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# Research on the Temperature Field Distribution Characteristics of Bottomhole PDC Bits during the Efficient Development of Unconventional Oil and Gas in Long Horizontal Wells

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**Abstract:** Unconventional tight oil and gas resources, including shale oil and gas, have become the main focus for increasing reserves and production. The safe and efficient development of unconventional oil and gas is a crucial demand for the energy development strategy. Deep tight oil and gas resource development generally adopts horizontal well drilling methods. During drilling, especially in long horizontal sections, the high temperature frequently causes failures of downhole drilling tools and rotary steering tools. The temperature rises sharply during rock breaking with the drill bit. Existing wellbore heat transfer models do not fully consider the impact of heat generated by the drill bit on the wellbore temperature field. This paper aims to experimentally study the temperature rise law of the cutting tooth of the bottom polycrystalline diamond compact (PDC) bit during rock breaking. A set of evaluation devices was developed to study the temperature field distribution characteristics at the bottom of the PDC bit during rock breaking under different experimental conditions. The results indicate that the flow rate of drilling fluid, bit rotation speed, and weight on bit (WOB) significantly affect the distribution of the temperature field at the well bottom. This experimental research on the temperature field distribution characteristics at the bottom of the PDC bit during rock breaking helps reveal the heat transfer characteristics of the long horizontal section wellbore, guide the optimization of drilling parameters, and develop temperature control methods. It is of great significance for the advancement of efficient development technologies for unconventional resources in long horizontal wells.

**Keywords:** unconventional oil and gas; long horizontal section; PDC bit; heat transfer; temperature control

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## 1. Introduction

China is rich in shale gas resources; during the 14th Five-Year Plan period, shale gas and other unconventional natural gases have become the main focus for increasing reserves and production. The safe and efficient development of shale gas is a crucial demand for the national energy development strategy [1–3]. The Sichuan Basin is the primary region for shale gas exploration and development in China, having undergone four phases: resource evaluation and area selection (2006–2009), pilot testing (2009–2014), demonstration construction (2014–2016), and large-scale exploitation (2017 to present). Currently, shale gas reservoirs at depths shallower than 3500 m have been developed on a large and commercial scale [4–6]. According to the development plan for shale gas, during the 14th Five-Year

Plan period, the production share of deep shale gas reservoirs at depths of 3500 to 4500 m will increase from 2% to 47%, making deep shale gas the current focus of exploration and development [7].

Compared to medium-depth shale gas, which has already achieved commercial development, deep shale gas presents more complex geological and engineering conditions [8]. The target Silurian Longmaxi Formation is buried deeper (generally greater than 3800 m) and the bottomhole circulating temperature is higher (generally above 140 °C). During drilling, the technical challenges include difficult horizontal well trajectory control, high failure rates of rotary steering instruments under high temperatures, and difficulties in fast drilling in long horizontal sections with high-density drilling fluid. The drilling techniques used for medium-depth shale gas are not sufficient to effectively address these issues.

As shown in Figure 1, the actual bottomhole circulating temperature of deep shale gas horizontal wells in the Luzhou block generally ranges from 140 °C to 150 °C, with an average final bottomhole circulating temperature of 146 °C and a maximum bottomhole circulating temperature reaching 167 °C [7]. This is significantly higher than the temperature in the Changning and Weiyuan medium-depth shale gas blocks. The prolonged operation of rotary steering instruments in high-temperature conditions leads to severe damage to electronic components. Field drilling data indicate that when the bottomhole circulating temperature exceeds 140 °C, multiple rotary steering instruments frequently exhibit unstable signal transmission and frequent failures. This significantly reduces the stable downhole operating time of rotary steering instruments, severely affecting drilling efficiency. In early horizontal well implementations, rotary steering instrument failures required an average of five trips per well, greatly increasing the drilling cycle of individual wells.

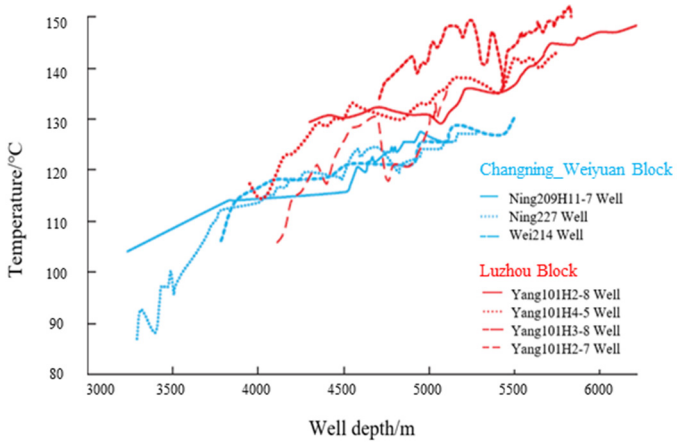



**Figure 1.** Comparison of bottomhole circulating temperature in horizontal wells across different shale gas blocks in Sichuan Basin.

