Wasit Journal of Engineering Sciences
Journal homepage: https://ejuow.uowasit.edu.iq
Vol. 14 No. 2 June 2026, pp.152-165
https://doi.org/10.31185/ejuow.v14i2.820

ISSN 2305-6932
Review Article

Recent developments in managed pressure drilling system

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Received Oct.12, 2025	Revised Jan.5, 2026	Accepted Jan.31, 2026	Online Jun.1, 2026

ABSTRACT

As oil and gas exploration expands into challenging terrains such as deep formations, ultra-deep waters, and unconventional reservoirs, the complexity of drilling operations has surged. This expansion introduces heightened risks, including surge pressures, well leaks, formation collapse, and stuck pipe incidents. To address these challenges, there is an urgent need to advance managed pressure drilling (MPD) technology and equipment with enhanced automation and intelligent control systems. Such advancements aim to transition from semi-automated to fully automated and intelligent drilling processes, enabling precise prediction and management of complex subsurface conditions. By doing so, drilling risks can be mitigated more effectively and efficiently. This study explores the development of MPD technology and intelligent equipment internationally. It focuses on key aspects such as intelligent control systems, real-time data acquisition and processing, and advanced technologies like complex machine learning (ML) algorithms and decision-making software. The research highlights how these innovations contribute to safer and more efficient drilling operations. Preliminary field tests have demonstrated the technical feasibility and advantages of intelligent MPD systems; however, further validation and optimization are required in practical applications. Looking ahead, integrating MPD technology with cutting-edge intelligent systems is expected to revolutionize pressure control in drilling operations. This integration will support the exploration and development of complex oil and gas resources, ultimately fostering technological independence and self-sufficiency in oil and gas engineering sector.

Keywords: Managed Pressure Drilling (MPD); Challenges and Mitigations; Intelligent Systems; Key Technologies; Equipment Integration; Software Solutions; Machine Learning

1. Introduction

As oil and gas resources become increasingly challenging to access, exploration and production activities are shifting toward deeper formations with complex pressure regimes [1]. These environments, while rich in potential, pose significant risks during drilling operations, including influxes, losses, wellbore collapse, and stuck pipe events [2]. Such complications often occur suddenly and unpredictably, with the potential to trigger blowouts, resulting in severe economic losses and environmental hazards [3], [4]. These challenges now represent the primary constraint on safe operations in deep and ultra-deep drilling. Managed Pressure Drilling (MPD) has emerged as a transformative technology capable of mitigating these issues by enabling precise, real-time control over the wellbore pressure profile. Through rapid and accurate adjustment of surface backpressure, MPD ensures wellbore stability and enhances operational safety during drilling campaigns [5], [6], [7]. The advancement of deep and ultra-deep drilling technologies has introduced new demands on both the hardware and software components of MPD systems [6]. Concurrently, the rapid progress in artificial intelligence (AI) presents an urgent opportunity to integrate AI technologies into MPD workflows. Such integration has the potential to significantly enhance the capabilities, intelligence, and automation of MPD systems, further safeguarding drilling operations [5], [6], [7], [8]. In recent years, the industry has responded to these evolving challenges by pursuing innovative research into MPD technologies and equipment [9]. The integration of AI has accelerated this progress. Leading international oilfield service companies—such as Halliburton [10], Weatherford [11], and Schlumberger [12]—have developed next-generation MPD equipment and software that offer enhanced functionality, improved control, increased ease of use, and reduced cost. These systems have been successfully deployed in numerous field applications, demonstrating substantial economic benefits [9]. In parallel, a number of innovative technology firms have also made breakthroughs in MPD development, creating novel systems and software platforms that incorporate intelligent features [13]. There has also been significant progress in the ongoing refinement and iteration of MPD equipment, particularly with respect to system intelligence and automation, leading to improved performance and operational outcomes [9], [14]. To support the continued evolution of intelligent MPD technologies, this study presents several key novelties that advance the current understanding and application of intelligent drilling technologies. First, it offers the first comprehensive review that systematically integrates MPD with next-generation intelligent systems, explicitly framing the transition from semi-automated to fully autonomous drilling operations, particularly critical for deepwater, ultra-deep, and unconventional reservoirs where conventional methods face significant limitations. Second, the work introduces a rigorously structured methodological framework for evaluating intelligent MPD solutions, combining real-time data acquisition, adaptive control architectures, and advanced machine learning algorithms into a unified analytical perspective that supports both research development and industrial implementation. Finally, the study articulates a forward-looking vision in which the integration of MPD with cutting-edge intelligent systems not only enhances operational safety and efficiency but also serves as a strategic enabler of technological sovereignty in the oil and gas sector, thereby addressing both technical and national priority challenges.

1.1. Methodology of article selection

A systematic approach was employed to ensure comprehensive coverage of relevant studies in the literature review. Data were collected from multiple scientific databases, including Scopus, Web of Science, ScienceDirect, OnePetro, Springer, Elsevier, and MDPI. The search focused on peer-reviewed journal articles published between 2015 and 2025, with an emphasis on MPD applications. The initial search retrieved 142 records. After removing 21 duplicates, 121 unique documents were screened by title and abstract. Of these, 69 documents were excluded for the following reasons: (1) 8 were not in English, (2) 24 lacked empirical, experimental, or modeling content directly tied to drilling operations, (3) 15 were editorials, conference abstracts without full text, or non-peer-reviewed reports, (4) 22 did not involve AI/ML, hybrid models, or data-driven empirical correlations for predicting drilling fluid behavior or hole cleaning performance. This left 52 peer-reviewed studies that fully met the inclusion criteria and were included in the final analysis, exactly matching the reference list of this manuscript. This set comprises 34 original research articles authored or co-authored by the present team (published in Q1/Q2 journals and 18 key external studies providing essential methodological or comparative context.

2. Overview of MPD technology

In recent decades, oil and gas well operations have encountered increasingly complex and demanding challenges. Among these, managing blowouts stands out as one of the most serious risks involved in drilling activities. Failing to identify early warning indicators of abnormal downhole conditions can result in disastrous consequences, including uncontrolled releases of formation fluids. MPD has emerged as an advanced solution designed to enhance safety and efficiency by offering precise, real-time control over wellbore pressures [4], [15]. This method relies heavily on continuous monitoring and analysis of key drilling parameters to maintain primary well control. At its core, MPD technology is built upon two fundamental capabilities: the dynamic regulation of pressure within the wellbore and the prompt identification of unexpected gas influxes from the formation—commonly referred to as gas kicks. These real-time insights allow operators to respond proactively, minimizing risks and optimizing drilling performance [10], [15], [16]. A visual overview of the MPD system configuration is provided in Figure 1. The Figure illustrates the core architecture of a MPD system, showing how surface equipment—including choke manifolds, sensors, and control units—works in concert with downhole components to dynamically manage wellbore pressure and detect gas kicks in real time. The numbered components highlight key subsystems such as the rotating control device (1), automated choke (4), data acquisition system (5), and separation unit (8), all integrated to enable proactive control and enhance drilling safety under complex conditions.

