Research on Low-Carbon, Energy-Saving Sintering Process with Uniform Temperature for Drill Bits

Jinlong Wang $^{1,2,3,4}$, Ke Gao $^{1,2,3,4}$, Peishu Li $^{1,2,3,4}$ and Yan Zhao $^{1,2,3,4,*}$

$^1$ College of Construction Engineering, Jilin University, Changchun 130026, China; wangjl21@mails.jlu.edu.cn (J.W.); gaokenm@jlu.edu.cn (K.G.); lips@mails.jlu.edu.cn (P.L.)
$^2$ Technology Innovation Center for Directional Drilling Engineering, Ministry of Natural Resources, Langfang 065000, China
$^3$ Innovation Base for Directional Drilling Engineering, Geological Society of China, Langfang 065000, China
$^4$ Engineering Research Center of Geothermal Resources Development Technology and Equipment, Ministry of Education, Jilin University, Changchun 130026, China
$^*$ Correspondence: zhaoyan1983@jlu.edu.cn

Abstract: A low-carbon and energy-saving sintering process with uniform temperature distribution has been developed to address several issues associated with the sintering of drill bits in medium-frequency furnaces, namely, the large circumferential temperature differences, uneven heating of the mold, and low energy utilization. Theoretical calculations indicated that the output energy of the conventional drill bit sintering process was 12.7 kW·h, with an energy loss of 8.84 kW·h. The low-carbon sintering process achieved an output energy of 4.2 kW·h, with an energy loss of only 0.26 kW·h. Consequently, the energy utilization rates for the two processes were 30.4% and 93.8%, respectively. It was observed through the experiment that when sintering 76/49 mm drill bits at insulation temperatures of 900 °C and 1080 °C, the circumferential temperature differences in the mold were 43.7 °C and 48 °C, respectively, in the conventional drill bit sintering process. In contrast, the circumferential temperature differences in the mold were reduced to 8.7 °C and 11.3 °C, respectively, in the low-carbon and energy-saving sintering process with uniform temperature. This indicates that the average circumferential temperature difference in the mold can be reduced by 81.61% at 900 °C and by 76.46% at 1080 °C, leading to improved drill bit quality.

Keywords: low carbon; energy saving; uniform temperature; drill bit sintering process; circumferential temperature difference; energy efficiency

1. Introduction

In line with the progress of the “double carbon” economic system, all industries in China are committed to reducing carbon emissions. In this global context, countries worldwide have agreed to reduce greenhouse gas emissions. Additionally, China, as a major global manufacturing hub with an increasingly mature industrial chain and an expanding domestic manufacturing and processing capacity, faces the challenge of escalating carbon emissions [1–4]. However, China has limited oil and gas resources, and in order to ensure energy supply, drilling operations have extended into deeper and more complex strata, resulting in increased energy consumption during the process of extracting oil and gas resources [5]. Drilling practices have evolved from relying on traditional uphole power to downhole power. The heavy and cumbersome drilling rigs have been progressively replaced by lightweight and flexible ones. There is also a growing emphasis on efficient and durable drill bits, which play a pivotal role in drilling operations. The quality of drill bits directly impacts the drilling cycle and associated costs. Higher drilling efficiency, longer lifespan, reduced frequency of starting and stopping drilling, shorter drilling cycles, and lower drilling costs are all desirable outcomes [6–13]. When considering the energy consumption in drilling, the energy required for the bit preparation is often overlooked,
as it appears insignificant compared to the energy consumed during drilling. However, it is crucial to recognize that the energy consumption for bit preparation is a shift from a quantitative to a qualitative aspect. Drill bits are consumables, with multiple bits needed for each well, and deep well drilling may require hundreds or even thousands of bits. For instance, the Songke No 2 well utilized approximately 400 bits for completion [14], while the SG-3 well consumed approximately 18,000 drill bits [15,16]. According to statistics, the domestic drilling industry consumed around 700,000 diamond bits in 2022 [17,18]. Therefore, the energy consumption involved in bit preparation is also substantial. The main objective of this research is to reduce energy consumption in the bit preparation process.

Currently, common methods of diamond bit preparation include pressureless infiltration fabrication technology, hot processing, electroplating processing, and secondary setting. There are two main methods of preparing drill bits with the pressureless infiltration fabrication technology [19,20]. The first method involves sintering drill bits in box-type furnaces and well-type furnaces. This approach is characterized by a pressureless or vacuum environment sintering, slow heating, heat transfer from the outside to the inside, uneven heating and temperature distribution in the mold, high external temperature and low internal temperature of the mold, extended processing time, and the ability to sinter multiple drill bits in a single furnace [21–24]. The second method involves sintering drill bits in medium-frequency furnaces. Medium-frequency furnace sintering can be combined with pressurized equipment and supports pressureless sintering and hot-pressing sintering techniques. This approach helps reduce significant heat loss, and the vacuum environment during insulation covers the entire drill die and induction coil. The cooling water inside the coil creates a cooling field within a specific range, facilitating heat circulation. However, this method leads to lower energy utilization during the sintering of the drill bits [25–29].