During the rock-breaking process of PDC bits, especially in long horizontal sections, the cutting teeth drill at high speed and generate intense friction with the rock. More than half of the energy supplied to the drill bit is converted into frictional heat. The combined effect of high-temperature formation and cutting friction heat causes the temperature of the drill bit to rise sharply [9]. Studying the temperature field distribution characteristics of PDC bits at the bottomhole during the efficient development of long horizontal wells in unconventional oil and gas reservoirs is crucial for optimizing drilling parameters, guiding drill bit selection, and guiding drill bit design optimization. The research objects of scholars on wellbore heat transfer mainly include heat transfer inside the wellbore and heat transfer between the wellbore and the formation, without fully considering the influence of heat generated by the bottom drill bit on the wellbore temperature field, and the calculation of the wellbore temperature field is not accurate enough. There is a significant gap with the actual drilling process, and the need is urgent to establish a more accurate prediction

model for the full wellbore temperature field by including the temperature rise law of the bottomhole temperature field during the PDC drill bit rock-breaking process.

## 2. Current Research Status on Temperature Rise Characteristics of PDC Cutting Teeth

Research on the temperature rise characteristics of PDC drill bit cutting teeth in rock drilling is relatively limited. Since the 1980s, researchers have begun systematic studies on the temperature rise of PDC drill bit teeth caused by frictional heat during cutting. In recent years, researchers both domestically and internationally have increasingly emphasized the study of cutting heat.

In 1984, Glowka et al. [10,11] established a finite element model of an individual PDC cutting tooth to predict the average cutting temperature of wear planes under steady-state and transient downhole conditions. The results showed a correlation between the temperature of the wear plane and the wear rate of the drill bit. Subsequent experiments confirmed the relationship between temperature and wear rate, suggesting a significant increase in the wear rate of the cutting tooth above 350 °C, contrary to the previously assumed 750 °C [12]. The increase in Rate of Penetration (ROP) significantly raised the temperature of the wear plane, exacerbating cutting tooth wear, indicating a correlation between ROP and drill bit life. Furthermore, friction at the cutting tooth–rock interface significantly raised the interface temperature, determining the wear rate of the PDC cutting tooth [13]. Zijsling et al. [14] established a theoretical thermal model similar to Glowka's to predict the temperature distribution of a cutting tooth mounted on a PDC drill bit under quasi-static drilling conditions. They found that the highest temperature occurred at the cutting edge of the PDC cutting tooth, which could be mitigated by reducing the ROP and the thickness of the diamond layer or increasing the number of cutting teeth on the drill bit. Glowka and Zijsling's models are based on Jaeger's proposed heat calculation model of a moving plane heat source, which can only predict the average temperature rise of the entire or partial wear-resistant plate, rather than the entire temperature distribution of the wear plane. Additionally, the interaction between the drill bit and the rock is often too intense to approach quasi-static drilling conditions. Due to these reasons, their models cannot accurately predict the impact of heat on drill bit performance. In 1993, Appl et al. [15] conducted direct experimental measurements of the temperature and wear rate of a cutting tooth when cutting granite for the first time, using a PDC cutting tooth. The research results showed that because the average temperature of the wear plane is constant, the wear rate of the drill bit is not constant, suggesting a need for revisions to previous thermal models.

A research group led by Li et al. conducted related studies on heat conversion and transfer processes during rock fragmentation by a hard alloy drill bit; they [16] established mathematical formulas for the internal temperature field of the drill bit under the action of a water jet and analyzed the factors affecting temperature rise. The results showed that the temperature rise of the front cutting face of the cutting tooth is positively correlated with the square root of the cutting speed when the drilling fluid is not considered; the presence of drilling fluid can significantly reduce the temperature of the cutting tooth. Yang et al. [17,18] investigated the temperature rise of the drill during rock fragmentation, conducted real-time measurements of the temperature of the drill bit during rock breaking using an infrared thermal imager, successfully collected the distribution of the temperature field, derived the analytical relationship of the temperature rise of the drill bit during rock fragmentation, and analyzed the influence of cutting parameters on drill bit temperature, thereby compensating for the shortcomings of experimental measurement methods. Shao et al. [19] embedded a special thermocouple into the cutting tooth to study the contact surface temperature between the cutting tooth and the rock material when cutting sandstone, and they explored the variation in cutting tooth temperature under different parameters. The results showed that the cutting tooth temperature is positively correlated with the cutting depth and cutting speed. The influence of cutting spacing on the temperature of the tooth tip is less than that of cutting depth and cutting speed. Kim et al. [20,21] studied the effect of the inclination

angle of a conical tooth on cutting temperature. The results showed a negative correlation between the surface area of the conical tooth and temperature.