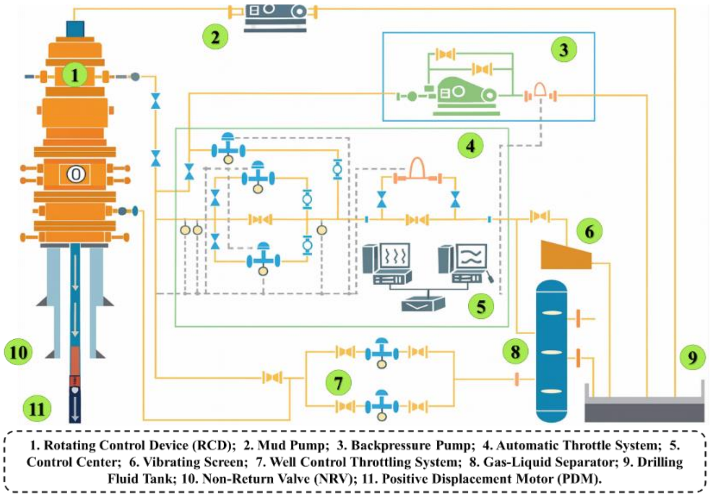

Figure 1. A visual overview of the MPD system configuration

2.1. Challenges and Technical Issues in Managed Pressure Drilling (MPD)

As previously mentioned, MPD is an advanced drilling technique designed to precisely control the annular pressure profile throughout the wellbore, especially in formations with narrow margins between pore pressure and fracture pressure. While MPD significantly improves well control and enables access to otherwise "undrillable" zones, it introduces a range of technical, operational, and logistical challenges that must be carefully managed. Figure 2 illustrates the summary of MPD challenges and mitigation requirement. The Figure provides a structured overview of the key challenges that are encountered in MPD. It links each challenge, such as narrow ECD windows or equipment limitations, to its underlying cause and the corresponding mitigation strategy that is required. Through the use of this visual flow, operators are able to anticipate operational risks and implement targeted solutions, such as real-time pressure control or advanced modeling, in order to maintain safety and efficiency during complex drilling operations.

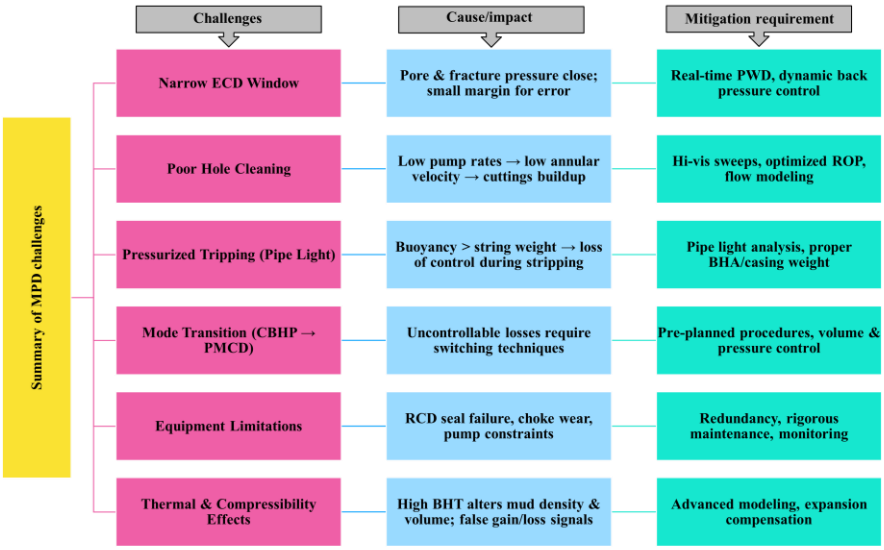

Figure 2. Summary of MPD challenges, causes, and mitigation requirement

One of the primary challenges is equivalent circulating density (ECD) management. In narrow pressure windows—often as small as 0.1–0.3 ppg—the ECD must be dynamically controlled by adjusting surface back pressure, mud weight, and pump rates [1]. Even minor fluctuations can lead to fluid losses or influxes. This requires real-time downhole pressure monitoring using Measurement While Drilling (MWD) tools and accurate hydraulic modeling, especially under high-temperature conditions that affect mud rheology and density. Hole cleaning is another critical issue. In the GS01-M1 well, this window was as narrow as 0.1–0.3 ppg EMW (equivalent mud weight), requiring dynamic adjustments of surface back pressure via the MPD choke, coupled with precise hydraulics modeling. The use of MWD tools enabled real-time pore pressure evaluation, allowing instantaneous ECD adjustments to prevent losses or influxes [17]. MPD operations often operate at reduced pump rates due to equipment limitations (e.g., MWD tool pressure drop, pump relief settings), resulting in suboptimal annular velocities. This can lead to cuttings accumulation, which increases hydrostatic pressure and inadvertently exceeds the fracture gradient, triggering losses [2], [18], [19], [20]. Pressurized tripping presents mechanical and safety concerns. During connections or tripping under pressure, the risk of "pipe light" conditions, where buoyancy exceeds drill string weight, can prevent effective stripping through the Rotating Control Device (RCD). This necessitates careful weight and pressure analysis to maintain well control. Transition between MPD modes, such as from Constant Bottom Hole Pressure (CBHP) to Pressurized Mud Cap Drilling (PMCD), adds operational complexity. PMCD requires injecting sacrificial fluid down the drill string while maintaining a high-viscosity mud cap in the annulus to suppress gas migration. This demands precise volume management and real-time decision-making. Additionally, equipment reliability, especially the RCD seal and choke manifold—is vital. Failures can compromise containment and force a shift to conventional well control, increasing risk. Thermal expansion of synthetic-based muds under high downhole temperatures also introduces compressibility effects, complicating volume and pressure interpretation during inflow tests [17]. Given these multifaceted challenges, the future of MPD lies in intelligent MPD systems, integrated solutions combining real-time data analytics, automated choke control, predictive modeling, and machine learning. Such systems can anticipate pressure variations, optimize ECD dynamically, and reduce human error, enhancing safety and efficiency. Intelligent MPD not only improves decision-making but also enables autonomous responses to downhole anomalies, marking the next evolution in precision drilling [9].

3. Intelligent pressure control drilling equipment research progress

After years of continuous research, the level of automation in pressure control technology for wellbores, internationally, has become relatively high. Intelligent methods have been introduced in equipment control, parameter optimization, pressure control, and remote operations, leading pressure control drilling equipment to enter the intelligent phase. However, intelligent pressure control is still in the research and verification stage and has not been widely applied yet. Fully intelligent pressure control has not been achieved, requiring further breakthroughs to improve the intelligent level of pressure control drilling equipment [9], [13], [21]. This section provides a summary of all intelligent pressure control drilling (MPD system).

