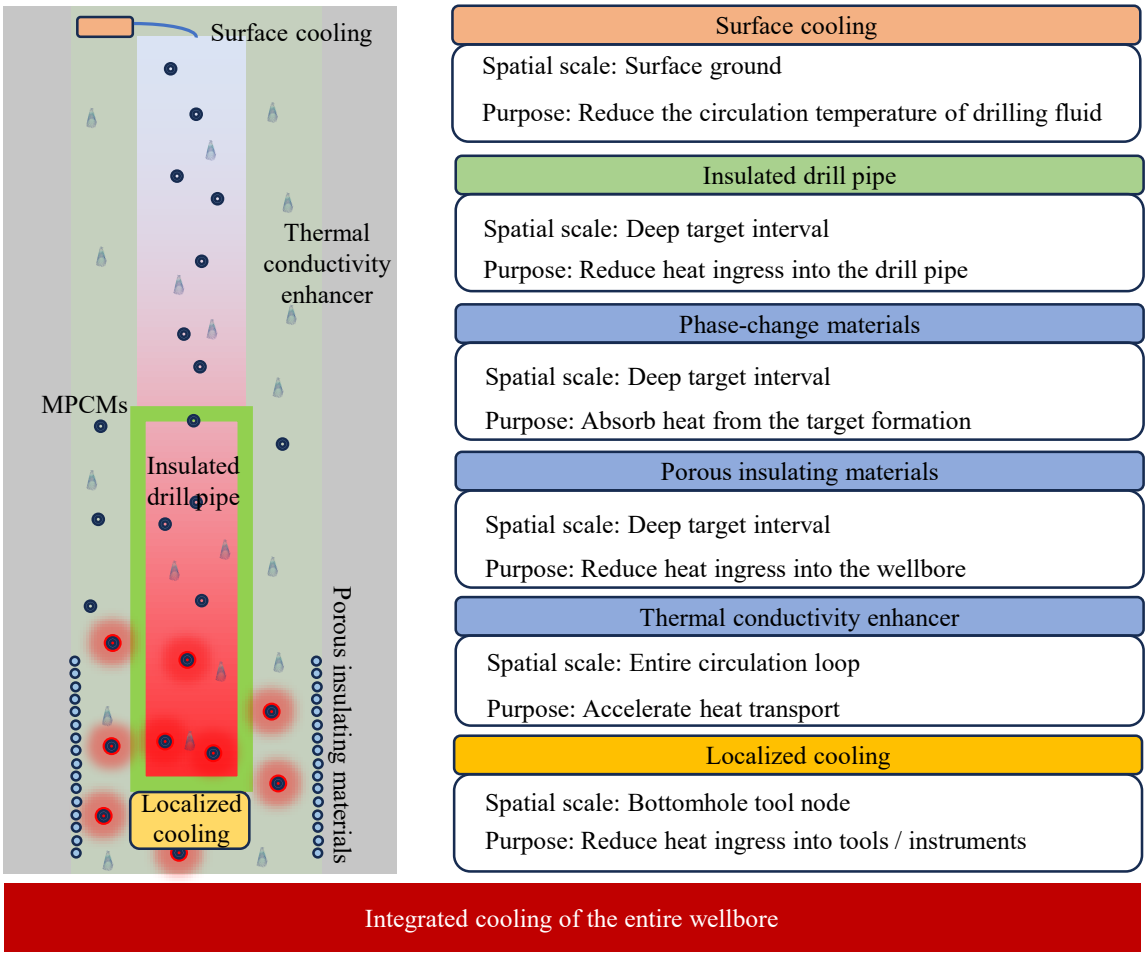


Fig. 5. Schematic diagram of entire wellbore integrated cooling.

in a measurable shift in the reflected Bragg wavelength. By tailoring the fiber composition or introducing sensitivity-enhancing coatings and packaging structures, the temperature responsivity of FBG sensors can be substantially increased. Liang et al. (2025) demonstrated a side-hole FBG configuration with polyurethane-based sensitivity-enhancing packaging that increased the temperature sensitivity from 11.23 to 34.63 pm/°C. Over the temperature range of 0-100 °C, the system exhibited a linearity exceeding 0.996, a repeatability error below 2%, and a maximum absolute error of only 0.414 °C. These results demonstrate the potential of FBG-based sensing to achieve high temperature-measurement accuracy under conditions representative of shallow-to-intermediate well sections.

Serial integration of multiple FBG sensors along a single optical fiber enables quasi-distributed temperature profiling, with each grating serving as an independent sensing node within a designated wavelength band (Hou et al., 2014). The spatial resolution is primarily determined by the sensor spacing and can be tailored to capture thermal gradients near critical downhole components, such as drill-bit assemblies, mud motors, and logging-while-drilling electronics. In a closed-loop thermal-management system, such spatially resolved temperature measurements can provide the primary observational input for updating the thermal model, reducing reliance on a limited number of discrete thermocouple measurements. The combination of high measurement accuracy (±0.1 °C), distributed sensing capability, and compatibility with harsh downhole environments makes FBG technology a promising front-end sensing technology for intelligent wellbore thermal management. Despite these advantages, FBG thermometry has an important limitation: Cross-sensitivity, whereby the Bragg wavelength shift depends on both temperature changes and mechanical strain. Consequently, downhole pressure fluctuations, vibration, and fiber bending can introduce strain-induced wavelength shifts, potentially leading to temperature measurement errors. In addition, the long-term stability and reliability of the fiber and grating under elevated-temperature conditions require careful consideration (Liu et al., 2025d; Hu et al., 2026).

5.2 Data assimilation for transient wellbore temperature prediction

Despite advances in distributed temperature sensing, accurately predicting transient wellbore temperature fields remains challenging (Ekechukwu and Sharma, 2023). Downhole heat transfer is governed by coupled partial differential equations describing forced convection within the drill string and annulus, conductive heat transfer between the wellbore and

surrounding formation, and internal heat generation associated with frictional and hydraulic dissipation (Wang et al., 2024a). Solving these coupled equations across the full depth of an ultra-deep well in real time can be computationally demanding. Consequently, practical engineering models often introduce simplifications, such as quasi-steady formation heat transfer, averaged fluid properties, and reduced-order representations of radial temperature distributions.