In terms of the numerical simulation of temperature, many researchers have established thermal–structural coupling simulation models of a PDC cutting tooth and rocks based on finite element software to study the temperature field of a cutting tooth. Shao et al. [22] studied the heat transfer in a diamond-embedded drill bit during rock fragmentation based on the finite element ANSYS program. The results showed that the temperature amplitude decreases with increasing depth. Wu et al. [23] analyzed the influence of different cutting depths, cutting line speeds, and other factors on the temperature of a PDC cutting tooth during rock fragmentation. The results showed that when the critical cutting depth is 4 mm and the critical cutting speed is 5 m/s, the temperature of the cutting tooth increases rapidly. Li et al. [24] studied the variation in temperature rise of individual PDC cutting teeth during the rock fragmentation process. The simulation results showed that the maximum temperature of the cutting tooth is on the front cutting face, not the tooth tip. Deng et al. [25] conducted a simulation and analysis of cutting tooth temperature, and the results showed that the numerical model can reliably simulate the relevant laws of cutting tooth temperature during rock fragmentation. Zhang et al. [26] analyzed the temperature distribution of the cutting tooth and rocks during rock fragmentation by a PDC cutting tooth. The simulation results showed different temperatures at different positions on the cutting tooth during rock fragmentation. Tan et al. [27] studied the variation in drill bit temperature with cutting depth, cutting speed, and other parameters through finite element models. The simulation results showed that the temperature of the front cutting face decreases with increasing cutting depth, while the temperature of the back cutting face increases linearly. Zhang et al. [28] conducted a simulation analysis of the temperature rise and tooth deformation of a PDC cutting tooth during rock fragmentation under different conditions by changing parameters such as cutting depth, cutting speed, and rake angle. The simulation results showed that cutting depth has the most significant effect on the temperature of the cutting tooth, and temperature has a more significant effect on tooth deformation than the cutting force received.

Cutting depth can alter the rock's failure mode and consequently affect the stress state of PDC composite cutters. However, the fundamental reason for an increased cutting temperature lies in the variation of cutting forces, thus altering the temperature field of the cutting tooth. Zhang et al. [29] analyzed the relationship between cutting depth and cutting temperature using the finite element software ABAQUS, and the results showed a positive correlation between the temperature of the back cutting face and cutting depth. Qian et al. [30] combined theoretical calculations with experiments to study the temperature variation of a diamond-embedded drill bit during the dry cutting of rocks. Their research indicated that weight on bit (WOB), bit size, and rotational speed are directly proportional to the temperature of the drill bit. Zhou et al. [31] investigated the mechanism of how the characteristics of rocks such as sandstone, marble, granite, and basalt affect the temperature of the cutting tooth. Their findings revealed that rock strength is a crucial factor influencing cutting temperature, with the highest temperature observed when fracturing granite and basalt, and the lowest temperature when fracturing sandstone. As the strength of the rock increases, the required cutting force also increases, leading to greater heat generation during cutting. Therefore, the temperature rise of different rocks increases with the increase in rock strength. Zheng et al. [32] studied the influence of the radius of the circular cutting tooth edge on cutting temperature; they found that when the radius of the edge is small, the cutting tooth temperature is lower and the temperature fluctuation curve is relatively stable, whereas when the radius is large, the cutting tooth temperature is higher.

Most of the aforementioned research methods are based on empirical models obtained through the curve fitting of experimental data and mathematical statistical analysis. The studied objects are mostly hard alloy drill bits, diamond-embedded drill bits, etc., and most of the experimental data are based on single-cutting tooth tests, which do not correspond well with actual drilling conditions. However, PDC drill bits differ structurally from other

drill bits, making existing models unsuitable for describing the temperature distribution of PDC cutting teeth. Therefore, further research is needed to investigate the temperature distribution of a multi-cutting teeth bit during rock breaking based on previous theoretical analyses.

## 3. Experimental Preparation

### *3.1. Experimental Equipment*

As shown in Figure 2, a rock-breaking drilling test platform has been established, mainly composed of a drilling rig rotation system, drilling rig lifting and lowering system, rock sample clamping system, drilling fluid circulation system, and data acquisition system. This test platform can alter drilling parameters during rock-drilling processes (such as a different flow rate of drilling fluid, the rotation speed of the drill bit, and WOB) and rock sample properties (different types of rocks) to simulate various drilling experimental conditions. It enables the study of the heat generation characteristics of friction between the drill bit and the rock, as well as the characteristics of drill bit wear under different experimental conditions, providing a theoretical basis for optimizing drill bit design.