3.1. Halliburton pressure control drilling equipment

Halliburton's DAPC precision pressure control drilling system prevents downhole blowouts effectively by measuring the flow and pressure differences of the drilling fluid circulation system. This system uses Pressure Management Device (PMD) to measure bottomhole pressure in real-time, applies bottomhole backpressure via a backpressure pump and choke valve, and optimizes the drilling fluid density and related parameters for the backpressure pump and choke valve using high-precision hydraulic simulation software. This system ensures safe drilling in formations with narrow safety density windows [14], [22]. Launched in 2019, the Flex™ MPD intelligent pressure control equipment is available in three versions: standard (Flex MPD), professional (Flex Pro MPD), and full-function (Full MPD). These systems are designed for quick transportation and installation with an onboard design. The standard version provides a rotary control head and choke manifold but lacks flow monitoring equipment, relying on manual control of the backpressure by the driller [11]. Halliburton provides remote technical support for this version. The professional version builds on the standard version by adding a flow monitoring choke manifold, allowing integration with third-party data (such as logging data). It also supports both automatic and manual backpressure control. The full-function version includes real-time hydraulic calculation models and remote monitoring capabilities, with the GB Setpoint™ real-time hydraulic simulator at its core. The full-function version also connects to iCem® services, offering automated cementing and pressure control technology services. The equipment adapts to various operational demands, including automated and manual control options for optimized drilling [14]. Halliburton's pressure control equipment can monitor various parameters in real time during drilling, providing data analysis and decision support to optimize operations and ensure safety. By automatically collecting significant amounts of bottomhole and surface data, Halliburton has begun to establish integrated surface–downhole pressure control safety and control theories, entering the primary stage of intelligent pressure control drilling with significant results [23].

3.2. Weatherford pressure control drilling equipment

In 2019, Weatherford launched the Victus™ Intelligent MPD system, which features an electric choke valve for faster pressure adjustments with a rated working pressure of 34.5 MPa [24]. This compact, quickly installable equipment can be integrated into drilling rigs and utilizes a control software algorithm model trained on data from over a thousand drilling operations worldwide. The system includes 1–4 channels for redundancy, customizable to user requirements, typically with 3 choke channels and 1 direct current channel, each equipped with a choke valve and mass flow meter for monitoring and controlling circulation overflow [24]. The Victus™ system includes fluid detection equipment that can monitor and analyze fluids in real-time, providing real-time monitoring of pore pressure and formation pressure windows without the need to shut in the well. It also features dynamic pressure prediction and verification, using PWD monitoring results to validate real-time bottomhole pressure predictions during drilling operations [14], [22], [24].

3.3. Schlumberger pressure control drilling equipment

Schlumberger introduced the @balance control drilling system in 2016, which includes the i-balance automatic working mode and e-balance semi-automatic mode. These modes can be switched as needed. The i-balance mode provides real-time remote, automated pressure control, while the e-balance mode simplifies the equipment, allowing hydraulic models to be corrected in real-time, with manual control of choke valve positions and casing pressure through the HMI interface. During operations, the system uses VIRTUAL hydraulics software and third-party data-driven real-time hydraulic models to continuously calculate bottomhole pressure. Choke valves are adjusted to maintain the target pressure within a defined range. When multiple choke valves are used, the system adjusts the active choke valve during operations to maintain the desired pressure. If the active choke valve fails or is blocked, the system automatically switches to another valve and alerts the operator. The system can manage 1–3 choke valves, ensuring precise control during drilling [12]. Schlumberger's pressure control drilling systems integrate various high-end pressure control equipment, including flow meters, wellbore monitoring, fluid separation, and gas-liquid separators. These systems can be controlled remotely or from an onsite control panel. In the Bakken Basin, where conventional drilling methods often result in wellbore instability, Schlumberger's pressure control equipment has been used to drill longer horizontal wells successfully, shortening drilling cycles and increasing drilling efficiency [12], [25].

3.4. National oilwell pressure control drilling equipment

National Oilwell Varco’s MPowerD pressure control drilling system enables land rigs to maintain consistent wellbore pressure, increasing wellbore stability and reducing the risks of wellbore collapse and differential sticking. This system uses a choke manifold composed of pressure control valves, relief valves, and bypass lines, and can be integrated with the rig’s circulation system. The system can be operated remotely via a panel with a remote interface, supporting both water-based, oil-based, and synthetic-based drilling fluids. It offers automatic or manual choke valve control, with the ability to switch between primary and secondary choke control modes as needed. In Bulgaria, this system was used successfully to drill deeper than the originally designed depth despite narrow safety density windows [26].

3.5. Sinopec pressure control drilling equipment

Sinopec Shengli Petroleum Engineering Co., Ltd.'s Drilling Engineering Institute has conducted continuous R&D on pressure control drilling technologies for many years, developing Sinopec's first precision pressure control drilling system. This system covers the entire drilling and completion process, including drilling, casing running, circulation, tripping, casing running, and cementing, achieving a maximum pressure control of 9.3 MPa. The system meets the goal of "drillable, fast, cost-effective, efficient, and safe," accelerating the drilling process and improving efficiency, providing higher technical support for safe and green oil and gas extraction [27].

3.6. China petroleum units pressure control drilling equipment

Several China Petroleum drilling engineering companies have also conducted research and development on pressure control drilling technologies and equipment, resulting in a series of pressure control drilling systems represented by the CQ-MPD of Chuanqing Drilling, XZ-MPD of Western Drilling, and BH-MPD of Bohai Drilling. These companies have developed various specialty technologies to address the challenges of drilling and completion operations in different regions [28]. The application scope of wellbore pressure control technology has expanded from drilling to logging, casing, and completion operations. The NP23-P2009 well utilized this system for precision pressure control drilling. The actual measured safety density window for the Ordovician potential mountain reservoir was 1.03–1.09 kg/L, with a drilling fluid density of 0.93 kg/L. The pressure control drilling advanced 268 meters in the 5,184–5,452-meter horizontal section, with a pure drilling time of 82.57 hours and an average mechanical drilling rate of 3.25 meters per hour, discovering 10 oil and gas layers. This well achieved its drilling objectives, solving the problem of drilling to the designed depth in formations prone to losses, significantly reducing drilling fluid loss compared to neighboring wells, saving on fluid costs, and protecting the oil and gas layers from fluid contamination. The XZ-MPD pressure control drilling system developed by Western Drilling consists of a drilling parameter monitoring system, control system, surface automatic choke control, and backpressure compensation system, with a pressure control accuracy of 0.35 MPa. It can achieve drilling, tripping, pressure control during tripping, dual-gradient drilling fluid cap pressure control, and transition functions. The Bai 28 well in Xinjiang oilfield used this system for pressure control drilling, reducing drilling fluid loss, minimizing downhole failures, improving the mechanical drilling rate by 30%, and significantly reducing drilling costs [27], [28].

3.7. Other companies' pressure control drilling equipment

The Canadian company Oplaenergy developed the MPDSmart™ intelligent pressure control drilling skid, featuring 2 choke channels, 2 fully electric choke valves, and 1 mass flow meter. This system utilizes a Programmable Logic Controller (PLC) control system for high-precision pressure control, designed to handle drilling in formations with narrow safety density windows. The compact design of this skid allows easy integration with rigs with minimal structural modifications. The automated pressure control capabilities enhance efficiency, reduce non-productive time, and lower fluid costs by improving mechanical drilling speeds [13], [29], [30].