These simplifications can introduce structural model errors that become particularly significant under transient operating conditions. During tripping, circulation startup, shutdown, or drilling-fluid property changes, the thermal inertia of the formation, heat-storage capacity of the casing and cement sheath, and latent-heat effects associated with multiphase flow can generate thermal lags that simplified models may fail to capture (Wu et al., 2025b; Zhang et al., 2025c). Furthermore, the insulating effect of low-thermal-conductivity drill pipe, multiple casing strings with different thermal properties, and spatial variations in the geothermal gradient contribute to a complex thermal environment that cannot be characterized reliably through laboratory measurements or offset-well data alone (Abdelhafiz et al., 2023).

In this context, real-time temperature measurements are valuable not merely for monitoring but also for continuously correcting the predicted thermal trajectory. Data assimilation refers to a class of mathematical methods that optimally combine model predictions with real-time observations to generate improved estimates of the system state and associated uncertainty. In wellbore thermal management, the state vector may include temperature distributions along the wellbore, formation temperatures, effective convective heat-transfer coefficients, and, where identifiable, parameters associated with cooling equipment. By assimilating sparse and noise-contaminated FBG measurements into a dynamic heat-transfer model, the evolving temperature field can be continuously updated, allowing the model to capture transient behavior that cannot be anticipated through offline calibration alone.

The principal challenges for data assimilation in this context are measurement sparsity, sensor noise, parameter uncertainty, and structural model inadequacy. An FBG array may provide only 10-30 measurement points along several thousand meters of wellbore, leaving substantial portions of the thermal field unobserved (Bassam et al., 2010). In addition, key thermophysical and heat-transfer parameters, including formation thermal conductivity, drilling-fluid heat capacity, and effective convective heat-transfer coefficients, are often only approximately known and may vary with temperature, pressure, fluid composition, and flow regime. Consequently, an effective data-assimilation framework must do more than interpolate measured temperatures. It should infer unobserved thermal states, quantify uncertainty, and, where sufficient observations exist, identify uncertain parameters or compensate for systematic model bias. This capability is essential for transforming distributed temperature measurements into reliable, real-time thermal-state estimates that can support subsequent cooling-control decisions.

5.3 Kalman filter-based strategies for real-time temperature updating

Sequential Bayesian filtering provides a natural framework for recursive state estimation in wellbore thermal models. Among the available algorithms, the unscented Kalman filter (UKF) and ensemble Kalman filter are particularly attractive because they can accommodate nonlinear thermal processes without requiring explicit linearization of the governing model equations (Naderi et al., 2024).

The UKF propagates a deterministic set of sigma points through the nonlinear thermal model to approximate the mean and covariance of the predicted state, generally providing a more accurate representation of nonlinear state transformations than the first-order Taylor expansion used in the extended Kalman filter (Chen et al., 2025a). At each time step, when a new FBG temperature measurement becomes available, the predicted state is updated through the Kalman gain, which weights the discrepancy between predicted and observed temperatures according to their respective uncertainties (Fig. 6). Wang et al. (2026a) developed a UKF-based framework in which a reduced-order finite-difference heat-transfer model was augmented with a depth-dependent bias state. This bias state was introduced to represent the cumulative effects of structural model errors, including unmodeled thermal-insulation effects and transient formation heat flux. By continuously estimating and correcting the bias using real-time temperature observations, the framework reduced the root-mean-square error of the predicted temperature profile by more than 90% compared with conventional parameter-tuning approaches without online data assimilation.

A complementary strategy has been to use the UKF to dynamically estimate the convective heat-transfer coefficient in the annulus (Götte and Timmermann, 2023; Chekhonin et al., 2025). This coefficient is difficult to prescribe accurately because it depends on flow regime, drilling-fluid rheology, pipe eccentricity, and other operating conditions that can evolve during drilling. By treating the convective heat-transfer coefficient as a slowly varying augmented state, the UKF can estimate its effective transient evolution from a limited number of downhole temperature measurements. When evaluated against field data from an ultra-deep well, one such approach achieved a bottomhole mean relative error of approximately 0.21%, demonstrating the potential for accurate temperature prediction even when key model parameters are initially uncertain.

The ensemble Kalman filter provides an alternative that is particularly attractive for complex or legacy thermal simulators because it does not require explicit access to model Jacobian matrices. Instead, an ensemble of model states is propagated simultaneously, and the forecast covariance is estimated directly from the ensemble statistics (Bassam et al., 2010). This ensemble-based approach is well suited to high-dimensional state vectors containing spatially distributed temperatures and uncertain parameters. However, its performance depends strongly on ensemble size, covariance estimation, and the treatment of sampling error and localization. Increasing the ensemble size improves statistical represen-