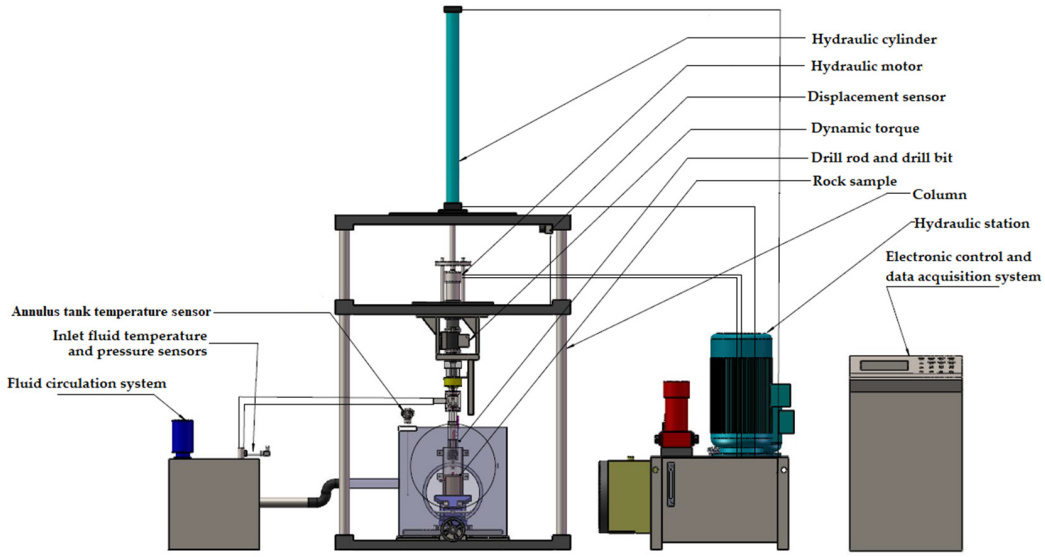



**Figure 2.** Schematic diagram of rock-breaking drilling test platform.

The drilling rig rotation system consists of a hydraulic motor, spindle, simulated drill rod, and drill bit. The rotation speed of the drill rod ranges from 0 to 200 rpm, with a torque testing range of 0 to 300 N·m. The specifications of the dynamic torque sensor are 500 N·m, with an accuracy of 0.3%. The torque signal frequency is 10 kHz. Five-nozzle PDC composite cutter drill bits designed for geological drilling, equipped with five cutting teeth, are used. The outer diameter of the drill bit is 60 mm, as shown in Figure 3. The PDC drill bits use polycrystalline diamond composite sheets as cutting teeth, which are composed of thin diamond layers and tungsten carbide substrates formed under a high temperature and pressure. The manufacturing process of PDC drill bits includes turning polycrystalline diamond into small cutting teeth and then sintering them onto the drill body. The drill bit body is a steel drill bit, made by milling steel.

The drilling rig lifting and lowering system includes a hydraulic cylinder, displacement plate, and columns. The hydraulic cylinder is mounted above the fixed plate frame and is used to lift or lower the drilling tool by applying WOB through the lower displacement plate. Based on drilling site conditions and similar principles, the WOB range is set to 0–30 kN.

As shown in Figure 4, a rock sample clamping system has been developed, including fixed and movable rock sample devices. The system can clamp rock samples with a maximum size of 300 mm × 150 mm. For this experiment, φ 105 mm × 150 mm cylindrical

rock samples are prepared, with simulated casings containing multiple temperature test points (inner diameter 105 mm, height 1000 mm) used for external clamping of the rock samples.

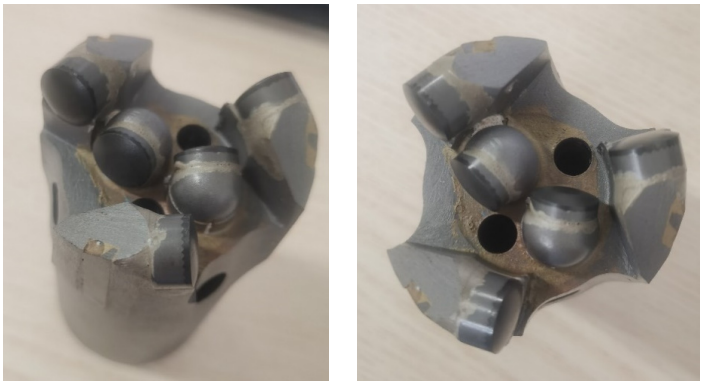


**Figure 3.** PDC composite cutter drill bit for geological drilling.

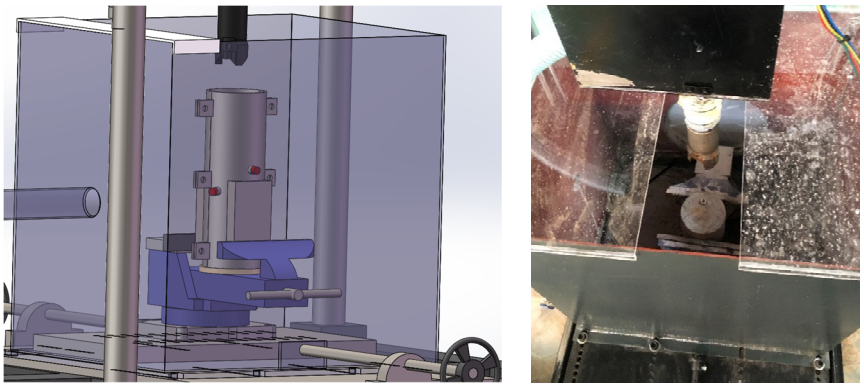


**Figure 4.** Rock sample clamping device.

The drilling fluid circulation system consists of a circulation pump (for subsequent high-pressure experiments, it can be connected to the high-pressure pump of the High-Pressure Water Jet Laboratory at the China University of Petroleum, with a maximum pump pressure of up to 100 MPa), a water tank, and circulation pipelines. The horizontal circulation pump has a flow rate of 12.5 $m^3$/h, equivalent to 208 L/min.

