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The Current Status of Wellbore Stability Research in Geothermal Drilling

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Abstract

Wellbore stability is crucial in geothermal drilling as it guides the setting and selection of many parameters, such as drilling fluid density, fracture pressure, drill bit speed, and well trajectory. However, it is unfortunate that research on wellbore instability in geothermal drilling is limited. The future large-scale development of higher temperature geothermal resources will require further study of wellbore instability, particularly under harsh conditions in different regions and rock layers. Additionally, improving and predicting wellbore instability is essential for enhancing efficiency and reducing costs during the drilling process.

Keywords

Wellbore stability; drilling fluid density.

1. Introduction

Energy serves as the cornerstone and impetus for the advancement of human civilization, profoundly influencing national economies, public welfare, security, and the sustainability of human existence. Its pivotal role in fostering socio-economic development and improving quality of life cannot be overstated. Conventional energy sources—coal, oil, and natural gas—have incurred escalating environmental costs, necessitating the emergence and expansion of renewable energy [1], which offers dual benefits: mitigating global energy shortages and preserving the Earth's ecological integrity. Geothermal energy, a renewable and clean resource, has emerged as a critical driver of global economic growth with substantial exploitation potential. Historically, humans have harnessed geothermal energy for applications ranging from therapeutic hot springs and space heating to agricultural greenhouses and industrial processes. However, systematic exploration and large-scale utilization of geothermal reservoirs only commenced in the mid-20th century. Driven by escalating energy demands and environmental concerns linked to fossil fuels, geothermal reservoirs are now recognized as a vital renewable energy alternative [2]. This recognition has spurred a marked increase in geothermal exploration wells and drilling initiatives over recent decades [3, 4].Geothermal energy extraction involves drilling into subsurface reservoirs to exploit naturally circulating fluids or engineered fluid injection systems that transfer thermal energy to the surface. Notably, geothermal drilling principles share fundamental similarities with petroleum well technologies [5, 6]. Innovations in the oil and gas sector have thus provided a theoretical foundation for advancing geothermal engineering practices [7]. Extensive research on high-temperature, high-pressure (HTHP) oil and gas wells—such as those in shale formations—has established mature methodologies. By leveraging parallels between HTHP hydrocarbon wells and geothermal systems, researchers can adapt lessons from petroleum engineering to address the complexities inherent in geothermal drilling. This study aims to synthesize key challenges in geothermal energy development, with a focus on wellbore stability in deep geothermal reservoirs, and to critically evaluate current research trends in this domain.

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1.1. The current status of geothermal energy development and utilization both domestically and internationally

In recent years, amidst the combustion of fossil fuels and the resultant resource depletion, humanity has been compelled to seek alternative supplementary energy sources. Geothermal energy, recognized as an inexhaustible and virtually pollution-free resource, has attracted global attention. Its applications span power generation, thermal spring utilization, and space heating [8]. Notably, the integration of CO2 as a working fluid in geothermal energy production and storage systems—where CO2 is sequestered in deep geological formations—holds significant potential to substantially contribute to greenhouse effect mitigation.Despite accounting for only 1% of its estimated global potential utilization, geothermal energy currently constitutes approximately 70% of newly developed renewable energy capacity. Geothermal power generation has achieved significant progress in technologically advanced nations, including the United States, Japan, France, Italy, and Iceland [9]. In 2005, global installed geothermal power generation capacity reached 8,900 megawatts (MW), while direct-use capacity surged to 27,825 MW—nearly double the 2000 baseline. This exponential growth was predominantly fueled by the rapid adoption of ground-source heat pump systems, with the United States and Western European countries spearheading these developments [10]. According to data from the U.S. Energy Information Administration (EIA), 27 nations—including the United States—collectively generated approximately 88 billion kilowatt-hours (kWh) of geothermal electricity in 2019. Indonesia emerged as the second-largest geothermal electricity producer after the United States, with an output nearing 14 billion kWh, equivalent to approximately 5% of the country's total electricity generation.Kenya is the eighth-largest producer of geothermal power, with an annual electricity generation of approximately 5 billion kilowatt-hours (kWh). Notably, it accounts for the largest proportion of global geothermal electricity generation, representing about 46% of the total. In 2020, the United States led in geothermal electricity production, generating 17 billion kWh; however, this constituted only 0.4% of the total utility-scale electricity generation in the country. Iceland, endowed with abundant geothermal resources, has been engaged in geothermal drilling since 1930 through its drilling companies. The cumulative depth of low-temperature geothermal wells drilled in Iceland exceeds 6,000 kilometers. In recent decades, the exploitation and utilization of geothermal resources have experienced rapid growth. By the end of the 20th century, out of 80 countries with geothermal resources, 58 had documented the utilization of these resources.