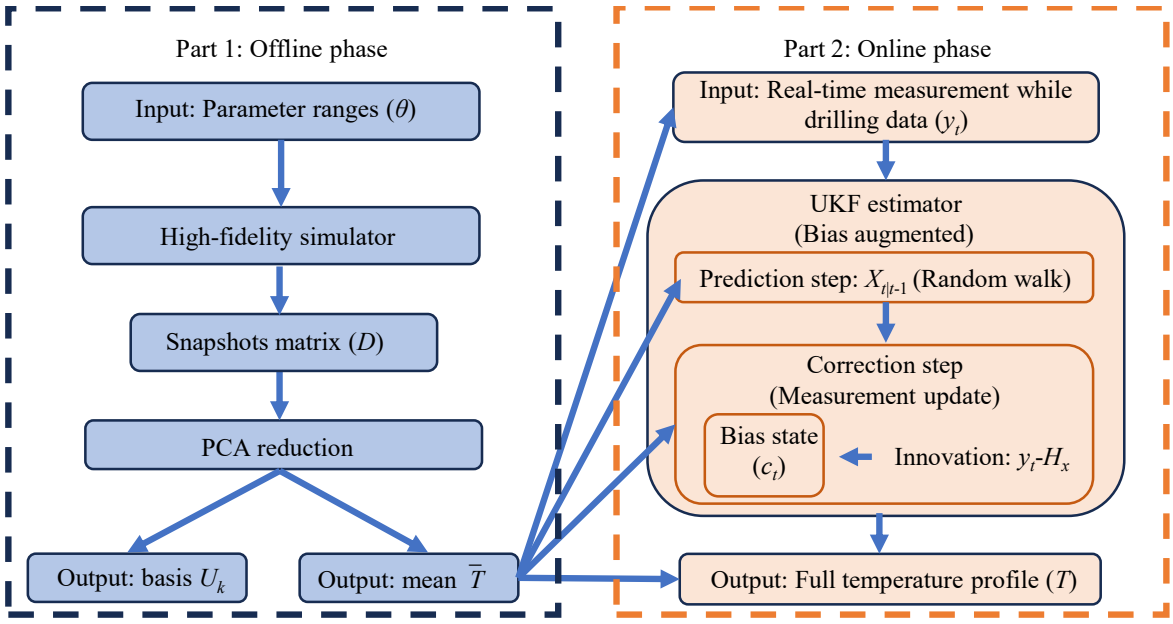


Fig. 6. Overview of the proposed real-time wellbore temperature updating framework.

tation but also increases computational cost. For deep-well applications requiring updates on a minute-by-minute basis, the trade-off between ensemble size, numerical stability, and prediction latency must therefore be carefully managed.

The demonstrated performance of Kalman-filter-based updating indicates that sparse and noisy temperature observations can substantially improve the accuracy of dynamic wellbore thermal-state estimation (Abdollahi and Dubljevic, 2013). In principle, this capability enables the development of a continuously updated digital thermal twin that tracks the evolving thermal state of the wellbore. However, the achievable accuracy depends on sensor coverage, observation uncertainty, model adequacy, parameter identifiability, and filter tuning (Duan et al., 2025). Reliable thermal-state estimation is therefore a necessary, but not sufficient, condition for closed-loop control. Before model predictions are applied to adjust surface cooling capacity, circulation rate, or other operational variables, the updated model must also satisfy computational, hydraulic, mechanical, and safety constraints.

5.4 Physics-informed machine learning for temperature field inversion and prediction

Alongside traditional data-assimilation methods, physics-informed machine learning has emerged as a complementary approach for wellbore thermal analysis. Physics-informed neural networks (PINNs) incorporate governing partial differential equations into the neural-network loss function, thereby constraining the predicted solution to remain consistent with the underlying physical laws while simultaneously fitting available observations (Sharma et al., 2023). For wellbore temperature problems, observational data may include sparse FBG measurements, known boundary conditions such as inlet temperature and geothermal conditions, and operational data such as drilling-fluid flow rate and circulation history.

Xie et al. (2025) applied a PINN framework to transient wellbore heat-transfer equations and employed it to infer the initial temperature distribution along the wellbore from a limited number of temperature observations. Once trained, the network could also accelerate forward thermal predictions under different operational conditions, providing substantially faster evaluations than conventional numerical solvers. This computational efficiency makes PINNs attractive for real-time scenario analysis, optimization, and decision support, particularly when repeated predictions are required within a thermal-control framework.

A major advantage of PINNs over purely data-driven machine-learning models is their incorporation of physical constraints, which can improve generalization and reduce dependence on large labeled datasets. Nevertheless, physical constraints do not guarantee reliable extrapolation beyond the training or parameter domain. PINNs also face several practical challenges. Training can be computationally intensive, particularly for problems involving sharp thermal gradients, strong nonlinearities, or multiple spatial and temporal scales. Model performance can also be sensitive to network architecture, loss-function weighting, collocation-point distribution, and optimization strategy. In addition, substantial changes in operating conditions, for example, switching from water-based mud to oil-based mud, can alter the governing thermophysical properties and constitutive relations. In such cases, the partial differential equation constraints, boundary conditions, or model parameters may need to be updated, potentially requiring retraining or transfer learning. To mitigate these risks in engineering practice, a practical generalization and validation workflow (Fig. S1) is recommended before a PINN model is applied to decision-making. The workflow begins by explicitly defining the training and application parameter domains, that is, identifying the applicable range of the model in terms of key wellbore parameters, including well geom-

etry, formation thermal properties, drilling-fluid conditions, and operational parameters. The model's predictive robustness should then be evaluated under diverse operating conditions through systematic parameter perturbations and additional test cases located both within and beyond the original training parameter space. In addition to statistical error metrics, physics-based consistency verification is necessary. Specifically, the predicted temperature fields should be assessed against governing-equation residuals, energy conservation, and boundary-condition consistency (Sharma et al., 2023). Model predictions should then be validated hierarchically against analytical solutions, high-fidelity numerical simulations, and available field measurements. Finally, the validated parameter range and remaining extrapolation limitations should be explicitly documented, and model updating with additional data should be performed whenever new operating conditions substantially exceed the original training domain.

Therefore, PINNs should not be regarded as a wholesale replacement for numerical simulators or sequential data-assimilation methods. Rather, they are better viewed as a complementary computational tool for tasks such as temperature-field inversion, parameter identification, surrogate modelling, and rapid scenario screening. A particularly promising architecture is a hybrid physics-data framework in which a mechanistic wellbore thermal model provides physical constraints, FBG measurements provide real-time observations, Kalman-filter-based assimilation updates the thermal state, and machine-learning surrogates accelerate repeated predictions and optimization. Such integration could provide the computational speed, physical consistency, and adaptability required for real-time closed-loop thermal management of deep and ultra-deep wells.

5.5 Remaining challenges and future perspectives

Real-time data assimilation can substantially improve wellbore temperature prediction. Kalman-filter methods have achieved over 90% reductions in root-mean-square error relative to open-loop models, while PINNs can reconstruct physically constrained temperature fields from sparse measurements. In validated cases, bottomhole temperature errors have been reduced to a few degrees or even fractions of a degree Celsius. However, performance depends strongly on sensor quality, model formulation, calibration, and validation data and should not be considered universally achievable.

Several challenges remain. Kalman filters may be inadequate under strongly nonlinear and nonstationary conditions because of their approximate Gaussian-error assumptions, while more general particle-filter or Bayesian approaches are computationally demanding. Real-time applications therefore require reduced-order or surrogate models that balance physical fidelity with update speed, together with uncertainty quantification to support reliable decisions.