A data acquisition system has been developed, including the collection and storage of data such as temperature, WOB, rotation speed, ROP, torque, pressure, and flow rate. Among these, temperature signals are measured by built-in thermocouples in real-time to monitor the temperature of the drill bit during the drilling process. Thermocouples placed at different positions inside the wellbore can measure the annular temperature during the return flow of drilling fluid. Thermocouples embedded in the rock can measure the internal temperature of the rock during drilling. This device utilizes K-type thermocouples with a diameter of 1 mm, a high accuracy, and rapid response, with an error of ±0.2 °C and a temperature measurement range of 0–1300 °C, meeting the temperature measurement range and accuracy requirements of the experiment. Temperature measurement points include inlet fluid temperature, PDC composite cutter temperature, drill rod temperature, formation rock temperature, and return flow temperature in the annulus. The locations of the temperature-testing points for the drill rod, annulus, and formation are shown in Figure 5, and the temperature-testing points on the PDC cutting teeth of the drill bit are shown in Figure 6. During the experiment, it was found that the temperature rise law of the inner and outer cutting teeth was basically consistent, so subsequent experiments only used the temperature of the inner cutting tooth for analysis. The temperature measurement method for the PDC cutting tooth is as follows: first, a small hole with a diameter of 2 mm

is drilled into the PDC cutting tooth, and the temperature thermocouple probe is placed inside the cutting tooth. To ensure intimate contact between the cutting tooth and the thermocouple probe, the hole is densely filled with thermally conductive silicone grease for better heat transfer and measurement accuracy. To prevent drilling fluid from entering the hole and affecting the measurement results, the hole is sealed with glass sealant.

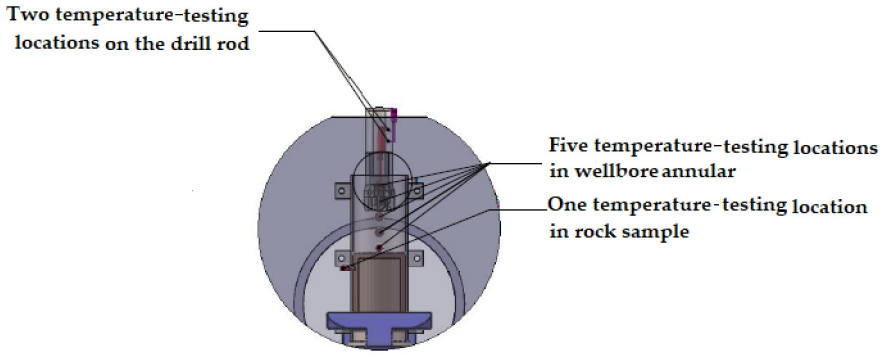



**Figure 5.** Schematic diagram of temperature sensors located at drill rod, annulus, and formation.

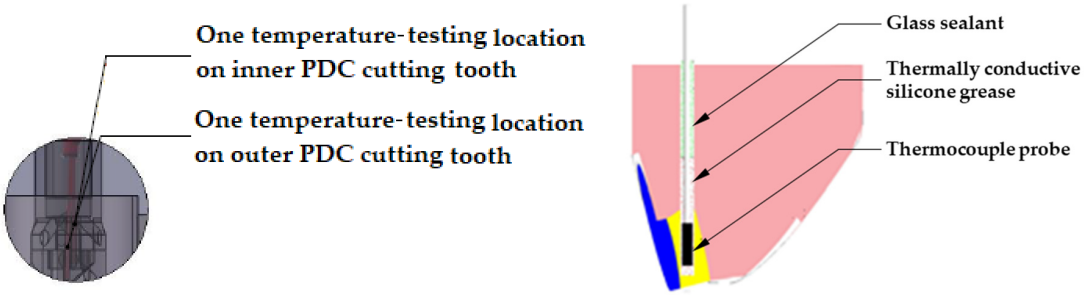



**Figure 6.** Schematic diagram of temperature sensors located at PDC drill bit cutting tooth.

The inlet fluid pressure is measured using an SB-131 pressure transmitter from Shuobo Intelligent Equipment Co., Ltd. in Qingdao Shandong of China, with a measurement range of 0~2 MPa. The pump flow rate is tested using a turbine flow transmitter, with a measurement range of 15 $m^3/h$, equivalent to 250 L/min, with an accuracy of 0.5%, and a pressure resistance of 6.3 MPa.

The entire process of lowering, rock breaking, and lifting is monitored and recorded using a DEPSTECH camera system from Botan Intelligence Co., Ltd. in Shenzhen Guangdong of China as shown in Figure 7, achieving visualization of the rock-breaking and drilling process.



**Figure 7.** DEPSTECH camera system.

### *3.2. Experimental Equipment Operation Process*

a. Firstly, power on the electronic control and data acquisition system and input parameters such as WOB (4.5 kN was used for general experiments; 1, 3, 4.5, 6, and 7.5 kN were used for WOB comparative experiments), rotation speed (50 r/min was used for general experiments; 50, 100, and 150 r/min were used for rotation speed comparative experiments), and lifting and lowering speed into the data acquisition control system.
b. Secondly, insert the experimental core sample (several typical core samples were prepared, including cement stone, sandstone, marble, and granite) and fix it in place.
c. Thirdly, start the circulation pump and adjust the fluid flow rate (50 L/min was used for general experiments; 0, 25, 50, 75, and 100 L/min were used for flow rate comparative experiments).
d. Fourthly, start the hydraulic system, rotate the drill rod and drill bit, and begin collecting data such as WOB, rotation speed, torque, ROP, drill bit temperature, bottomhole temperature, annulus temperature, inlet fluid temperature, and inlet fluid pressure.
e. Then, lower the drill rod and drill bit and start breaking and drilling after touching the rock core. After drilling to the predetermined depth or time, stop drilling, and lift up the drill rod and drill bit.
f. Finally, turn off the hydraulic system, stop the circulation pump, and output and analyze the experimental data.