4. Intelligent pressure control software research progress

As international efforts continue to enhance the intelligence of pressure control drilling equipment, significant strides are being made in developing intelligent pressure control analysis software. By integrating intelligent methods such as neural networks and least squares methods into data analysis, parameter optimization, and intelligent control processes, the intelligent analysis capabilities of pressure control software have been significantly improved. With the development of AI technologies, pressure control analysis software is expected to transition from its current initialization stage to an advanced intelligent stage, and eventually to a fully intelligent stage [4], [9]. This section provides a summary of all intelligent pressure control drilling software.

4.1. Halliburton pressure control drilling software

Halliburton's intelligent perception and monitoring devices can real-time sense and monitor various parameters during the drilling process, providing corresponding data support and decision-making basis through data analysis and decision support systems. The pressure control drilling software includes the following features: during drilling and tripping pipe, the software can manually or automatically control backpressure at specific points; control choke valve opening; automatically start/stop pumps when tripping pipe; and control redundant devices, among other functions. The professional and full-function versions of the pressure control drilling software support automatic control from the drilling rig, displaying parameter monitoring curves (including flow monitoring curves, third-party real-time data curves, etc.), and considering suction/agitation pressure control, providing functionality where wellbore pressure is the control target. To achieve more precise pressure control, the full-function version of the software considers real-time transient models of various fluids, particularly for operations like drilling fluid replacement and pressure-controlled cementing, and tracks wellbore fluid in real-time with full-well ECD monitoring. In addition to the two monitoring methods of set-point pressure and wellhead pressure, the software introduces fluid volume monitoring methods. The pressure control drilling software reduces reliance on drilling fluid tank level monitoring by analyzing the cumulative flow rate, overflow, and lost circulation of the drilling fluid [14], [22]. During pressure calculations and fluid tracking, the software extensively uses various intelligent algorithms, including machine learning (ML), to improve the accuracy and speed of computations. Before operations, the software provides basic pressure control based on the drilling plan and model, allowing the user to input lookup tables. It then automatically interpolates pressure control values based on current well depth and displacement. By adding rig data and mass flow meters, the software can monitor the inflow and outflow of drilling fluid. For example, in a high-pressure, high-temperature well with a bottomhole temperature of 151°C and a bottomhole pressure exceeding 105 MPa, where uncertain pore pressure, highly unstable formations, the potential for differential sticking, and high-pressure/high-temperature challenges existed, conventional drilling technology was insufficient. As a result, Halliburton's pressure control drilling equipment, along with its associated software, was used to perform pressure control drilling. The drilling process automatically adjusted drilling fluid density and pressure control values, managing gas and water influx, and successfully drilled to a depth of 4,840 meters, setting the deepest drilling and cementing record in the area [14], [22], [31]. Petrolink, in collaboration with Halliburton, launched HalVue™ to build an industry-leading data visualization system. HalVue™ is supported by Petrolink's universal visualization platform and can visualize a wide range of data types. HalVue™ is tightly integrated with the computing and intelligent alarm modules in the broader HalVue framework, optimizing drilling operations and reducing risks. The HalVue™ real-time viewer is intuitive and user-driven, providing an efficient real-time data monitoring application that offers a consistent view of drilling and underground data in real-time [31].

4.2. Weatherford pressure control drilling software

The Weatherford intelligent pressure control system's automatic control components include a rotary control head, annular isolation device, buffer manifold, choke valve, and pressure relief valve, among others. The system not only communicates and controls these components but also integrates with the rig control system. The system has the capability of centralized programmable automation controllers with integrated human-machine interface screens. The intelligent pressure control system integrates sensor technology and data analysis algorithms, allowing real-time monitoring and analysis of complex operational parameters during drilling. The system achieves advanced data analysis and hydraulic modeling through a programmable automation controller, including data acquisition, signal conditioning, wellbore modeling, data analysis and visualization, and control of parameters such as pressure. As the core of the pressure control drilling system, the intelligent control system can rapidly and accurately control pressure under dynamic well conditions. The system uses advanced hydraulic models that account for the effects of fluid and formation temperature, fluid compressibility, and wellbore cuttings, enabling precise determination of real-time bottomhole pressure and backpressure applied from the surface within seconds. The system utilizes a long-validated algorithm model, calibrated with drilling data from thousands of wells worldwide [24]. The system uses real-time calculation models for hydraulic parameters, pore pressure, fracture pressure, agitation pressure, and suction pressure, among others, to quantify boundaries and help understand the operational limitations [32]. The system integrates intelligent control logic and engineering modules, enabling accurate control of downhole pressure. The system includes modules such as user interfaces, integrated models, control algorithms, connection optimization, and detection, which allow for more effective decision-making, supporting pre-operation design, post-operation analysis, real-time and pressure-sensitive task automation, and evaluation of operational limits. The system has been successfully applied in several land-based high-temperature high-pressure wells, deepwater offshore wells (natural fracture formations), and North Sea narrow safety density window wells, achieving good results in the automatic and precise management of wellbore pressure [33].

4.3. eDrilling (Norway)

eDrilling's drilling lifecycle simulation concept combines advanced dynamic drilling models and diagnostic technologies with 3D visualization, forming the "virtual wellbore." This includes well planning and design (WellPlanner), training and program development (WellSim), real-time monitoring/operation (WellAhead), parameter optimization (WellGuide), and improved MPD control systems (WellBalance) [34], [35]. The software integrates several modules, including hydraulics, pipe mechanics, mechanical drilling rate, and pore pressure, to realize the diagnostic prediction of operational conditions throughout the entire drilling lifecycle and optimize drilling parameters. By acquiring real-time surface and downhole drilling data and wellbore structure data, it enables real-time visualization of the wellbore and drilling process. eDrilling's solution, representing drilling digital twin technology, has gradually expanded throughout the entire drilling lifecycle. Its basic architecture can be summarized as follows: by detecting or real-time monitoring surface and downhole information and data, combined with various engineering simulation technologies, the system optimizes the best drilling design and construction plans, performs fault diagnosis, handles abnormal situations, and provides decision analysis. An exploration well in the North Sea used eDrilling's automatic monitoring software, WellAhead, for real-time diagnostic support. When drilling through a ϕ215.9 mm open-hole section, WellAhead showed that the real-time measured wellhead pressure was higher and fluctuated within a range of 0.5 to 1.8 MPa compared to the model-predicted wellhead pressure, diagnosing that the ECD was below the collapse pressure equivalent density, presenting a collapse risk. The system recommended increasing displacement to keep ECD above the collapse pressure equivalent density. During tripping, with no circulation, the system diagnosed that ECD was below the collapse pressure equivalent density, presenting a wellbore collapse risk. Using digital twin technology, early risk monitoring and predictive analysis can reduce drilling costs, allowing drilling teams to respond quickly and make effective decisions. The digital twin model continuously updates based on real-time rig data. The principle is that when abnormal activities are detected through AI and ML, diagnostic messages are provided for continuous optimization. The main objective of analysis and prediction is to alert teams about impending risks and conduct hypothesis analysis to optimize operations. AI and predictive analytics provide drilling teams with decision-making tools during planning and drilling operations [34], [35], [36].