For the equipment for preparing drill bits via hot processing as described above, firstly, the metal powder of the skeleton of the matrix is mixed according to the designed proportion, and a certain concentration of diamond is mixed in the working layer and loaded into the graphite mold; the heating and pressurization are carried out according to the designed sintering process (generally full pressure of 10–15 Mpa, maximum temperature of about 1000 °C), and the impregnated diamond drill bits can be made [30,31]. The main advantage of electroplating processing is that in the manufacturing process, the diamond does not come into contact with high temperatures; the carbonization phenomenon in diamond particles does not exist; the principle is that nickel, cobalt, and a class of metal will be deposited to the body of the drill bit in the electroplating tank; and at the same time, it scatters layers of diamond particles on the coating surface. The layers of deposited metal are used to incubate diamonds in the matrix. The disadvantage of this method is the long production cycle [32,33]. The secondary setting method involves sintering the diamond-containing nuggets via hot processing or using pressureless infiltration fabrication technology, then brazing the nuggets to the pre-sintered bit body [34]. This research primarily focuses on the process of sintering drill bits in medium-frequency furnaces in order to reduce energy consumption and improve energy utilization.

2. Materials and Methods
2.1. Experiment
2.1.1. Structural Design

During the operation of a medium-frequency furnace, the induction coil generates high-density magnetic lines that intersect with the metal material (conductive material) placed within the coil. This interaction induces eddy currents in the conductive material, which possess some characteristics of medium-frequency currents. As a result, the free electrons within the conductive material flow through the conductor, generating heat due to resistance. This phenomenon is known as electromagnetic induction [35]. In the case of sintering drill bits using a medium-frequency furnace, the heat generated for heating the mold and the steel body of the drill bit is referred to as effective heat. However, in practical production processes, a significant portion of this effective heat is dissipated into
the air and carried away by the coolant within the coil. This dissipation occurs through heat radiation, conduction, and convection, as illustrated in Figure 1 (medium-frequency furnace sintering drill principle). To maintain a consistent level of effective heat for the sintered drill bits, compensating for heat loss, the output energy of the medium-frequency furnace also increases. This relationship between energy conservation and energy utilization in the medium-frequency furnace is expressed through Equations (1) and (2).

\[ Q_a = Q_b + Q_c \]  
\[ \mu = \frac{Q_a}{Q_b} \]

Here, \( Q_a \) is the output energy of the medium-frequency furnace; \( Q_b \) is the energy of the sintered drill bit; \( Q_c \) is the energy loss during the sintering of the drill bit; and \( \mu \) is energy utilization.

As evident from Equations (1) and (2) and the drill bit sintering principle depicted in Figure 1, the enhancement of energy utilization in the sintering of drill bits can only be accomplished by reducing energy loss during the process. During drill bit sintering, heat dissipation occurs through heat radiation, heat conduction, and heat convection. The high-temperature field generated around the steel body and mold dissipates outward into the surrounding low-temperature environment (low-temperature field) via heat radiation and conduction (with air as the conduction medium). Additionally, a small portion of heat is carried away by the air and coolant through heat convection. The significant heat loss substantially reduces the energy utilization rate of drill sintering. To mitigate heat...
dissipation from the drill bit mold and steel body to the environment through heat radiation, conduction, and convection, it is proposed to minimize heat conduction energy loss, alter the heat convection medium, avoid heat convection dissipation, and redirect heat radiation toward the high-temperature field. This approach aims to improve the energy utilization rate of drill bit sintering, as illustrated in Figure 2. Asbestos material possesses excellent refractory, electrical insulation, and adiabatic properties, making it a valuable material for fireproofing, insulation, and thermal insulation purposes. In this study, heat insulation materials are employed to hinder heat conduction and convection between the mold and steel body. These materials also reflect heat radiation and facilitate heat circulation within the internal space created by the heat insulation sleeve and pads. Consequently, heat loss is reduced, and the energy utilization rate is improved.