## 4. Experimental Results and Discussion

### *4.1. Analysis of Temperature Rise Law during PDC Bit Drilling*

Maintaining a constant WOB of 4.5 kN, a fluid flow rate of 50 L/min, and a drilling time of 150 s, the temperature rise process of a PDC cutting tooth during the drilling of marble under the influence of circulating water at 0 °C was analyzed. As shown in Figure 8, the temperature rise curve of the PDC bit drilling process can be divided into three stages: Stage I—a rapid-rise period; Stage II—a slow-rise period; and Stage III—a relatively stable period.

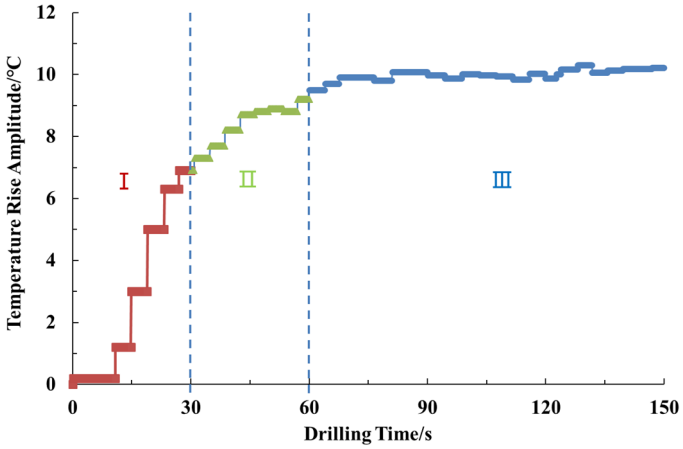



**Figure 8.** Temperature rise process of PDC cutting tooth during drilling.

During the initial 0 to 30 s of drilling, a large amount of heat is generated instantaneously due to friction and collision between the PDC bit and the rock under the action of WOB. Due to the different thermal conductivity coefficients of the rock and the drill bit, this heat is not diffused to the rock quickly, leading to a rapid rise in the temperature of the drill bit. As drilling continues, from 30 to 60 s, the temperature continues to rise, but the rate of the temperature rise slows down significantly compared to the first 30 s. This is because the contact area between the drill bit and the rock gradually increases, leading to intensified heat conduction and transfer, with some heat being carried away by the drilling fluid, resulting in a reduction in the rate of the temperature rise of the drill bit. In the

stage from 60 to 150 s, the heat generated by the drill bit is approximately equal to the convective heat exchange and heat dissipation, and its temperature eventually reaches a dynamic equilibrium.

### *4.2. Drilling Experiment under Different Rotation Speed Conditions*

Maintaining a constant WOB of 4.5 kN, a fluid flow rate of 50 L/min, and a drilling time of 60 s, the temperature rise law of a PDC cutting tooth during the drilling of marble under the influence of circulating water at 0 °C was analyzed at rotation speeds of 50, 100, and 150 r/min, respectively, as shown in Figure 9. The experiment revealed that the maximum temperature rise of the PDC drill bit cutting tooth is closely related to the drill bit rotation speed. The higher the rotation speed, the higher the temperature of the cutting tooth. At rotation speeds of 50, 100, and 150 r/min, the maximum temperature rise of the PDC drill bit cutting tooth was 10.3, 16.1, and 20.1 °C, respectively. The temperature of the cutting tooth increases with time until reaching dynamic equilibrium. The temperature rise rate of the PDC drill bit cutting tooth is also closely related to the drill bit rotation speed. When the rotation speed is 150 r/min, the temperature rise rate of the cutting tooth is the highest, and when the rotation speed is 50 r/min, the temperature rise rate of the cutting tooth is the lowest. There is a positive correlation between the temperature of the drill bit and the rotation speed. This is because, during the process of drilling and rock fragmentation, the number of frictional contacts between the cutting tooth and the rock increases with the increase in rotation speed per unit time, leading to increased frictional heat generation and thus an increase in the temperature of the cutting tooth.