The greatest opportunity lies in integrating sensing and data assimilation with cooling materials and equipment. FBG networks can monitor downhole temperature, while data assimilation provides an updated temperature field and uncertainty for evaluating cooling performance and detecting insulation degradation, thermal bridging, or changing heat-transfer conditions. Incorporating PCM heat absorption, insulation resistance, and refrigeration capacity and power consumption could further enable coordinated optimization of circulation rate, surface cooling, material concentration, and active cooling power.

Ultimately, low-latency telemetry, efficient assimilation algorithms, standardized data interfaces, and fault-tolerant operation are required to realize a closed-loop system. Integrating FBG sensing, Kalman filtering, and physics-informed machine learning with cooling technologies could transform wellbore temperature control from a pre-planned open-loop operation into an adaptive system that continuously senses, predicts, evaluates, and regulates downhole thermal conditions.

6. Conclusions and future directions

Wellbore cooling in deep and ultra-deep drilling is transitioning from passive temperature prediction toward active thermal regulation and intelligent control. This review summarizes advances in wellbore temperature modelling, functional thermal-management materials, cooling technologies and equipment, and real-time sensing and model updating, highlighting the shift from isolated cooling technologies toward integrated thermal management. The most promising direction is to develop a closed-loop system integrating predictive modelling, functional materials, cooling equipment, real-time sensing, and adaptive data assimilation. Given the different maturity levels of these technologies, future research should proceed through near-, medium-, and long-term priorities.

Near-term priorities (1-3 years) should focus on standardization, performance benchmarking, and field validation of existing cooling materials and technologies. Key objectives include establishing standardized testing protocols for MPCMs, porous microspheres, and thermal-conductivity enhancers; developing benchmark databases that link material properties with wellbore-temperature-control performance; quantifying thermal cycling stability, compatibility with drilling fluids, and cost-effectiveness; and validating the combined application of surface cooling and wellbore cooling materials under realistic operating conditions. The major bottlenecks are the absence of unified evaluation standards, insufficient long-term stability and economic data, and limited full-scale field validation. Expected outcomes include standardized evaluation protocols, open benchmark datasets, and field-validated cooling strategies with clearly defined performance and reliability metrics.

Medium-term priorities (3-5 years) should shift toward multimodal system integration and closed-loop thermal management. Research should focus on developing low-cost, high-performance cooling materials with improved thermal stability and compatibility with drilling fluids; integrating complementary cooling technologies with fiber-optic temperature sensing, real-time data assimilation, and predictive thermal models; and demonstrating pilot-scale closed-loop thermal-management systems in deep and ultra-deep wells. Key challenges include balancing cooling performance with material and operational costs, meeting power and heat-rejection

requirements, and maintaining reliable temperature sensing under high-temperature conditions, particularly above 200 °C. Expected outcomes include field-tested closed-loop thermal-management prototypes and real-time digital thermal twins capable of temperature prediction, monitoring, and active regulation.

Long-term priorities (5-10 years) autonomous, uncertainty-aware, and self-optimizing thermal management integrated with intelligent drilling systems. Key directions include developing physics-informed machine-learning models that explicitly quantify uncertainty and generalize across diverse wells and operating conditions; enabling molecular- and microstructural-level design of next-generation cooling materials; and developing autonomous decision-making algorithms that dynamically coordinate cooling materials, engineered cooling technologies, drilling parameters, and heat-rejection capacity. Major bottlenecks will include long-term reliability of materials, sensors, and cooling equipment; the computational cost of real-time high-fidelity prediction and optimization; and the absence of widely accepted industry standards for integrated thermal management. Expected outcomes include commercially deployable intelligent thermal-management systems, standardized design and evaluation frameworks, and autonomous temperature regulation integrated into intelligent drilling operations.

Realizing this roadmap requires interdisciplinary collaboration across drilling engineering, materials science, heat transfer, sensing, artificial intelligence, and data science. It is believed that such cross-disciplinary integration will be essential for translating advances in individual cooling materials and technologies into reliable, intelligent, and field-deployable thermal-management systems, ultimately enabling safer, more efficient, and more sustainable drilling in deep and ultra-deep wells.

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Supplementary file

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Conflicts of interest

The authors declare no competing interest.

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References

Abdelhafiz, M. M., Oppelt, J., Mahmoud, O., et al. Effect of drilling and wellbore geometry parameters on wellbore temperature profile: Implications for geothermal production. Advances in Geo-Energy Research, 2023, 8(3): 170-180.

Abdollahi, J., Dubljevic, S. Transient fluid temperature estimation in wellbores. IFAC Proceedings Volumes, 2013, 46(14): 108-113.

Aftab, A., Ismail, A. R., Ibupoto, Z. H., et al. Nanoparticles based drilling muds a solution to drill elevated temperature wells: A review. Renewable and Sustainable Energy Reviews, 2017, 76: 1301-1313.

Ali, I., Khan, M. A., Ding, Y., et al. Recent advances in thermally insulated drilling pipes: Materials, design strategies, and future directions. Polymers, 2026, 18(8): 1004.

Alosail, M. S., Razak, R., Musa, K. I., et al. Novel insights into the effect of drilling fluid particle size distribution on filter cake permeability. Advances in Geo-Energy Research, 2026, 19(3): 268-284.

Bassam, A., Santoyo, E., Andaverde, J., et al. Estimation of static formation temperatures in geothermal wells by using an artificial neural network approach. Computers & Geosciences, 2010, 36(9): 1191-1199.

Beirute, R. M. A circulating and shut-in well-temperature-profile simulator. Journal of Petroleum Technology, 1991, 43(9): 1140-1146.

Cha, H. -A., Jo, M. -G., Moon, Y. K., et al. Highly porous YSZ ceramic foams using hollow spheres with holes in their shell for high-performance thermal insulation. Journal of the European Ceramic Society, 2023, 43(15): 7041-7052.

Chang, Z., Wang, K., Wu, X., et al. Review on the preparation and performance of paraffin-based phase change microcapsules for heat storage. Journal of Energy Storage, 2022, 46: 103840.