![Figure 2](image_url)

**Figure 2.** Principle of low-carbon, energy-saving sintered drill bit with uniform temperature.

The low-carbon and energy-saving sintering structure with uniform temperature, depicted in Figure 3, has been designed based on the principles of low-carbon and energy-saving sintering with uniform temperature for drills shown in Figure 2. The structure consists of several components: the insulated cap (1), insulated housing (2), and insulation pads (6), which collectively create a heat insulation space. This space effectively isolates the steel body (4) and mold (5) used in the sintering of the drill bit from heat dissipation. The large-diameter insulation pad (7), slightly larger than the insulation pads (6), helps stabilize the overall structure, preventing instability in the center of gravity and further isolates heat between the insulation pads (6) and the rotating mechanism. The rotating mechanism involves the rotating platform (8), bearings (9), fixed platform (10), and motor (11). During the sintering process of the drill bit, this mechanism ensures smooth and slow rotation, promoting more uniform sintering and improving drill bit quality. Temperature
measurement holes (13) are provided to monitor the temperature and adjust the sintering temperature of the drill bit and the circumferential temperature difference of the mold during the sintering process. Wiring holes (14) are used to connect the motor via cables, providing electrical power. The insulated housing fixing projection (15) and the induction coil (3) serve to secure the insulated housing in place.

The large-diameter insulation pad (7), slightly larger than the insulation pads (6), helps stabilize the overall structure, preventing instability in the center of gravity and further isolates heat between the insulation pads (6) and the rotating mechanism. The rotating mechanism involves the rotating platform (8), bearings (9), fixed platform (10), and motor (11). During the sintering process of the drill bit, this mechanism ensures smooth and slow rotation, promoting more uniform sintering and improving drill bit quality. Temperature measurement holes (13) are provided to monitor the temperature and adjust the sintering temperature of the drill bit and the circumferential temperature difference of the mold during the sintering process. Wiring holes (14) are used to connect the motor via cables, providing electrical power. The insulated housing fixing projection (15) and the induction coil (3) serve to secure the insulated housing in place.

Figure 3. Low-carbon, energy-saving sintering structure with uniform temperature. (1) Insulated cap; (2) insulated housing; (3) induction coil; (4) steel body; (5) mold; (6) insulation pad; (7) large-diameter insulation pad; (8) rotating platform; (9) bearing; (10) fixed platform; (11) motor; (12) base; (13) temperature measurement hole; (14) wiring hole; and (15) insulated housing fixed.

2.1.2. Experiment

In order to assess the viability of the low-carbon and energy-saving sintering structure with uniform temperature, an experimental investigation was conducted. The study encompassed two comparative experiments: one on the energy consumption of the sintered drill bit and the other on the temperature uniformity of the sintered drill bit. The experimental methodology involved measuring the electric energy utilized for sintering a drill bit of the same size using both the conventional sintering method and the low-carbon and energy-saving sintering method with uniform temperature, employing an electric energy meter. Furthermore, an infrared thermometer was employed to measure the circumferential temperature difference during the sintering process between the conventional method and the low-carbon, energy-saving sintering method with uniform temperature. The sintered drill bit under investigation had dimensions of 76/49 mm and was a center-set impregnated diamond drill bit.

Energy Consumption Comparison Experiment

Figure 4 depicts the equipment used in the drill bit sintering process. The electric energy meter is installed at the input of the medium frequency furnace to measure the electric energy consumed during the sintering of the drill bit. The medium-frequency furnace consists of the control box, transformer, cooling pool, and induction coils. The cooling pool serves as a connection between the transformer and the induction coils. To regulate the sintering temperature of the drill bits and monitor the circumferential temperature difference of the mold, an infrared thermometer is positioned on the outer
layer of the coils. The thermometer is connected to a temperature display that presents the sintering temperature.

Figure 4. Drill bit sintering process equipment.

By conducting a comparison between the conventional drill bit sintering process and the low-carbon and energy-saving sintering process with uniform temperature, the power consumption in each process was measured separately. Figure 5a illustrates the conventional drill bit sintering process, while Figure 5b depicts the low-carbon and energy-saving sintering process with uniform temperature. The corresponding temperature curves are presented in Figure 6. From Figure 6, it is apparent that the overall trends of the sintering temperature curves in both processes are similar. Initially, the temperature rises to 450 °C, where it is held for 2 min to dry the mold and skeleton material. Subsequently, it is heated to 900 °C and held for 5 min to ensure complete melting of the silver brazing flux, which fills the capillary channels formed by the skeleton material. The temperature is then increased to 1080 °C and maintained for 20 min to achieve the melting of the bonding metal, resulting in the encapsulation of the diamond with the skeleton material. The final step involves natural cooling to complete the drill sintering process. While the heating time, heating power, and heat preservation power slightly differ between the two processes, the overall sintering procedure follows a similar pattern. In the conventional drill bit sintering process, heating is carried out at 10 kW for 4 min to reach 450 °C, followed by a 2 min heat preservation period. Subsequently, the temperature is raised to 900 °C with a heating power of 20 kW for 5 min, followed by a 5 min heat preservation period. Finally, the temperature is further increased to 1080 °C using a heating power of 30 kW for 5 min, followed by a 20 min heat preservation period under 20 kW power. In the low-carbon and energy-saving sintering process with uniform temperature, the heating procedure involves 10 kW of power for 1 min to reach 450 °C, followed by a 2 min heat preservation period. The temperature is then raised to 900 °C with 20 kW power for 2 min, followed by a 5 min heat preservation period. Finally, the temperature is increased to 1080 °C using 20 kW power for 2 min, and a 20 min heat preservation period is maintained under 1–2 kW power. The changes in the electric energy meter during the sintering of one drill bit using the conventional drill bit sintering process are presented in Figure 7, while Figure 8 illustrates the changes in the electric energy meter before and after sintering one drill bit using the low-carbon and energy-saving sintering process with uniform temperature. The specific electric energy consumption values are provided in Table 1.