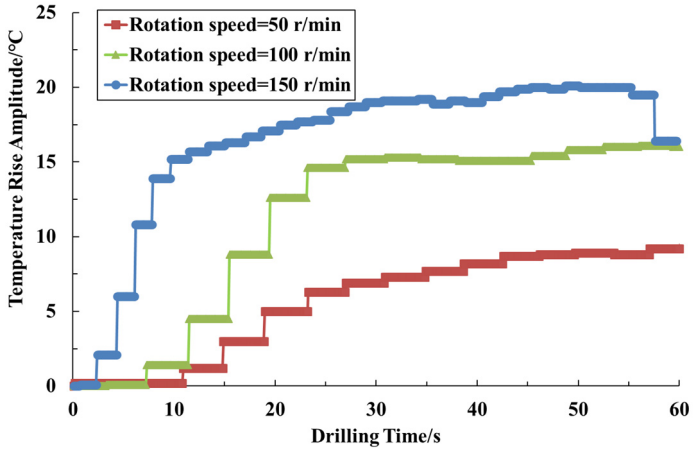



**Figure 9.** Temperature variation of PDC cutting tooth under different rotation speeds.

### *4.3. Drilling Experiment under Different WOB Conditions*

Maintaining a constant rotation speed of 50 r/min, a flow rate of 50 L/min, and a drilling time of 120 s, the temperature rise law of a PDC cutting tooth during the drilling of marble under the influence of circulating water at 0 °C was analyzed at WOBs of 1, 3, 4.5, 6, and 7.5 kN, as shown in Figure 10. The experiment revealed that the temperature of the cutting tooth increases with the increase in drilling time, and the higher the WOB, the greater the increase in temperature of the cutting tooth. There is a positive correlation between the WOB and the temperature of the cutting tooth. Under WOBs of 1, 3, 4.5, 6, and 7.5 kN, the maximum temperature rise of the PDC drill bit cutting tooth was 2.1, 6.6, 10.3, 12.4, and 13.7 °C, respectively. The greater the WOB applied to the PDC drill bit, the greater the axial force it bears, the deeper the PDC cutting teeth penetrate the rock, and the greater the torque it bears. Therefore, as the WOB on the rock increases, the friction between the cutting teeth and the surrounding compacted area significantly increases, resulting in more cutting friction heat and a sharp increase in the temperature of the drill bit.

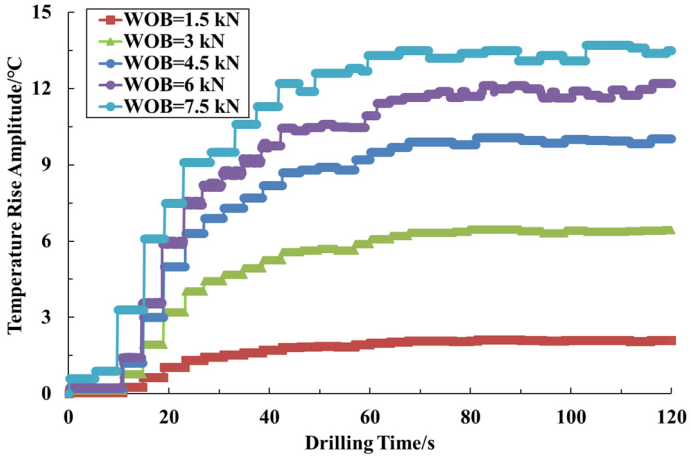



**Figure 10.** Temperature variation of PDC cutting tooth under different WOBs.

### *4.4. Drilling Experiment under Different Drilling Fluid Flow Rate Conditions*

The WOB was maintained at 4.5 kN, with a rotation speed of 50 r/min, and the drilling time was set to 120 s. The temperature rise of a PDC cutting tooth during the drilling process in marble was analyzed under the action of circulating water at 0 °C for drilling fluid flow rate values of 0, 25, 50, 75, and 100 L/min, as shown in Figure 11. From the figure, it can be observed that the temperature rise trends of the cutting tooth are generally similar under different drilling fluid flow rate conditions. They all initially increase rapidly with drilling time, then gradually rise, and finally reach a dynamically stable equilibrium state. The larger the drilling fluid flow rate, the smaller the temperature rise of the cutting tooth, showing a negative correlation between drilling fluid flow rate and cutting tooth temperature. Under conditions without circulating water, the highest temperature of the PDC drill bit cutting tooth reached 75.2 °C. However, as the flow rate of circulating drilling fluid increased from 25, 50, and 75 to 100 L/min, the highest temperature of the PDC drill bit cutting tooth continuously decreased from 23.3, 10.3, and 8.2 to 6.8 °C. It can be seen that the circulation of drilling fluid plays an important role in reducing the temperature of the drill bit.

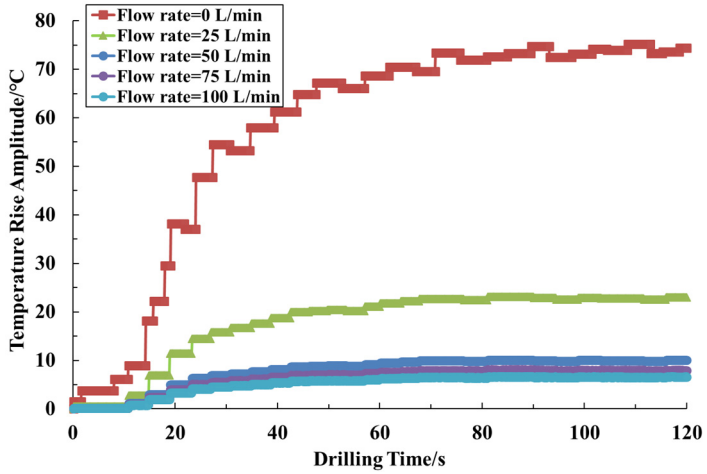



**Figure 11.** Temperature variation of PDC cutting tooth under different drilling fluid flow rates.

### *4.5. Drilling Experiment under Different Rock Type Conditions*

The WOB was maintained at 4.5 kN, with a rotation speed of 50 r/min and a drilling fluid flow rate of 50 L/min. The drilling time was set to 120 s. In order to study the temperature rise law of drill bits when drilling into different rock formations, several typical rocks were selected in order of strength from low to high, such as cement stone,

sandstone, marble, and granite. Their uniaxial compressive strength was 35.1, 77.3, 101.6, and 158.4 MPa, respectively. Under the action of circulating water at 0 °C, the temperature rise law of a PDC cutting tooth during the drilling process in different typical rocks such as cement stone, sandstone, marble, and granite was analyzed. The samples of marble and cement stone before and after drilling are shown in Figure 12.