China possesses exceptionally abundant geothermal resources, accounting for 7.9% of the global total geothermal energy reserves, according to China's energy data. Over the past two decades, China has led the world in the direct utilization of geothermal energy, reaching 17,870 MWt in 2014, with a consistent upward trend. However, research on hot dry rock (HDR) resources in China is still in its early stages. The energy stored in HDR at depths of 3.0–10.0 km is estimated to be 4,500 times China's total energy consumption in 2013 [11]. In 2017, the Chinese government elevated geothermal energy development to a national energy strategy in its 13th Five-Year Plan [12]. Sinopec [13] is the largest geothermal development enterprise in China and has established the "National Research Center for Geothermal Energy Development and Utilization and Technology Promotion." The "Xiong County Model," a geothermal energy development project, is being vigorously promoted by the National Energy Administration as a benchmark for geothermal heating.After the construction of the first geothermal power plant by Italians in 1904, China's geothermal power generation lagged behind. By 2010, the global installed capacity of geothermal power had reached 10,716.7 megawatts (MW), while China's installed capacity was only 24 MW, ranking 18th globally [14]. Overall, the development and exploration of geothermal energy in China have fallen short of expectations. Although China is rich in geothermal resources and has promising prospects for Enhanced Geothermal Systems (EGS), the development has been slow due to emerging technologies (such as hydraulic

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fracturing) and concerns over environmental impacts (such as induced microseismic activity). As a result, these resources have yet to be commercially developed [15].

1.2. The main challenges of geothermal drilling

The development of geothermal resources is highly complex, particularly due to the harsh reservoir environment, which poses significant challenges to drilling operations. These challenges include issues such as lost circulation, well control, and well integrity [16, 17]. Under high-temperature and high-pressure conditions, drilling operations encounter additional complexities. High-temperature drilling fluid systems used in geothermal drilling and exploration have certain limitations, such as complicated formulations, inconvenient preparation, inappropriate additive selection, and unstable high-temperature performance [18]. Therefore, specialized drilling mud formulations with high thermal stability and excellent rheological properties are required to ensure the functionality of the drilling fluid. Rheological properties significantly influence many drilling parameters, including hole cleaning, fluid and wellbore stability, hydraulic pressure in the wellbore, torque and drag, as well as other drilling-related issues [19].Furthermore, the drilling fluid generates a temperature gradient at the bottom of the well, which can cause damage to the rock formations at the wellbore [20, 21]. The rocks in geothermal reservoirs are predominantly volcanic rocks (such as granite, quartzite, limestone, etc.), which have high wear resistance and hardness. During drilling operations in hot dry rock formations, due to the low permeability and extreme hardness of granite, hydraulic fracturing is required to create fractures for enhanced production. Predicting and controlling the variations in permeability near the wellbore has been one of the most challenging issues in geothermal and hydrocarbon reservoir systems [22, 23].Secondly, deep well drilling, especially for hard rocks like granite, causes drill bit wear, thereby shortening the lifespan of the drill bit. Therefore, the limitations of drill bit technology in geothermal operations are also a challenging issue [24]. High temperature and high pressure can also cause changes in the mechanical and physical properties of the geothermal reservoir rocks, affecting the formation of fractures and the physical parameters [25, 26]. Several studies have shown that wellbore stability is a major challenge in geothermal drilling operations [27-30], and the complexity of downhole conditions increases the difficulty of prediction under multiple field coupling effects. Although geothermal resources are promising, they can also lead to side effects. For instance, thermal extraction from hot dry rock requires Enhanced Geothermal Systems (EGS), which connects injection wells and production wells through hydraulic fracturing to create extensive fractures [31]. During the fracturing process, due to the high rock hardness, the fracturing pressure is high, and the fractures tend to be singular [32]. Additionally, the formation of geothermal fractures can also induce seismic events, and large seismic occurrences pose a threat to public safety [33]. Another challenge in geothermal drilling is cost. Due to the complexity of drilling, well construction accounts for 80% of the total investment in geothermal projects [34]. The cost of geothermal wells is much higher than that of oil and gas wells, being approximately 2-5 times more for the same depth [35].