Temperature Distribution Uniformity Comparison Experiment

In the conventional drill bit sintering process, the mold remains fixed during sintering. However, due to the unique structure of the induction coils, the magnetic induction lines they generate are not uniform. As a result, there are local variations in heating rate during the sintering process, with some areas heating too quickly while others heat slowly. This research focuses on addressing this issue through optimization. The goal is to achieve a uniform heating of the mold throughout the sintering process. This is approached in
two ways. Firstly, by improving the distribution of magnetic induction lines generated with the heating coils. Secondly, by allowing the fixed mold to rotate at a consistent speed. This rotation ensures that the magnetic induction lines pass through every part of the mold, resulting in a more even heating of the drill bit during sintering. Figure 9 illustrates the rotary sintering mechanism designed in this study, comprising rotating platforms (8), bearings (9), fixed platforms (10), and motors (11). The motor is selected as a PFDE68KYYZ synchronous motor, and the corresponding parameters of rotational speed and torque are as follows in Table 2. The motor drives the rotation of the mold at a uniform speed, enabling even heating. Additionally, the rotating mechanism can complete one rotation to measure the circumferential temperature difference during the conventional drill bit sintering process. Therefore, in this paper, the combination of low speed and high torque is selected; the motor speed is 1.2 r/min, and the torque is 7.0 N·cm. Experimental data on the circumferential temperature difference between the conventional drill bit sintering process and the low-carbon and energy-saving sintering process with uniform temperatures for drill bit sintering and insulation at 900 °C and 1080 °C are provided in Table 3. Furthermore, Figure 10 displays the four drill bits sintered during the experiments. Since this paper mainly studies the sintering process of the drill bits, the matrix of four drill bits is without a diamond. In order to further test the hardness of the drill bits and whether they can meet the drilling demand in the field test, the drill bits were prepared and tested for hardness, as shown in Figure 11, and the hardness of the working layer was tested to be 38 (HRC) in the plane of the two cutting teeth opposite to each other of the drill bits. At the same time, the drilling was carried out in the field test in Tangshan City, Hebei Province, China. The test results show that the drill bit wear resistance, impact strength, and other parameters can meet the normal drilling requirements.

Figure 5. Bit sintering without pressure.
Figure 6. Sintering temperature curve of drill bit.

(a) Conventional sintering process
(b) Low-carbon and energy-saving sintering process

Insulation power: 20KW
Insulation power: 1~2KW

Sintering time (min)

Figure 7. Electricity consumption of conventional drill bit sintering process (a) Before sintering; (b) After sintering.

(a) (b)

Figure 8. Power consumption of low-carbon, energy-saving sintering process with uniform temperature. (a) First drill bit; (b) second drill bit; and (c) third drill bit.

(a) (b) (c)
Table 1. Comparison of the power consumption of two sintering processes.

<table>
<thead>
<tr>
<th>Sintering Process</th>
<th>Insulation Time (min)</th>
<th>Insulation Power (kW)</th>
<th>Insulation Power (kW)</th>
<th>Electric Energy Consumption (kW·h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional drill bit sintering process</td>
<td>20</td>
<td>20–21</td>
<td>41</td>
<td>15.2</td>
</tr>
<tr>
<td>Low-carbon, energy saving sintering process with uniform temperature</td>
<td>20</td>
<td>1–2</td>
<td>32</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Table 2. Rotation speed and torque parameters.

<table>
<thead>
<tr>
<th>rpm</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque(N·cm)</td>
<td>7.0</td>
<td>6.0</td>
<td>3.2</td>
<td>2.4</td>
<td>1.6</td>
<td>1.2</td>
<td>0.95</td>
<td>0.55</td>
<td>0.45</td>
<td>0.37</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Figure 9. Rotary sintering mechanism. (8) Rotating platform; (9) bearing; (10) fixed platform; and (11) motor.
Table 3. Experimental data of circumferential temperature difference.