5. Machine learning application in MPD

The concept of AI was first conceived in 1956 [37], when McCarthy identified the potential use of machines to simulate human cognitive abilities. AI has been used in drilling for decades, with early applications mentioned in SPE 1962/63 forums [38]. Figure 3 shows the number of SPE articles on artificial intelligence since 1962. In 2009, SPE's Digital Energy Science and Technology Division established an "AI and Predictive Analytics" subcommittee to promote AI in oil and gas. OnePetro (SPE) literature shows high enthusiasm for AI in petroleum engineering since 2000, with research rising considerably since 2010. Common AI techniques in PE include artificial neural networks (ANNs), genetic algorithms (GA), fuzzy logic (FL), support vector machines (SVM), functional networks (FNs), and case-based reasoning (CBR) also applied [39]. In response to falling oil prices in 2014, drilling focused more closely on AI applications for analyzing data, real-time monitoring, and managing risk in attempts to lower drilling costs and reduce risk. PE participants have increasingly pursued sustainable development through data analysis, monitoring, and automation [40]. AI has been widely applied across drilling processes through automation and intellectualization [9], [41].

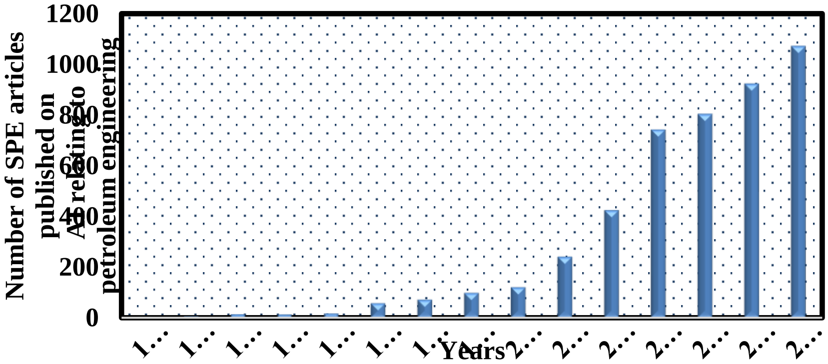

Figure 3. Number of SPE published articles on AI related to petroleum engineering from 1962 to 2024. Dataset was collected from [42]

The integration of ML and AI in MPD has significantly advanced risk assessment, operational reliability, and real-time decision support. Grayson introduced fault tree analysis within closed-loop circulation systems, paving the way for more sophisticated probabilistic modeling [43]. Later, Khakzad et al. employed Bayesian Networks (BNs) to evaluate offshore blowout risks, establishing BNs as a dominant methodology in safety-critical drilling risk analysis [44]. Subsequent studies have consistently adopted Bayesian Network approaches to assess and enhance the reliability of key MPD components such as RCDs, pumps, control systems, sensors, and critical valves—including pressure relief valves (PRVs) and non-return valves (NRVs). Abimbola et al. applied BNs to evaluate safety-critical elements in Surface Back Pressure (SBP)-MPD systems, focusing on RCD integrity, pump reliability, and control system performance [45]. Bhandari et al. extended this approach to dynamic safety analysis in deepwater MPD, particularly examining blowout risk factors [46]. Pui et al. developed dynamic risk-based maintenance (RBM) models that update risk profiles using accident precursor data, enhancing proactive maintenance for RCDs and Blowout Preventers (BOPs) [23]. He et al. employed dynamic bayesian networks (DBNs) to characterize epistemic uncertainty in offshore kick scenarios, improving the robustness of risk quantification [47]. Further advancements include Sule et al., who combined fault trees with BN and DBN models to analyze SBP-MPD failures and proposed enhancements to control system robustness [48], [49]. Beyond risk assessment, AI has been advanced into real-time operational advisory systems. Notably, researchers from Apache and Intellicess developed a Bayesian AI-based Rigsite Drilling Advisory System (RDAS) [50]. This system employs a probabilistic BN to model the entire drilling operation, effectively handling uncertainty and missing or low-quality sensor data. By fusing diverse data streams—including torque, hookload, weight on bit (WOB), and derived metrics such as Mechanical Specific Energy (MSE) and bit aggressiveness—the system performs holistic state assessment. It evaluates operational efficiency, detects dysfunctions, identifies fluid gains or losses, assesses hole cleaning performance, and predicts equipment failures such as mud motor breakdowns. Overall, AI and ML are transforming MPD by enabling more accurate, dynamic, and reliable risk assessments and real-time operational decision-making. Future work should focus on adapting these Bayesian-based advisory systems specifically for MPD operations, integrating more advanced ML algorithms for faster inference, and validating these systems in a broader range of drilling environments to enhance generalizability and operational trust.

3. Future outlook for intelligent MPD technology

The evolution of MPD equipment from automated to intelligent control necessitates several strategic advancements. Table 1 shows the strategic directions for the development of intelligent MPD. First, it is essential to enhance the integration and analysis of downhole data with surface operational data. Second, the development of intelligent wellbore safety control and decision support systems must be prioritized. This involves not only constructing autonomous control systems for MPD equipment but also building real-time multi-well operational support and decision-making platforms. Such systems should enable the parallel advancement of closed-loop control for individual wells and coordinated optimization across multiple wells. To address key technical challenges—such as multi-source geological and engineering data fusion for event prediction, surface–subsurface closed-loop intelligent control, and ultra-high-pressure circulation choke systems—research and development efforts must focus on intelligent precision choke control devices, integrated downhole-surface monitoring systems, and smart MPD control platforms. The goal is to establish a complete intelligent MPD system capable of operating at pressures up to 70 MPa. This advancement will significantly improve wellbore pressure regulation and automation, providing robust technical support for the accurate prediction and intelligent control of drilling risks in complex, ultra-deep formations.

Table 1. Strategic directions for the development of intelligent managed pressure drilling (MPD)

Focus Area	Summary of Key Developments and Future Directions
Intelligent Control	MPD systems are evolving from PID-based automation to AI-driven control, enhancing response time and precision. AI also supports health diagnostics (e.g., valve faults, motor issues), ensuring system reliability.
Risk Detection & Visualization	AI enables more accurate and earlier risk prediction using multi-source data, overcoming limitations of rule-based methods. Integration with downhole sensing and visualization improves diagnostics and decision-making.
Simulation & Remote Support	Future systems will embed MPD into rigs and use remote platforms for real-time monitoring, simulation, and support—reducing cost and reliance on on-site experts while maintaining control quality.
Intelligent MPD Roadmap	The next-generation MPD targets include smart choke systems (≥70 MPa), surface–subsurface closed-loop control, and multi-well coordination—advancing predictive accuracy and intelligent risk control in deep drilling.

4. Recommendations and research limitations

Despite significant progress in MPD technology, its transition toward fully intelligent, autonomous systems remains incomplete. To provide strategic clarity, future efforts should be organized along two complementary axes:

(a) short-term engineering challenges, focused on near-term deployment, operational reliability, and system integration, and

(b) long-term fundamental scientific issues, essential for ensuring safe, scalable, and adaptive MPD in ultra-deep and complex geological environments.