1.3. The factors affecting wellbore stability in geothermal drilling and their significance

Drilling is the first step in geothermal exploration and development. However, the issue of wellbore instability often limits geothermal development, severely hindering the rapid progress of geothermal utilization. Wellbore instability can lead to wellbore collapse, which may result in stuck pipe, fishing operations, sidetracking, reaming, or even the well becoming a lost well. Since the wellbore stability issue has gained attention since 1980, it has become increasingly challenging due to the complex and diverse downhole environments [36]. It is estimated that unplanned operations caused by wellbore instability account for at least 10% of the average well budget. The global annual cost may approach 1 billion USD. The factors influencing wellbore stability are diverse and result from a coupling of multiple fields and factors [37]. Due to the growing complexity of drilling needs, more complicated well trajectories, such as multilateral wells, horizontal wells, and deviated wells, have emerged, which exacerbate the problem of wellbore instability.Zhang et al. [38] analyzed the wellbore stability of vertical and inclined boreholes using five strength criteria. Well inclination and azimuth have significant effects on wellbore stability during drilling and production under different in-situ stress conditions. Interestingly, the optimal direction for wellbore stability during drilling is also the best direction for production wells [39]. Under different angles of inclination and wellbore azimuth, the dip angle and dip direction of weak bedding planes have a significant impact on wellbore stability. Regarding the influence of in-situ stress conditions, it was found that down-dip wells are generally more stable [40]. During drilling operations, the mechanical properties of rocks, such as elastic modulus, uniaxial compressive strength, and cohesion, can also affect instability [41]. For dry hot rocks (granite), with increasing in-situ stress, the absolute values of axial thermal strain and volumetric thermal strain gradually decrease. Under high-temperature and high-pressure conditions, granite tends to fail by shear failure. As temperature increases, the elastic modulus decreases following a negative exponential law, and the Poisson's ratio shows an increasing trend [42]. At different temperatures and depths, granite containing boreholes will undergo three stages: viscoelastic deformation, viscoelastic-plastic deformation, and failure [43]. In-situ stress is an important parameter for rock mass stability. In-situ stress affects the mud pressure window, thereby impacting wellbore stability. Therefore, determining in-situ stress parameters is crucial for borehole stability.Under the high temperature and high pressure conditions in geothermal environments, due to the coupling effects of the seepage field, temperature field, and stress field, there is a redistribution of the stress and pore pressure around the wellbore. This redistribution varies over time [44]. However, no accurate model currently exists to precisely analyze the in-situ stress, especially when the rock is heated. Thermal expansion can significantly increase pore fluid pressure, and the resulting changes in in-situ stress, pore pressure, and thermal gradients can lead to various instability issues, such as induced fractures and wellbore failure [45]. Another factor affecting wellbore stability is the drilling fluid. During the drilling process, drilling fluid serves to cool the drill bit, carry rock cuttings, and balance pressure. A proper drilling fluid density helps to stabilize the wellbore. A density lower than the estimated value may trigger shear failure of the wellbore, while a density higher than expected may lead to tensile failure. By designing the optimal drilling fluid density, wellbore displacement can be minimized, reducing the risk of collapse or fractures that may affect the wellbore [46].During the drilling process, due to the hydraulic, chemical, and thermal potential gradients between the drilling fluid and formation fluids, the pore pressure and stress distribution near the wellbore will change over time, leading to wellbore instability during drilling in dense formations [47]. Particularly under high-temperature and high-pressure conditions, the drilling fluid must have high-temperature resistance. The liquid column pressure of the drilling fluid during circulation also disrupts the distribution of in-situ stress. Furthermore, there is limited research on the impact of drill string interaction with the wellbore on wellbore collapse and failure in geothermal environments. Some scholars have used simulation and experimental methods to establish the relationship between drill string impact and cuttings volume, demonstrating that drill string collisions have a significant effect on wellbore stability [48]. Other researchers have studied the impact of drill string rotation on wellbore instability. Considering various factors such as different drilling speeds, drilling pressure, and drilling fluid pressure, it was found that drill string rotation has a greater effect on wellbore enlargement. The higher the rotation speed, the more severe the wellbore collapse. The weight of the drill string on the drill bit also contributes to the enlargement of the wellbore,