<table>
<thead>
<tr>
<th>Drill Sintering Process</th>
<th>Insulation Temperature (°C)</th>
<th>Minimum Temperature (°C)</th>
<th>Maximum Temperature (°C)</th>
<th>Mean Temperature Difference (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional drill bit sintering process</td>
<td>900</td>
<td>873</td>
<td>918</td>
<td>43.7</td>
</tr>
<tr>
<td></td>
<td>1080</td>
<td>1043</td>
<td>1090</td>
<td>48</td>
</tr>
<tr>
<td>Low-carbon, energy-saving sintering process with uniform temperature</td>
<td>900</td>
<td>891</td>
<td>904</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>1080</td>
<td>1079</td>
<td>1093</td>
<td>11.3</td>
</tr>
</tbody>
</table>

Figure 10. Experimental sintered drill bits.

2.1.3. Analysis of Experimental Results

The results of the energy consumption comparison experiment reveal that, under the same experimental conditions, sintering one drill bit using the conventional drill bit sintering process requires 41 min and consumes 15.2 kW·h of electrical energy. On the other hand, sintering one drill bit using the low-carbon and energy-saving sintering process with uniform temperature requires 32 min and has an average electrical energy consumption of 6.63 kW·h. When compared to the conventional process, the low-carbon and energy-saving sintering process with uniform temperature achieves a time reduction of 21.95% and a decrease of 56.38% in electrical energy consumption. Shortening the sintering time enhances drill bit production efficiency, while reducing energy consumption during the sintering process lowers the production costs and improves efficiency. The temperature distribution uniformity comparison experiment demonstrates that, under the same sintering parameters, the average circumferential temperature difference between the mold at the insulation temperature of 900 °C and 1080 °C is 47.3 °C and 48 °C, respectively, in the conventional drill bit sintering process. Conversely, in the low-carbon and energy-saving sintering process with uniform temperature, the average circumferential temperature difference between the mold at the insulation temperature of 900 °C and 1080 °C is 8.7 °C and 11.3 °C, respectively. Compared to the conventional process, the average circumferential temperature difference of the 900 °C mold is reduced by 81.61%, while that of the 1080 °C mold is reduced by 76.46%.
2.2. Energy Loss Calculation

In order to assess the energy loss in both the conventional drill bit sintering process and the low-carbon energy-saving sintering process with uniform temperature, calculations were performed using Fourier’s Law, Stefan–Boltzmann Law, and Newton’s Law of Cooling. These calculations were used to determine the heat loss of the graphite mold in both the ambient air and the insulation system, where the primary material used was asbestos material [36–38].

2.2.1. Energy Loss of Conventional Drill Bit Sintering Process

In this study, we selected Φ76/49 mm center-set impregnated diamond drill bits as our case study. The graphite mold used had a diameter of 200 mm and a height of 300 mm. The calculations are presented below:
The output energy of a medium-frequency furnace for the conventional drill bit sintering process $Q_1$ is as follows:

$$Q_1 = P_{n1} \cdot T_{n1} = 10 \times \frac{4 + 2}{60} + 20 \times \frac{5 + 5 + 20}{60} = 12.7 \text{ kW} \cdot \text{h} \quad (3)$$

The energy loss of sintered drill bits via the conventional drill bit sintering process $Q_2$ is as follows:

$$Q_2 = \begin{cases} \frac{(V_1 + V_2 + V_3) \cdot t_1}{d_1} \\ V_1 = k_1 \cdot A \cdot (T_1 - T_2) \\ V_2 = \varepsilon \cdot \sigma \cdot A \cdot (T_1^4 - T_2^4) \\ V_3 = h_1 \cdot A \cdot (T_1 - T_2) \end{cases} \quad (4)$$

The sintering of drill bits consists of two processes: the warming sintering process and the heat preservation sintering process. The warming sintering process comprises three stages, while the heat preservation sintering process also consists of three stages. The calculations for these stages are as follows:

$$Q_2 = \sum_{i=1}^{6} (V_{1i} + V_{2i} + V_{3i}) \cdot t_i$$

The calculation using Equation (5) leads to

$$Q_2 \approx 3.2 \times 10^7 \approx 8.84 \text{ kW} \cdot \text{h} \quad (6)$$

Effective energy of sintering drill bits via the conventional drill bit sintering process $Q_3$:

$$Q_3 = Q_1 - Q_2 = 12.7 - 8.84 = 3.86 \text{ kW} \cdot \text{h} \quad (7)$$

Energy utilization ratio $\mu_1$:

$$\mu_1 = \frac{Q_3}{Q_1} = \frac{3.86}{12.7} = 30.4\% \quad (8)$$

The meanings of the letters in the equations are listed in Table 4.