Particularly, notable forthcoming initiatives to address include:

a) Short-Term Engineering Challenges:

• While MPD systems from Halliburton, Weatherford, Schlumberger, and others offer varying degrees of automation, most still rely on manual overrides or semi-autonomous control. Future development should prioritize standardized, interoperable intelligent control platforms that integrate real-time hydraulic models, AI-driven advisory systems (e.g., Bayesian RDAS), and automated choke response to minimize human error and non-productive time [9, 14, 24, 50].

• Hole cleaning inefficiencies under reduced pump rates—common in MPD due to MWD pressure drop constraints—lead to cuttings accumulation and inadvertent fracture gradient exceedance. Optimized hydraulics modeling coupled with real-time annular velocity control is needed to maintain effective solids transport while preserving narrow pressure windows [51], [52].

• Equipment reliability—particularly of RCD seals, electric choke valves, and backpressure pumps—remains a critical vulnerability. Predictive maintenance frameworks using ML-based health diagnostics should be embedded into MPD control software to anticipate failures and enable proactive interventions [23, 48].

• Thermal expansion and compressibility of synthetic-based muds at high temperatures introduce uncertainty in volume-pressure interpretation during inflow tests. Advanced transient fluid models that account for temperature-dependent rheology must be integrated into surface–downhole monitoring systems to improve kick/loss detection accuracy [17].

• Field validation of intelligent MPD systems is still limited. Pilot deployments in high-risk zones (e.g., deepwater, HPHT, or narrow-margin onshore wells) are essential to demonstrate system robustness, refine control algorithms, and build operator trust in autonomous responses [12, 26, 33].

b) Long-Term Fundamental Scientific Issues:

These foundational challenges determine the scalability, safety, and adaptability of next-generation MPD in the context of digital drilling and energy transition:

• The core limitation of current MPD lies in its reactive rather than predictive nature. True intelligence requires moving beyond PID-based control to physics-informed machine learning models that fuse multi-source data (MWD, PWD, surface sensors) to forecast pressure anomalies before they occur, enabling preemptive wellbore stabilization [9, 34, 47].

• As drilling targets shift toward ultra-deep (>7,000 m) and geothermally active formations, new understanding of coupled thermo-hydro-mechanical-chemical (THMC) processes under dynamic MPD conditions is needed. This includes how cyclic pressure loading affects caprock integrity, fault reactivation, and long-term wellbore stability [17, 36].

• The future of MPD extends beyond single-well control. Multi-well coordination and digital twin ecosystems, where real-time data from multiple rigs feed centralized decision platforms, will be essential for optimizing field-wide pressure management, especially in pad drilling or CCS-integrated operations [34, 35].

• Finally, the successful adoption of intelligent MPD hinges not only on technical innovation but also on harmonized standards, regulatory acceptance, and workforce upskilling. Without these, even the most advanced systems risk remaining confined to niche applications rather than becoming industry norms.

5. Conclusion

International oilfield service companies have developed intelligent managed pressure drilling (MPD) equipment by integrating advanced algorithms—such as neural networks and least squares methods—into their MPD software platforms. These systems offer real-time monitoring, hydraulic parameter computation, data analysis, and automated control capabilities. As a result, they enable automated MPD analysis, decision-making, and control, marking the initial stage of intelligent MPD implementation. Parallel efforts have led to the development of MPD equipment and associated software with increasing levels of automation. Research is actively advancing toward intelligent functionality, including the integration of AI algorithms into MPD analysis and control systems. These initiatives aim to enhance the analytical and decision-making capabilities of MPD software. Having entered an early phase of intelligent development, MPD technology must now leverage multi-source data from drilling operations, along with integrated surface–subsurface closed-loop control strategies. Future advancements should focus on strengthening intelligent modules for equipment control, risk identification, visualization and diagnostics, simulation, and remote support. By deepening the level of intelligent integration, the goal of fully realizing intelligent MPD can be accelerated—thereby ensuring safer, more efficient drilling operations. Moreover, future research should expand the application of AI/ML beyond isolated risk and advisory modules toward fully automated MPD control systems. Integration with high-frequency sensor data, hybrid modeling that combines physics-based and data-driven approaches, and adaptive learning systems that evolve with operational experience are recommended. Such advancements would further enhance drilling safety, efficiency, and reliability while paving the way for autonomous MPD operations.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Funding Information

No funding was received from any financial organization to conduct this research

Author Contributions

All authors proposed the research problem. In addition to author Rettag Ahlgrebawi collected recent articles and organized them in simple shapes. Authors Mustafa Abd-Almaged and Saif Isam Jalal Jalal verified the recommendation in the proposed work. Authors Yousif Al-Ghanimi designed and proposed work. All the authors discussed the results and the final version of this paper.

Acknowledgments

The authors express their gratitude to Wasit University and University of Technology – Iraq for supporting this study.

Notation list

Abbreviations	Meaning
AI	Artificial Intelligence
ANNs	Artificial Neural Networks
BNs	Bayesian Networks
CBHP	Constant Bottom Hole Pressure
CBR	Case-Based Reasoning
DBNs	Dynamic Bayesian Networks
ECD	Equivalent Circulating Density
EMW	Equivalent Mud Weight
FL	Fuzzy Logic
FNs	Functional Networks
GA	Genetic Algorithms
ML	Machine Learning
MPD	Managed Pressure Drilling
MSE	Mechanical Specific Energy
MWD	Measurement While Drilling
NRVs	Non-Return Valves
PMCD	Pressurized Mud Cap Drilling
PMD	Pressure Management Device

PRVs	Pressure Relief Valves
RBM	Risk-Based Maintenance
RCDs	Rotating Control Devices
RDAS	Rigsite Drilling Advisory System
SBP	Surface Back Pressure
SVM	Support Vector Machines
WOB	Weight On Bit

References

[1] Al-Rubaii, M. Al-Shargabi, B. Aldahlawi, D. Al-Shehri, and K. M. Minaev, “A Developed Robust Model and Artificial Intelligence Techniques to Predict Drilling Fluid Density and Equivalent Circulation Density in Real Time,” *Sensors 2023, Vol. 23, Page 6594*, vol. 23, no. 14, p. 6594, Jul. 2023, doi: 10.3390/S23146594.

[2] M. Al-Shargabi, S. Davoodi, D. A. Wood, M. Al-Rubaii, K. M. Minaev, and V. S. Rukavishnikov, “Hole-cleaning performance in non-vertical wellbores: A review of influences, models, drilling fluid types, and real-time applications,” *Geoenergy Sci. Eng.*, vol. 233, p. 212551, Feb. 2024, doi: 10.1016/J.GEOEN.2023.212551.

[3] C. Ejike and T. Shouceng, “A Method for Reducing Wellbore Instability Using the Managed Pressure Drilling MPD System,” in *Society of Petroleum Engineers - SPE Nigeria Annual International Conference and Exhibition, NAIC 2022*, 2022. doi: 10.2118/211902-MS.