Chekhonin, E. M., Akchurin, R. Z., Ramazanov, A. S., et al. Estimation of geothermal temperature and gradient using inversion of transient wellbore temperature measurements. Applied Thermal Engineering, 2025, 263: 125309.

Cheng, C., Hu, L., Seidu, R. K., et al. Development of phase change materials directly encapsulated within gold shell microcapsules for flexible intelligent textile with energy storage and photo-thermal conversion ability. Nano Energy, 2025, 143: 111295.

Chen, W., Wang, C., Li, J., et al. Research on optimization of drilling fluid continuous wave signal for measurement-while-drilling in deepwater extended reach wells. Ocean Engineering, 2025a, 340: 122342.

Chen, X., He, M., Sun, P., et al. An integrated multi-objective optimization method for downhole cooling during deepwater high temperature and high pressure drilling. Ocean Engineering, 2025b, 334: 121253.

Chen, X., Wang, S., He, M., et al. A comprehensive prediction model of drilling wellbore temperature variation mechanism under deepwater high temperature and high

pressure. Ocean Engineering, 2024a, 296: 117063.

Chen, Y., Zhang, Q., Wu, K., et al. Phase change double-shelled polyaniline microcapsules with low leakage rate, high thermal conductivity, solar-thermal conversion properties for thermal energy harvesting and anti-corrosive coatings. Journal of Energy Storage, 2024b, 100: 113480.

Chen, Z., Yue, W., Xiong, C., et al. Phase change material microcapsules used for cooling of ultra-deep oil/gas and geothermal drilling fluids. Petroleum, 2025c, 11(4): 465-474.

Cool, D. The geo-cooler mud cooling system, 2026.

Dang, Z., Chen, X., Yao, X., et al. Transient prediction model of wellbore temperature in ultra-deep wells considering cementing quality. Applied Sciences, 2025, 15(22): 12029.

Deng, C., Wei, F., Peng, J., et al. Numerical and experimental study of an integrated thermoelectric active cooling system for ultra-high temperature downhole electronics. Applied Thermal Engineering, 2025a, 271: 126341.

Deng, P., Liu, X., Zhang, T., et al. Konjac glucomannan-based foams incorporating cellulose phase change microcapsules for efficient thermal energy regulation. Carbohydrate Polymers, 2025b, 352: 123191.

Ding, Y., Liu, C., Xu, G., et al. Biomass-based porous materials for thermal insulation. Materials Science and Engineering: R: Reports, 2026, 168: 101138.

Ding, Y., Yang, L., Yang, M., et al. Electrospinning of SiO_2-based composites embedded TiO_2 nanoparticles with ultra-strong suppression of radiative heat transfer. Journal of Alloys and Compounds, 2023a, 957: 170331.

Ding, Y., Yang, L., Yang, M., et al. Optimization of ultralight SiO_2/TiO_2 nanofibrous aerogel for high-temperature application. Ceramics International, 2023b, 49(23, Part A): 38058-38069.

Dong, W., Shen, R., Liang, Q. Model calculations and factors affecting wellbore temperatures during SRV fracturing. Arabian Journal for Science and Engineering, 2018, 43(11): 6475-6480.

Dong, X., Zhou, J., Li, C., et al. Highly thermally conductive and light-responsive phase-change cellulose film. Journal of Forestry Engineering, 2026, 11(4): 259-269. (in Chinese)

Duan, S., Song, X., Cui, Y., et al. Formation parameter inversion model based on unscented kalman filter during drilling kick. Geoenergy Science and Engineering, 2025, 247: 213634.

Ekechukwu, G., Sharma, J. Degradation analysis of single-mode and multimode fibers in a full-scale wellbore and its impact on DAS and DTS measurements. IEEE Sensors Journal, 2023, 23(9): 9287-9300.

Gao, W., Liu, K., Dou, X., et al. Numerical investigation on cooling effect in the circuit cabin of active cooling system of measurement-while-drilling instrument based on split-stirling refrigerator. Case Studies in Thermal Engineering, 2021, 28: 101621.

Gao, Y., Liu, H., Gui, H., et al. Solid-liquid phase change materials microcapsules: Synthesis strategies, thermal storage and beyond. Progress in Natural Science: Materials International, 2024, 34(4): 615-631.

Garcia, A., Hernandez, I., Espinosa, G., et al. TEMLOPI: A thermal simulator for estimation of drilling mud and formation temperatures during drilling of geothermal wells. Computers & Geosciences, 1998a, 24(5): 465-477.

Garcia, A., Santoyo, E., Espinosa, G., et al. Estimation of temperatures in geothermal wells during circulation and shut-in in the presence of lost circulation. Transport in Porous Media, 1998b, 33(1): 103-127.

Gautam, S., Guria, C., Rajak, V. K. A state of the art review on the performance of high-pressure and high-temperature drilling fluids: Towards understanding the structure-property relationship of drilling fluid additives. Journal of Petroleum Science and Engineering, 2022, 213: 110318.

Götte, R. S., Timmermann, J. Estimating states and model uncertainties jointly by a sparsity promoting UKF. IFAC-PapersOnLine, 2023, 56(1): 85-90.

Gou, T., Xu, Z., Yuan, Z., et al. CFD-machine learning hybrid modeling for horizontal wellbore temperature prediction considering drill string eccentricity. SPE/AAPG/SEG Unconventional Resources Technology Conference, Houston, Texas, 22-24 June, 2026.

Guenot, A., Maury, V. Practical advantages of mud cooling systems for drilling. SPE Drilling & Completion, 1995, 10(1): 42-48.

Guo, P., Qiu, Z., Zhang, Y., et al. Preparation and characterization of phase change microcapsules for improving the applicable temperature and stability of high temperature resistant drilling fluids. Chemical Engineering Research and Design, 2024, 201: 389-398.

Han, L., Li, M., Zhang, X., et al. Preparation of wood-derived laser-induced graphene catalyzed by iron ion and its seawater desalination properties. Journal of Forestry Engineering, 2025, 10(3): 122-129. (in Chinese)

Hasan, A. R., Kabir, C. S. Aspects of wellbore heat transfer during two-phase flow. SPE Production & Facilities, 1994, 9(3): 211-216.