2.2.2. Energy Loss of Low-Carbon, Energy-Saving Sintering Process with Uniform Temperature

Low-carbon, energy-saving sintering process with uniform temperature and medium-frequency furnace output energy $Q_4$:

$$Q_4 = P_{n2} \cdot T_{n2} = 10 \times \frac{1 + 2}{60} + 20 \times \frac{2 + 5 + 2}{60} + 1.5 \times \frac{20}{60} = 4.2 \text{ kW} \cdot \text{h} \quad (9)$$

During the sintering of drill bits using the low-carbon, energy-saving sintering process with uniform temperature, heat is dissipated through both heat conduction and heat radiation. The heat transferred through heat radiation from the graphite mold follows two paths: it is either reflected by the asbestos insulation material or absorbed by the asbestos material. The heat radiation that is reflected by the asbestos is redirected back to the graphite mold, effectively reusing the heat. However, the portion absorbed by the asbestos material results in heat loss. The absorption capacity of a material for heat radiation
depends on factors such as the material itself, its color, thickness, and surface roughness. In this study, a white asbestos hollow column with a thickness of 10 mm was chosen as the insulation material. Due to its extremely low rate of heat radiation absorption, the radiation energy absorbed by the asbestos insulation material was disregarded. Therefore, the heat conduction between the graphite mold and the asbestos insulation material was the focus of consideration.

Table 4. Letter meaning.

<table>
<thead>
<tr>
<th>Name</th>
<th>Meaning</th>
<th>Unit</th>
<th>Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q_1</td>
<td>Medium-frequency furnace output energy</td>
<td>kW·h</td>
<td></td>
</tr>
<tr>
<td>P_{n1}</td>
<td>Medium-frequency furnace output power</td>
<td>kW</td>
<td></td>
</tr>
<tr>
<td>T_{n1}</td>
<td>time</td>
<td>h</td>
<td></td>
</tr>
<tr>
<td>Q_2</td>
<td>Energy loss of sintered drill bits via conventional drill bit sintering process</td>
<td>J</td>
<td></td>
</tr>
<tr>
<td>Q_3</td>
<td>Effective energy of sintering drill bits via conventional drill sintering process</td>
<td>kW·h</td>
<td></td>
</tr>
<tr>
<td>V_1</td>
<td>Air heat transfer rate</td>
<td>W/(m·°C)</td>
<td></td>
</tr>
<tr>
<td>V_2</td>
<td>Graphite mold heat radiation rate</td>
<td>W/(m·°C)</td>
<td></td>
</tr>
<tr>
<td>V_3</td>
<td>Air heat convection rate</td>
<td>W/(m·°C)</td>
<td></td>
</tr>
<tr>
<td>t_1</td>
<td>Sintering time of conventional drill bit sintering process</td>
<td>s</td>
<td></td>
</tr>
<tr>
<td>k_1</td>
<td>Air thermal conductivity coefficient</td>
<td>W/(m·°C)</td>
<td>0.026</td>
</tr>
<tr>
<td>A</td>
<td>Heat source surface area</td>
<td>m²</td>
<td>0.2512</td>
</tr>
<tr>
<td>T_1</td>
<td>Graphite mold temperature</td>
<td>°C</td>
<td>20</td>
</tr>
<tr>
<td>T_2</td>
<td>Air temperature</td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>d_1</td>
<td>Distance between graphite mold and air</td>
<td>m</td>
<td>0.15</td>
</tr>
<tr>
<td>ε</td>
<td>Graphite mold thermal emissivity</td>
<td></td>
<td>0.8~0.9</td>
</tr>
<tr>
<td>σ</td>
<td>Stephan–Boltzmann constant</td>
<td>W/(m²·°C⁴)</td>
<td>5.67×10⁻⁸</td>
</tr>
<tr>
<td>h_1</td>
<td>Convection heat transfer coefficient</td>
<td></td>
<td>9.85</td>
</tr>
<tr>
<td>µ_1</td>
<td>Energy utilization ratio</td>
<td>%</td>
<td></td>
</tr>
</tbody>
</table>

Low-carbon, energy-saving sintering process with uniform temperature sintering drill bit energy loss Q_5 is as follows:

\[ Q_5 = V_4 \cdot t_2 = 2\pi k_2 L \cdot \sum_{i=1}^{6} \left( \frac{T_{1i} - T_{3i}}{\ln \frac{r_2}{r_1}} \right) \cdot \sum_{i=1}^{6} t_i = 933348 \text{ J} \approx 0.26 \text{ kW·h} \]  

(10)

Low-carbon, energy-saving sintering process with uniform temperature sintering drill bit effective energy Q_6 is as follows:

\[ Q_6 = Q_4 - Q_5 = 4.2 - 0.26 = 3.94 \text{ kW·h} \]  

(11)

Energy utilization ratio µ_2:

\[ \mu_2 = \frac{Q_6}{Q_4} = \frac{3.94}{4.2} = 93.8\% \]  

(12)

The meanings of the letters in the equations are listed in Table 5.