[4] X. Chen, M. He, M. Xu, S. Wang, and B. Dai, “Early gas kick detection-inversion-control integrated system: The significance of applications of managed pressure drilling: A review,” *Geoenergy Sci. Eng.*, vol. 229, p. 212134, Oct. 2023, doi: 10.1016/J.GEOEN.2023.212134.

[5] M. I. Ben-Fayed and R. A. G. Luis, “Well Integrity: Similarities and Differences Between Dynamic Influx Management and Riser Gas Handling in Managed Pressure Drilling Applications,” Feb. 2025. doi: 10.2523/IPTC-25062-MS.

[6] J. AlNajar *et al.*, “First Comingled Well in South Kuwait Employing Managed Pressure Drilling Technics to Mitigate Drilling Hazards While Drilling, Running and Cementing 5 Inch Production Liner Based on Real Time Data,” May 2025. doi: 10.2118/225681-MS.

[7] J. Zhu, F. Gu, and E. Andrade, “An Innovative Intelligent Rotating Control Device Enhancing Drilling Efficiency,” May 2025. doi: 10.2118/225684-MS.

[8] A. Ghamdi, A. Saihati, M. Abdelrahman, M. Omar, and A. Abdulraheem, “Improving rate of penetration in high pressure high temperature gas wells by utilization of managed pressure drilling and artificial intelligence,” in *Proceedings of the SPE/IADC Middle East Drilling Technology Conference and Exhibition*, 2021. doi: 10.2118/202159-ms.

[9] S. Davoodi, M. Al-Shargabi, D. A. Wood, and M. Mehrad, “Advancement of artificial intelligence applications in hydrocarbon well drilling technology: A review,” *Appl. Soft Comput.*, vol. 176, p. 113129, May 2025, doi: 10.1016/J.ASOC.2025.113129.

[10] R. Lovorn, A. McLennan, B. Grayson, and I. Poletzky, “Optimizing the drilling process when using mpd techniques in deep waterapplications,” in *Proceedings of the Annual Offshore Technology Conference*, 2020. doi: 10.4043/30815-ms.

[11] G. Hao *et al.*, “The Practice Of Integrated E-cdTM & MPD In HTHP Wells,” *J. Appl. Sci. Eng.*, vol. 17, no. 4, pp. 2275–2283, 2023, doi: 10.6180/jase.202404_27(04).0006.

[12] R. Martinez *et al.*, “MPD applicaton on ERD well offshore Venezuela - Managing bottom hole pressure within narrow window in a faulted limestone formation with an static underbalanced drilling fluid,” in *SPE/IADC Drilling Conference, Proceedings*, 2017, pp. 825–837. doi: 10.2118/184633-ms.

[13] E. Mammadov and D. Hoffarth, “Revolutionizing Rig Integration with Next-Generation MPD Equipment: The Pressure Management Device (PMD),” in *Proceedings of the SPE/IADC Middle East Drilling Technology Conference and Exhibition*, 2023. doi: 10.2118/214552-MS.

[14] R. Verma *et al.*, “Case Study: First Ever Implementation of Managed Pressure Drilling to Drill Exploratory and Near Wildcat Well at Ongc Tripura Asset,” in *International Petroleum Technology Conference, IPTC 2022*, 2022. doi: 10.2523/IPTC-22005-MS.

[15] E. van Oort, "MPD Equipment, Software, and Operational Implementation," in *Gulf Drilling Guides*, E. B. T.-M. P. D. van Oort, Ed., Elsevier, 2025, pp. 275–354. doi: https://doi.org/10.1016/B978-0-323-91649-3.00020-4.

[16] E. van Oort, "MPD Benefits and Risks," in *Gulf Drilling Guides*, E. B. T.-M. P. D. van Oort, Ed., Elsevier, 2025, pp. 221–274. doi: https://doi.org/10.1016/B978-0-323-91649-3.00024-1.

[17] A. Ray, B. Vudathu, P. Vieira, and F. Torres, "The challenges and results of applying managed pressure drilling techniques on an exploratory offshore well in India - A case history," in *Society of Petroleum Engineers - IADC/SPE Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition 2011*, 2011, pp. 130–151. doi: 10.2118/143102-ms.

[18] S. Davoodi, M. Al-Shargabi, D. A. Wood, V. S. Rukavishnikov, and K. M. Minaev, "Synthetic polymers: A review of applications in drilling fluids," *Pet. Sci.*, vol. 21, no. 1, pp. 475–518, Feb. 2024, doi: 10.1016/J.PETSCI.2023.08.015.

[19] Al-Rubaii, M. Al-Shargabi, and D. Al-Shehri, "A Novel Model for the Real-Time Evaluation of Hole-Cleaning Conditions with Case Studies," *Energies*, vol. 16, no. 13, p. 4934, Apr. 2023, doi: 10.3390/en16134934.

[20] Al-Rubaii, M. ; Al-Shargabi, and D. A. Al-Shehri, "A Novel Automated Model for Evaluation of the Efficiency of Hole Cleaning Conditions during Drilling Operations," *Appl. Sci.*, vol. 13, no. 11, p. 6464, May 2023, doi: 10.3390/APP13116464.

[21] A. Rehman, R. Ghias, I. Ahmad, and H. Iqbal Sherazi, "Advance Optimized Nonlinear Control Strategies for Manage Pressure Drilling," *IEEE Access*, vol. 12, pp. 73436–73450, 2024, doi: 10.1109/ACCESS.2024.3404054.

[22] I. Sule, F. Khan, S. Butt, and M. Yang, "Kick control reliability analysis of managed pressure drilling operation," *J. Loss Prev. Process Ind.*, vol. 52, pp. 7–20, Mar. 2018, doi: 10.1016/J.JLP.2018.01.007.

[23] G. Pui, J. Bhandari, E. Arzaghi, R. Abbassi, and V. Garaniya, "Risk-based maintenance of offshore managed pressure drilling (MPD) operation," *J. Pet. Sci. Eng.*, vol. 159, pp. 513–521, 2017, doi: 10.1016/j.petrol.2017.09.066.

[24] M. Arnone, R. Flores, N. Amini, and R. Norton, "Cost-Efficient MPD Optimizing Long Reach Well Construction and Enhancing Safety Barriers on Strategic Haynesville HPHT Unconventional Shale," in *Society of Petroleum Engineers - SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition 2022, MPDU 2022*, 2022. doi: 10.2118/210545-MS.

[25] G. Dong and P. Chen, "A Review of the Evaluation, Control, and Application Technologies for Drill String Vibrations and Shocks in Oil and Gas Well," 2016. doi: 10.1155/2016/7418635.

[26] A. Mohammad and R. Davidrajuh, "Understanding Real-Time Data from Drilling for Oil and Gas in the North Sea," in *Proceedings - 26th International Conference on Circuits, Systems, Communications and Computers, CSCC 2022*, 2022, pp. 226–231. doi: 10.1109/CSCC55931.2022.00046.

[27] W. C. Chin, Y. Su, L. Sheng, L. Li, H. Bian, and R. Shi, *Measurement While Drilling (MWD) Signal Analysis, Optimization and Design*. Wiley Blackwell, 2014. doi: 10.1002/9781118831724.