Hasan, A. R., Kabir, C. S. Wellbore heat-transfer modeling and applications. Journal of Petroleum Science and Engineering, 2012, 86-87: 127-136.

He, J., Wang, Q., Wu, J., et al. Hybrid thermal management strategy with PCM and insulation materials for pulsed-power source controller in extreme oil-well thermal environment. Applied Thermal Engineering, 2022, 214: 118864.

He, M., Sun, P., Chen, X., et al. Coupled effects of swirl flow and drill string vibration on deepwater wellbore temperature and cooling optimization. Physics of Fluids, 2025, 37(11): 113106.

Holmes, C. S., Swift, S. C. Calculation of circulating mud temperatures. Journal of Petroleum Technology, 1970, 22(6): 670-674.

Hou, Q., Jiao, W., Ren, L., et al. Experimental study of leakage detection of natural gas pipeline using FBG based strain sensor and least square support vector machine. Journal of Loss Prevention in the Process Industries, 2014, 32: 144-151.

Hou, X., Wang, Y., Du, D., et al. Multi-functional thermal infrared stealth leather based on PA@SiO_2/ZnO/SA phase change microcapsules. Journal of Energy Storage, 2024, 101: 113971.

Hu, X., Su, D., Yang, C., et al. High-stability, high-temperature and high-pressure FBG sensor with thin-wall TC4 structure for oil and gas wells. Sensors and Actuators A: Physical, 2026, 402: 117575.

Ji, J., Song, X., Xu, F., et al. Effects of variable thermophysical properties of water on the heat extraction of an enhanced geothermal system: A numerical case study. Applied Thermal Engineering, 2022, 217: 119050.

Kabir, C. S., Hasan, A. R., Kouba, G. E., et al. Determining circulating fluid temperature in drilling, workover, and well control operations. SPE Drilling & Completion, 1996, 11(2): 74-79.

Kang, I., Yoo, H., Lee, J. Productivity analysis by insulation design of well with vacuum insulated tubing in SAGD process. Geoenergy Science and Engineering, 2025, 244: 213422.

Keller, H. H., Couch, E. J., Berry, P. M. Temperature distribution in circulating mud columns. Society of Petroleum Engineers Journal, 1973, 13(1): 23-30.

Khan, M. A., Lv, K., Sun, J., et al. Enhanced filtration performance of cellulose nanofiber/bentonite water-based drilling fluids with temperature- and salt-resistant polymers for extreme conditions. SPE Journal, 2025, 30(9): 5327-5349.

Khan, N. U., May, R. A generalized mathematical model to predict transient bottomhole temperature during drilling operation. Journal of Petroleum Science and Engineering, 2016, 147: 435-450.

Li, G., Liu, K., Gao, W., et al. Cooling performance and test verification of active cooling device in ultra-high temperature environment while drilling. Acta Petrolei Sinica, 2025a, 46(10): 1960-1969. (in Chinese)

Li, M., Ding, Y., Sun, J., et al. Research progress and prospect of wellbore cooling technology. Acta Petrolei Sinica, 2025b, 46(4): 789-800. (in Chinese)

Li, W., Xie, T., Xu, K., et al. Thermal insulation performance evaluation and installation length optimization of inner coating thermal insulation drillpipe. Chemistry and Technology of Fuels and Oils, 2023, 59(5): 1003-1011.

Li, S. -Y., Huo, Y. -J., Yan, T., et al. Sugarcane derived carbon@CuS-octadecanol composite phase change materials for efficient solar thermal storage. Progress in Natural Science: Materials International, 2024, 34(4): 803-813.

Li, X., Xin, X., Xu, T., et al. Novel wellbore-reservoir coupling fluid flow model for natural gas hydrate production. Energy & Fuels, 2025c, 39(49): 23098-23112.

Li, X., Zhao, H., Mi, K., et al. A transient cooling mechanism and multi-parameter design guidance for an insulated drill-pipe in ultra-deep wells based on coupled thermal resistance and sensitivity analysis. Processes, 2026a, 14(15): 2494.

Li, Z., Zhang, B., Jiang, L., et al. Advances in numerical simulation of coupled wellbore fluid flow and heat transfer during drilling and well construction: Models, CFD, validation, and AI-assisted deployment. Processes, 2026b, 14(14): 2342.

Liang, L., Cao, Y., Jiang, K., et al. Enhanced pressure sensitivity of side-hole fiber bragg grating sensor for downhole pressure and temperature measurement. Sensors and Actuators A: Physical, 2025, 391: 116692.

Liang, X. Some effects of interface on fluid flow and heat transfer on micro- and nanoscale. Chinese Science Bulletin, 2007, 52(18): 2457-2472.

Liu, F., Zhang, Z., Liao, B., et al. Recent advances in phase change microcapsules for oilfield applications. Advances in Geo-Energy Research, 2025a, 16(3): 211-228.

Liu, H., Wang, Z., Sun, Q., et al. An improved thermal model for predicting wellbore temperature distribution in deepwater gas well. Applied Thermal Engineering, 2022, 205: 118029.

Liu, H., Xu, Q., Zhang, X., et al. Preparation of high-rate anode materials based on porous highly conductive carbon coating and SiOx disproportionation reaction. Progress in Natural Science: Materials International, 2024, 34(4): 739-746.

Liu, J., Zhu, X., Dai, J., et al. Integration of sustainable polymers with phase change materials. Progress in Materials Science, 2025b, 151: 101447.

Liu, K., Gao, W., Fan, J., et al. Design and numerical study of active cooling device for high temperature oil and gas wells based on regenerative refrigerator. Scientific Reports, 2025c, 15(1): 22832.

Liu, Z., Cheng, J., Li, J., et al. Fiber optic fabry-perot interferometer pressure sensors for oil well. Sensors, 2025d, 25(20): 6297.

Liu, Z., Wang, R., Zhang, X., et al. Memory thermochromic microcapsules based on alkyl benzoate phase change materials: Synthesis and characterization. Journal of Energy Storage, 2025e, 139: 118816.