2.2.3. Calculation of Carbon Dioxide Emissions

The following is derived from experimental and theoretical calculations: The actual energy consumption for sintering one drill bit in the conventional sintering process is 15.2 kW·h, while the actual energy consumption for sintering one drill bit in the low-carbon, energy-saving sintering process with uniform temperature is 6.63 kW·h; standard coal produces about 300 g/kW·h of electricity, and standard coal contains about 0.862% carbon [39]. Then, the standard coal consumption and carbon dioxide emissions from the sintering processes of two drill bits for the preparation of one drill bit of a size of 76/49 mm are given in the following equations:
(1) Conventional drill bit sintering process

\[ M_1 = Q_{\text{as1}} \times \varphi = 15.2 \times 300 = 4560 \text{ g} \quad (13) \]

\[ M_{C1} = 4560 \times 0.862 \times 44 = 172951.68 \text{ g} \quad (14) \]

(2) Low-carbon, energy-saving sintering process with uniform temperature

\[ M_2 = Q_{\text{as2}} \times \varphi = 6.63 \times 300 = 1989 \text{ g} \quad (15) \]

\[ M_{C2} = 1989 \times 0.862 \times 44 = 75438.792 \text{ g} \quad (16) \]

\[ \mu_1 = \frac{M_{C1} - M_{C2}}{M_{C2}} \times 100\% = 56.38\% \quad (17) \]

Here, \( M_1 \) is the mass of standard coal required for sintering a 76/49 mm drill bit using a conventional drill bit sintering process; \( M_2 \) is the mass of standard coal required for sintering a 76/49 mm drill bit using a low-carbon, energy-saving uniform temperature sintering process; \( M_{C1} \) is the mass of carbon dioxide emitted by sintering a 76/49 mm drill bit in a conventional drill sintering process; \( M_{C2} \) is the mass of carbon dioxide emitted by sintering a 76/49 mm drill bit in a low-carbon, energy-saving sintering process with uniform temperature; and \( \mu_1 \) is the percentage reduction in carbon dioxide emissions.

### Table 5. Letter meaning.

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Meaning</th>
<th>Unit</th>
<th>Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q4</td>
<td>Low-carbon, energy-saving sintering process with uniform temperature</td>
<td>medium-frequency furnace output energy</td>
<td>kW·h</td>
<td></td>
</tr>
<tr>
<td>Q5</td>
<td>Low-carbon, energy-saving sintering process with uniform temperature</td>
<td>sintering drill bit energy loss</td>
<td>J</td>
<td></td>
</tr>
<tr>
<td>Q6</td>
<td>Low-carbon, energy-saving sintering process with uniform temperature</td>
<td>sintering drill bit effective energy</td>
<td>J</td>
<td></td>
</tr>
<tr>
<td>V4</td>
<td>Low-carbon, energy-saving sintering process with uniform temperature</td>
<td>Asbestos heat transfer rate</td>
<td>W/(m·°C)</td>
<td></td>
</tr>
<tr>
<td>t2</td>
<td>Low-carbon, energy-saving sintering process with uniform temperature</td>
<td>sintering time</td>
<td>s</td>
<td></td>
</tr>
<tr>
<td>k2</td>
<td>Asbestos thermal conductivity ( k = 0.04 \sim 0.06 )</td>
<td></td>
<td>W/(m·°C)</td>
<td>0.05</td>
</tr>
<tr>
<td>L</td>
<td>Asbestos length</td>
<td></td>
<td>m</td>
<td>0.3</td>
</tr>
<tr>
<td>T1</td>
<td>Graphite mold temperature</td>
<td></td>
<td>°C</td>
<td>20</td>
</tr>
<tr>
<td>T3</td>
<td>Asbestos temperature</td>
<td></td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>r1</td>
<td>Asbestos inner radius</td>
<td></td>
<td>m</td>
<td>0.1</td>
</tr>
<tr>
<td>r2</td>
<td>Asbestos outer radius</td>
<td></td>
<td>m</td>
<td>0.12</td>
</tr>
<tr>
<td>µ2</td>
<td>Energy utilization ratio</td>
<td></td>
<td>%</td>
<td></td>
</tr>
</tbody>
</table>