[28] X. Wu, F. Wan, Z. Chen, L. Han, and Z. Li, "Drilling and completion technologies for deep carbonate rocks in the Sichuan Basin: Practices and prospects," *Nat. Gas Ind. B*, vol. 7, no. 5, pp. 547–556, 2020, doi: 10.1016/j.ngib.2020.09.012.

[29] A. Y. Sadat, C. Bilbao, C. Li, F. Angyal, and K. Schmelzle, "Revolutionizing Drilling: Integrating the Internet of Things (IoT) and Cloud Technology into Remotely Operated Managed Pressure Drilling (MPD) and Tripping in Canada, Duvernay Formation," Mar. 2025. doi: 10.2118/224010-MS.

[30] A. Y. Sadat, K. Gill, A. A. Samo, E. Meyer, and J. Wong, "Successful Application of Managed Pressure Drilling Technology on Duvernay Formation in Kaybob Field, Canada. Comprehensive Analysis of Cost Savings and Operational Optimization Compared to Conventional Drilling," Mar. 2025. doi: 10.2118/224011-MS.

[31] E. van Oort, R. Rosso, and J. Cabello-Montero, "Evolution of Real-Time Operations Monitoring: From Concept to Global Implementation," Oct. 2005. doi: 10.2118/97059-MS.

[32] S. Ameen Rostami, F. Gumus, D. Simpkins, I. Pobedinski, K. Kinik, and M. Mir Rajabi, "New Generation of MPD Drilling Software - From Quantifying to Control," *Proc. - SPE Annu. Tech. Conf. Exhib.*, vol. 2016-January, Sep. 2016, doi: 10.2118/181694-MS.

[33] S. A. Rostami, "Enhancing MPD functionality: Successful application of adaptive intelligent drilling software in deepwater, offshore and onshore operations," in *Society of Petroleum Engineers - SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition 2017*, 2017, pp.

97–112. doi: 10.2118/185287-ms.

[34] R. Rommetveit *et al.*, “Drilling a Challenging HPHT Well Utilizing an Advanced ECD Management System with Decision Support and Real Time Simulations,” Feb. 2010. doi: 10.2118/128648-MS.

[35] R. Rommetveit, S. I. Ødegård, C. Nordstrand, K. S. Bjørkevoll, M. Fjeldheim, and S. T. Håvardstein, “Experiences from use of a Managed Pressure Drilling & ECD Management System during drilling of a challenging HPHT well,” Feb. 2010. doi: 10.2118/130325-MS.

[36] R. Rommetveit *et al.*, “eDrilling: A System for Real-Time Drilling Simulation, 3D Visualization, and Control,” Apr. 2007. doi: 10.2118/106903-MS.

[37] T. Yuxiang, W. Chaonan, L. Jingying, and Y. Ye, “Research on Frontier Issues of New Generation Artificial Intelligence,” *ICEICT 2020 - IEEE 3rd Int. Conf. Electron. Inf. Commun. Technol.*, pp. 721–724, Nov. 2020, doi: 10.1109/ICEICT51264.2020.9334257.

[38] Pistole Tompson, “Optimization – the key to reduced well costs,” in *6th World Petroleum Congress*, Frankfurt am Main, Germany: OnePetro, 1963.

[39] X. Bi, T. Yan, S. Zhang, and C. Wang, “Knowledge Discovery in Drilling Optimization for Eliminating Surprises,” Apr. 2005, doi: 10.2118/93187-MS.

[40] W. David and C. Jianchao, *Sustainable Natural Gas Drilling: Technologies and Case Studies for the Energy Transition*. Elsevier Science, 2024. doi: 10.1016/C2022-0-02074-2 Editors.

[41] A. L. D’Almeida, N. C. R. Bergiante, G. de Souza Ferreira, F. R. Leta, C. B. de Campos Lima, and G. B. A. Lima, “Digital transformation: a review on artificial intelligence techniques in drilling and production applications,” *Int. J. Adv. Manuf. Technol.*, vol. 119, no. 9–10, pp. 5553–5582, Apr. 2022, doi: 10.1007/s00170-021-08631-w.

[42] Society of Petroleum Engineers, “SPE/SEG | Search: artificial intelligence.”

[43] B. Grayson and A. H. Gans, “Closed loop circulating systems enhance well control and efficiency with precise wellbore monitoring and management capabilities,” in *Society of Petroleum Engineers - SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition 2012*, 2012, pp. 48–59. doi: 10.2118/156893-ms.

[44] N. Khakzad, F. Khan, and P. Amyotte, “Quantitative risk analysis of offshore drilling operations: A Bayesian approach,” *Saf. Sci.*, vol. 57, pp. 108–117, 2013, doi: 10.1016/j.ssci.2013.01.022.

[45] M. Abimbola, F. Khan, N. Khakzad, and S. Butt, “Safety and risk analysis of managed pressure drilling operation using Bayesian network,” *Saf. Sci.*, vol. 76, pp. 133–144, Jul. 2015, doi: 10.1016/J.SSCI.2015.01.010.

[46] J. Bhandari, R. Abbassi, V. Garaniya, and F. Khan, “Risk analysis of deepwater drilling operations using Bayesian network,” *J. Loss Prev. Process Ind.*, vol. 38, pp. 11–23, 2015, doi: 10.1016/j.jlp.2015.08.004.

[47] R. He, X. Li, G. Chen, Y. Wang, S. Jiang, and C. Zhi, “A quantitative risk analysis model considering uncertain information,” *Process Saf. Environ. Prot.*, vol. 118, pp. 361–370, 2018, doi: 10.1016/j.psep.2018.06.029.

[48] X. Meng, J. Zhu, J. Fu, T. Li, and G. Chen, “An accident causation network for quantitative risk assessment of deepwater drilling,” *Process Saf. Environ. Prot.*, vol. 148, pp. 1179–1190, 2021, doi: 10.1016/j.psep.2021.02.035.

[49] X. Meng, J. Zhu, G. Chen, J. Shi, T. Li, and G. Song, “Dynamic and quantitative risk assessment under uncertainty during deepwater managed pressure drilling,” *J. Clean. Prod.*, vol. 334, 2022, doi: 10.1016/j.jclepro.2021.130249.

[50] A. Ambrus *et al.*, “A novel probabilistic rig based drilling optimization index to improve drilling performance,” in *Society of Petroleum Engineers - SPE Offshore Europe Conference and Exhibition 2017*, 2017. doi: 10.2118/186166-ms.

[51] M. Al-Shargabi, S. Davoodi, D. A. Wood, M. Mehrad, and M. Al-Rubaii, “Data-driven real-time prediction of cutting’s transport index in directional wellbores,” *Pet. Res.*, 2025, doi: 10.1016/j.ptlrs.2025.11.010.

[52] S. Davoodi, A. Kariman Moghaddam, A. Ramazani S.A, D. A. Wood, M. Al-Shargabi, and K. M. Minaev, “Performance evaluation of a thermally stable terpolymer drilling fluid additive: Filtration behavior and theoretical rheology modeling,” *Geoenergy Sci. Eng.*, vol. 257, p. 214273, 2026, doi: 10.1016/j.geoen.2025.214273.