Ma, Y., Shang, B., Hu, R., et al. Thermal management of downhole electronics cooling in oil & gas well logging at high temperature. 2016 17th International Conference on Electronic Packaging Technology (ICEPT), Wuhan, China, 16-19 August, 2016.

Mao, L., Wei, C., Jia, H., et al. Prediction model of drilling wellbore temperature considering bit heat generation and variation of mud thermophysical parameters. Energy, 2023, 284: 129341.

Molenaar, M. M., Hill, D. J., Webster, P., et al. First downhole application of distributed acoustic sensing for hydraulic-fracturing monitoring and diagnostics. SPE Drilling & Completion, 2012, 27(1): 32-38.

Naderi, S., Velmurugan, N., Nannapaneni, P., et al. An Integrated Data and Physics-based Temperature Model for Real-time Estimation of Bottomhole Temperature for Downhole Tool Failure Prevention. 49th Workshop on Geothermal Reservoir Engineering. Stanford, California, 12-14 February, 2024.

Nakamoto, R., Leggett, S. Development of a transient wellbore heat transfer model validated with distributed temperature sensing data. Sensors, 2025, 25(21): 6583.

National Oilwell Varco. Tundra offshore mud cooler, 2026.

Peng, J., Deng, C., Wei, F., et al. A hybrid thermal management system combining liquid cooling and phase change material for downhole electronics. Journal of Energy Storage, 2023a, 72: 108610.

Peng, J., Lan, W., Wei, F., et al. A numerical model coupling multiple heat transfer modes to develop a passive thermal management system for logging tool. Applied Thermal Engineering, 2023b, 223: 120011.

Ramey, H. J., Jr. Wellbore heat transmission. Journal of Petroleum Technology, 1962, 14(4): 427-435.

Raymond, L. R. Temperature distribution in a circulating drilling fluid. Journal of Petroleum Technology, 1969, 21(3): 333-341.

Shang, B., Ma, Y., Hu, R., et al. Passive thermal management system for downhole electronics in harsh thermal environments. Applied Thermal Engineering, 2017, 118: 593-599.

Sharma, P., Evans, L., Tindall, M., et al. Stiff-PDEs and physics-informed neural networks. Archives of Computational Methods in Engineering, 2023, 30(5): 2929-2958.

Shi, H., Wang, J., Ni, X., et al. Preparation and evaluation of phase-change microcapsules for drilling fluid cooling. Journal of Physics: Conference Series, 2025, 3043(1): 012010.

Su, J., Li, S., Tan, Y. Performance evaluation and feasibility analysis of new phase change microcapsules in drilling fluid cooling. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2025, 722: 137253.

Suganthi, K. S., Rajan, K. S. Metal oxide nanofluids: Review of formulation, thermo-physical properties, mechanisms, and heat transfer performance. Renewable and Sustainable Energy Reviews, 2017, 76: 226-255.

Sun, J., Wen, Z., Khan, M. A., et al. A review of cellulose nanomaterial-stabilized pickering foam: Formation, properties, and emerging oilfield applications. International Journal of Biological Macromolecules, 2024a, 281: 136274.

Sun, J., Xu, G., Ding, Y., et al. Advances and future prospects of shale oil and gas drilling fluid technology. Petroleum Exploration and Development, 2025, 52(6): 1609-1623.

Sun, J., Yang, J., Bai, Y., et al. Research progress and development of deep and ultra-deep drilling fluid technology. Petroleum Exploration and Development, 2024b, 51(4): 1022-1034.

Tang, S., Gao, W., Liu, K. Design and numerical study of active cooling system of measurement while drilling for high temperature based on supersonic. Case Studies in Thermal Engineering, 2023, 50: 103460.

Ugueto C, G. A., Huckabee, P. T., Molenaar, M. M., et al. Perforation cluster efficiency of cemented plug and perf limited entry completions; insights from fiber optics diagnostics. SPE Hydraulic Fracturing Technology Conference, Texas, USA, 9-11 February, 2016.

Vetsak, A., Besoiu, C., Zatonski, V., et al. The insulated drill pipe - field experience and thermal model validation. IADC/SPE International Drilling Conference and Exhibition, Texas, USA, 5-7 March, 2024.

Wang, C., Liu, H., Yu, G.-W., et al. Wellbore-heat-transfer-model-based optimization and control for cooling downhole drilling fluid. Petroleum Science, 2024a, 21(3): 1955-1968.

Wang, C., Wang, S., Zhang, J., et al. Fabrication and characterization of thermally stable and durable phase change microcapsules by *in-situ* polymerization with high-shear homogenization. Journal of Energy Storage, 2025a, 122: 116678.

Wang, G., Song, X., Shi, Y., et al. Heat extraction analysis of a novel multilateral-well coaxial closed-loop geothermal system. Renewable Energy, 2021, 163: 974-986.

Wang, J., Shi, J., Zhao, Y., et al. Real-time wellbore thermal profiling via probabilistic state updating: Overcoming the limitations of input-parameter tuning. Applied Thermal Engineering, 2026a, 290: 130127.

Wang, J., Song, Z., Wang, H., et al. Experimental study on thermal insulation performance of low thermal conductivity mud cake containing porous hollow microspheres. Journal of Molecular Liquids, 2026b, 458: 129775.

Wang, J., Wang, R., Ren, H., et al. Hollow silica nanospheres as wellbore thermal insulation materials in water-based drilling fluids. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2026c, 749: 141216.

Wang, J., Wang, R., Wang, Q., et al. A wellbore wall thermal-insulating hollow microsphere and preparation method thereof. CN202511106125.7, 2025b. (in Chinese)

Wang, P., He, B., An, Z., et al. Hollow glass microspheres embedded in porous network of chitosan aerogel used for thermal insulation and flame retardant materials. International Journal of Biological Macromolecules, 2024b, 256: 128329.

Wang, Q., Xu, Z., Jia, W., et al. Active wellbore cooling during deep drilling circulation via microencapsulated phase change materials: Energy redistribution mechanism and inverse design. Energy, 2026d, 360: 141647.

Wei, M., Cai, W., Xu, M., et al. Active cooling system for downhole electronics in high-temperature environments. Journal of Thermal Science and Engineering Applications, 2022, 14(8): 081009.