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with heavier drill bits resulting in larger wellbore diameters. The microcracks caused by tool impact have a far-reaching impact [49].

Due to the complex and variable environment in which geothermal energy is located, there is still limited understanding of the wellbore stability issues in geothermal drilling operations, with few studies both domestically and internationally. Solving the problem of geothermal wellbore instability is a key step to improving drilling speed, reducing drilling costs, and enhancing the safety of geothermal wells during development and production. The increase in geothermal production, economic benefits, and sustainable utilization all depend on wellbore stability. Therefore, understanding the mechanism of wellbore instability, analyzing the causes of wellbore failure, ensuring drilling safety, and improving drilling speed and efficiency are of utmost importance.

2. Technological Advancements in Improving Wellbore Stability in Geothermal Drilling

In the research conducted by scholars both domestically and internationally, although there are still many aspects to be improved in the theoretical studies of geothermal development, the urgent need for energy in various countries has made the development of geothermal resources a priority. Based on previous theoretical research on wellbore stability, many scholars have proposed specific technical approaches to improve wellbore stability and have published numerous papers, providing valuable engineering references for further geothermal development. Zhou, Guangxu et al. [50] employed core CT scanning technology and used drill cuttings to reconstruct the rock framework in order to analyze sections of the well prone to wellbore instability, offering references for drilling operations. Ashena, R et al. [51] proposed a drilling-with-casing (CWD) system to address the issue of long rig-up and rig-down times for casing, which affect wellbore stability. The system utilizes cable recovery to minimize drilling time and, when combined with a continuous circulation system (CCS), prevents well control issues. Abdollahpour, Pouya et al. [52] introduced the stress frame technology, a mechanical sealing method that strengthens the wellbore formation to prevent the initiation of induced fractures. Hamza, Ahmed et al. [53] proposed a drilling fluid loss material to fill potential fractures and cavities that may form during the drilling process. Magzoub, Musaab I [54], Bo, Kehao [55], and Du, Weichao [56] focused on improving the density of drilling fluids or modifying the added chemical substances, particularly enhancing their high-temperature resistance in high-temperature environments.

3. Conclusion

The following conclusions can be drawn based on the current state of geothermal research:

The complex environment of geothermal wells makes geothermal drilling operations a significant challenge. The harsh conditions demand more stringent material selection for drilling fluids, casings, downhole equipment, etc., requiring them to withstand high temperatures and pressures.

Geothermal drilling and oil drilling share similarities in technology and principles, which makes the implementation of geothermal drilling more feasible for an industry lacking technical expertise. This facilitates the transfer of technology between the two fields, helping to reduce extraction costs and enhance safety.

Wellbore stability is crucial in geothermal drilling as it guides the setting and selection of many parameters, such as drilling fluid density, fracture pressure, drill bit penetration rate, and well trajectory. Unfortunately, research on wellbore instability in geothermal drilling is scarce. For the large-scale development of higher temperature geothermal resources in the future, further

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research on wellbore instability is necessary, especially under the harsh conditions of different regions and rock formations. Additionally, improving and predicting wellbore instability will be important for enhancing efficiency and reducing costs in the drilling process.

The issue of wellbore stability in geothermal drilling should not only focus on mechanism research. It is equally crucial to address how to solve wellbore instability. The development of engineering application technologies to resolve wellbore instability is key to the large-scale exploitation of deep geothermal resources. However, research in this area is lacking, with most technologies being limited to only a few factors that influence wellbore instability. Therefore, further research is still needed.

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