**Figure 12.** Different rocks before and after drilling experiments (**upper**: marble, **lower**: cement stone).

From Figure 13, it can be observed that the temperature rise trend of the cutting tooth during drilling in the four types of rocks is generally similar, showing an overall fluctuating increase. However, the temperature fluctuation of the cutting tooth during drilling in granite is significantly greater than that of the drilling in marble, sandstone, and cement stone. The temperature of the cutting tooth increases rapidly with drilling time, then gradually rises, and finally reaches a dynamically stable equilibrium state.

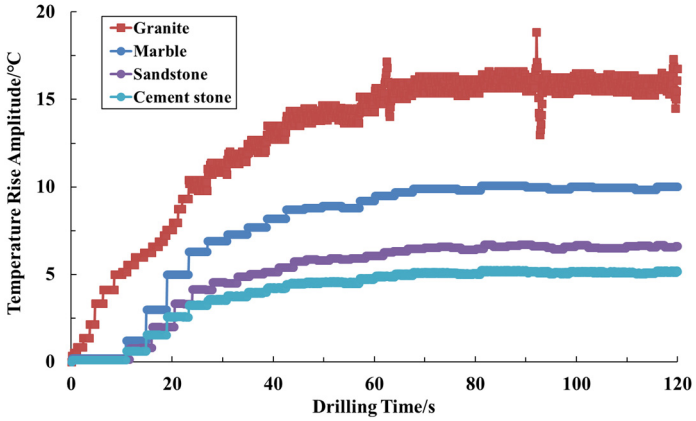



**Figure 13.** Temperature variation of PDC cutting tooth under different rock types.

As shown in Table 1, there are significant differences in the temperature rise amplitude, temperature rise rate, and ROP of the cutting tooth when PDC bits break different rocks. It can be clearly seen that when drilling granite, the temperature rise amplitude of the cutting tooth is significantly greater than when drilling marble, sandstone, and artificial cement stone, while the ROP is exactly the opposite. For granite, marble, sandstone, and

cement stone, the highest temperature rise of the PDC bit cutting tooth was 17.9, 10.3, 6.7, and 5.3 °C, respectively. When breaking sandstone and cement stone, the temperature rise rates of the cutting tooth were relatively small, at 0.056 °C/s and 0.044 °C/s, respectively, while when breaking granite and marble, the temperature rise rates were relatively large, at 0.158 °C/s and 0.086 °C/s, respectively. The rock sample also affects temperature fluctuations, with a maximum temperature fluctuation of ±3 °C when drilling granite. Therefore, it can be concluded that the temperature rise amplitude, temperature rise rate, and temperature fluctuation of a PDC bit cutting tooth all increase with the increase in rock strength, while the ROP decreases with the increase in rock strength.

**Table 1.** Statistical characteristics of temperature rise of cutting tooth under different rock types.

| Rock Type | Drilling Time (s) | Temperature Rise Amplitude (°C) | Temperature Rise Rate (°C/s) | Drilling Depth (mm) | ROP (mm/s) |
|---|---|---|---|---|---|
| Granite | 120 | 18.9 | 0.158 | 12.5 | 0.104 |
| Marble | 120 | 10.3 | 0.086 | 23.5 | 0.196 |
| Sandstone | 120 | 6.7 | 0.056 | 51.4 | 0.428 |
| Cement stone | 120 | 5.3 | 0.044 | 66.5 | 0.554 |

## 5. Conclusions

The distribution characteristics of the bottomhole temperature field are influenced by various factors, including drilling parameters such as drilling fluid flow rate, drill bit rotation speed, and WOB, as well as rock properties and drilling fluid properties. Based on the evaluation device for the distribution characteristics of the bottomhole temperature field during the rock-breaking process of a PDC drill bit developed in this study, experiments were conducted under different conditions to assess the temperature rise law of a PDC at the bottom of the well, yielding the following conclusions:

(a) The temperature rise curve during the PDC drill bit drilling process exhibits three stages: a rapid increase stage, a slow increase stage, and a relatively stable stage, with the temperature ultimately reaching dynamic equilibrium.
(b) The higher the rotation speed and the greater the WOB, the higher the temperature rise of the cutting tooth of the PDC drill bit.
(c) There is a negative correlation between flow rate and cutting tooth temperature. In this experiment, under conditions without circulating water, the highest temperature rise amplitude of the cutting tooth reached 75.2 °C.

The temperature rise amplitude, rise rate, and temperature fluctuation of the cutting tooth of the PDC drill bit increase with increasing rock strength, while the ROP decreases with increasing rock strength.

In the process of developing unconventional oil and gas using long horizontal wells, the high-speed drilling of PDC drill bits causes severe friction with formation rocks, and the combined effect of high formation temperature and cutting friction heat leads to a sharp rise in the temperature of the drill bit. Currently, the wellbore temperature calculation model ignores the impact of this temperature rise. The temperature rise law obtained by using the five-nozzle PDC composite cutter drill bit is closer to the actual drilling situation, and the relevant experimental results can be used to effectively correct the current temperature calculation model and ultimately improve the temperature prediction accuracy of the entire wellbore.

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