Wei, M., Chen, X., Duan, X., et al. Physically constrained intelligent interpretation of production profiles for multilayer oil wells based on distributed fiber optic temperature monitoring. Advances in Geo-Energy Research, 2026, 19(1): 30-42.

William, J. K. M., Ponmani, S., Samuel, R., et al. Effect of CuO and ZnO nanofluids in xanthan gum on thermal, electrical and high pressure rheology of water-based drilling fluids. Journal of Petroleum Science and Engineering, 2014, 117: 15-27.

Wooley, G. R. Computing downhole temperatures in circulation, injection, and production wells. Journal of Petroleum Technology, 1980, 32(9): 1509-1522.

Wu, J., Yu, P., Wang, L., et al. Reversible thermochromic phase change material microcapsules with high latent heat via cellulose nanocrystal stabilized pickering emulsion for smart coatings. Small, 2025a, 21(35): 2505575.

Wu, X., Hou, Z., Li, Z., et al. Numerical calculation of

bottom hole circulating temperature in wellbore cementing processes with multi-fluid and multi-step. Petroleum Science, 2025b, 22(4): 1578-1595.

Wu, Z., Chang, Y. Research and application of microcapsule technology in the wood industry. Journal of Forestry Engineering, 2025, 10(3): 1-12. (in Chinese)

Xi, Y., Jiang, M., Guo, Q., et al. Research on the spatio-temporal dynamic evolution model and influencing factors of geothermal wellbore temperature distribution based on insulated drill pipes. Geoenergy Science and Engineering, 2026, 264: 214578.

Xiao, D., Chen, C., Tang, G., et al. A wellbore flow model for large-size-disparity annulus based on downhole flow-splitting tool. Physics of Fluids, 2026, 38(1): 013114.

Xiao, D., Hu, Y., Wang, Y., et al. Wellbore cooling and heat energy utilization method for deep shale gas horizontal well drilling. Applied Thermal Engineering, 2022, 213: 118684.

Xiao, D., Xiao, H., Song, W., et al. Utilization method of low-grade thermal energy during drilling based on insulated drill pipe. Renewable Energy, 2024, 225: 120363.

Xie, J., Zhang, J., Cheng, Y., et al. Real-time prediction of wellbore temperatures in deep shale gas drilling using a combination of PINN and heat transfer models. Applied Thermal Engineering, 2025, 279: 127984.

Xu, S., Yang, D., Liu, B., et al. Multi-field coupling controls the formation and evolution of deep reservoirs. Advances in Geo-Energy Research, 2025, 17(2): 176-178.

Yan, H., Liu, Z., Lv, K., et al. Boron nitride nanosheets enabled high-thermal-conductivity water-based drilling fluids for enhanced surface cooling. Progress in Natural Science: Materials International, 2026, 36(4): 988-1001.

Yang, H., Li, J., Zhang, H., et al. Numerical analysis of heat transfer rate and wellbore temperature distribution under different circulating modes of reel-well drilling. Energy, 2022, 254: 124313.

Yang, J., Bai, H., He, Z., et al. Design of passive insulation system and optimization of thermal insulation material for deep in-situ condition-preserved coring. Advances in Geo-Energy Research, 2025, 15(2): 99-111.

Yang, M., Luo, D., Chen, Y., et al. Establishing a practical method to accurately determine and manage wellbore thermal behavior in high-temperature drilling. Applied Energy, 2019, 238: 1471-1483.

Yao, X., Song, X., Zhou, M., et al. A modified heat transfer model for predicting wellbore temperature in ultra-deep drilling with insulated drill pipe. Energy, 2025, 331: 136981.

Zhang, C., Sun, J., Huang, X., et al. Preparation of polymer-coated SiO_2 aerogel for weakening wellbore instability caused by heat transfer between the drilling fluid and well wall. Geoenergy Science and Engineering, 2025a, 247: 213611.

Zhang, C., Sun, J., Huang, X., et al. Research progress and prospect of cooling technology for drilling fluid in deep and ultra-deep wells. Chinese Journal of Engineering, 2025b, 47(6): 1161-1174. (in Chinese)

Zhang, G., Tang, M., He, S., et al. Wellbore-formation transient temperature distribution considering heat transfer by fluid seepage while drilling in horizontal well. Geoenergy Science and Engineering, 2025c, 251: 213886.

Zhang, H. -R., Su, Y. -N., Liao, M. -L., et al. Effects of different thermal insulated drill pipe deployment methods on wellbore temperature control in ultra-deep wells. Petroleum Science, 2025d, 22(10): 4174-4194.

Zhang, Y., Ashok, P., Chen, D., et al. Tripping and staging into geothermal wells while assuring thermal protection of downhole tools and sensors. Geothermics, 2026, 136: 103598.

Zhang, Z., Wei, Y., Xiong, Y., et al. Influence of the location of drilling fluid loss on wellbore temperature distribution during drilling. Energy, 2022, 244: 123031.

Zhang, Z., Xiong, Y., Pu, H., et al. Effect of the variations of thermophysical properties of drilling fluids with temperature on wellbore temperature calculation during drilling. Energy, 2021, 214: 119055.

Zhao, L., Wang, G., Li, J., et al. Preparation of medium temperature phase-change nanocapsules for thermal regulation of deep well drilling. Case Studies in Thermal Engineering, 2026a, 77: 107562.

Zhao, S., Xu, K., Li, Z., et al. The current status and prospects of cooling technology for offshore high-temperature drilling wells. Chemistry and Technology of Fuels and Oils, 2025, 61(5): 1255-1262.

Zhao, X., Zhang, X., Zhu, X., et al. Development and feasibility study of phase-change microcapsules for intelligent cooling of drilling fluids in high-temperature deep wells. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2026b, 740: 140177.

Zhu, S., Zhao, N., Li, J., et al. Hard-template synthesis of three-dimensional interconnected carbon networks: Rational design, hybridization and energy-related applications. Nano Today, 2019, 29: 100796.

Zhuang, X., Wang, W., Su, Y., et al. Physical-geochemical coupling in wellbore-reservoir systems: Thermo-hydro-mechanical-chemical processes for subsurface energy development and storage. Gas Science and Engineering, 2026, 150: 205855.