### 2.2.4. Analysis of Calculation Results

The calculations reveal that the output energy of the medium frequency furnace for sintering 76/49 mm drill bits using the conventional drill bit sintering process is 12.7 kW·h. On the other hand, the output energy of the medium-frequency furnace for sintering drill bits using the low-carbon, energy-saving sintering process with uniform temperature is 4.2 kW·h. This translates to energy losses of 8.84 kW·h and 0.26 kW·h, respectively. The effective energy required for sintering drill bits is calculated to be 3.86 kW·h and 3.94 kW·h for the conventional and low-carbon, energy-saving sintering processes with uniform temperature, respectively. Theoretically, the effective energy for sintering drill bits should be the same in both processes. However, since the radiation energy in the low-carbon, energy-saving sintering process with uniform temperature was not taken into account, the effective energy for sintering drill bits in this process is slightly higher than in the conventional drill bit sintering process. The energy utilization rates for sintering drill bits are determined to be 30.4% for the conventional process and 93.8% for the low-carbon,
energy-saving sintering process with uniform temperatures. Clearly, the energy utilization rate for sintering drill bits is significantly higher in the low-carbon, energy-saving sintering process with uniform temperatures compared to the conventional drill bit sintering process.

3. Discussion

Based on the drill bit sintering experiments and theoretical calculations, the following conclusions can be drawn: Under identical conditions, the power consumption for sintering a $\Phi 76/49$ mm drill bit using the conventional drill bit sintering process is 15.2 kW·h, while the theoretically calculated output power of the medium-frequency furnace is 12.7 kW·h. In contrast, the average power consumption for sintering a $\Phi 76/49$ mm drill bit using the low-carbon, energy-saving sintering process with uniform temperature is 6.63 kW·h, with a corresponding theoretical output power of 4.2 kW·h for the medium-frequency furnace. It should be noted that the actual power consumption of a drill bit sintered in the medium-frequency furnace is slightly higher than the calculated value. This additional power consumption is defined as auxiliary power consumption, which includes the power consumed via the cooling pump in the cooling pool and the power generated via the transformer heating. The specific values are as follows:

$$Q_{a1} = Q_{s1} - Q_1 = 15.2 - 12.7 = 2.5 \text{ kW·h}$$  \hspace{1cm} (18)

$$Q_{a2} = Q_{s2} - Q_4 = 6.63 - 4.2 = 2.43 \text{ kW·h}$$  \hspace{1cm} (19)

In the equation:

- $Q_{a1}$ represents the auxiliary power consumption of the conventional drill bit sintering process;
- $Q_{a2}$ represents the auxiliary power consumption of the low-carbon, energy-saving sintering process with uniform temperature;
- $Q_{s1}$ denotes the electric energy consumption of the experimentally sintered drill bit using the conventional drill bit sintering process;
- $Q_{s2}$ corresponds to the power consumption of the experimentally sintered drill bit using the low-carbon, energy-saving sintering process with uniform temperature.

Through calculations, it is observed that the auxiliary electrical energy consumption of the low-carbon, energy-saving sintering process with uniform temperature is slightly lower compared to the conventional drill bit sintering process. This difference arises from the fact that the auxiliary electrical energy consumption is dependent on the sintering time. In the conventional process, it takes 41 min to sinter one drill bit, whereas the low-carbon, energy-saving sintering process with uniform temperature only requires 32 min. As the sintering time increases, more energy is needed for the cooling pump and transformer heating, resulting in higher auxiliary electrical energy consumption. Consequently, the low-carbon, energy-saving sintering process with uniform temperature exhibits relatively lower auxiliary electrical energy consumption.

The output energy of the medium-frequency furnace for sintering 76/49 mm drill bits is calculated as 12.7 kW·h for the conventional drill sintering process and 4.2 kW·h for the low-carbon, energy-saving sintering process with uniform temperature. This indicates energy losses of 8.84 kW·h and 0.26 kW·h, respectively. The effective energy required for sintering drill bits is calculated as 3.86 kW·h and 3.94 kW·h for the conventional and low-carbon, energy-saving sintering processes with uniform temperature, respectively. As the sintered drill bits are of the same size, the effective energy required for sintering is similar in both processes. The low-carbon, energy-saving sintering process with uniform temperature effectively mitigates heat convection through the use of asbestos material and reflects heat radiation back into the high-temperature environment. Additionally, the low thermal conductivity of asbestos material contributes to improved energy utilization.
4. Conclusions

This research investigates the low-carbon, energy-saving sintering process with uniform temperature from three perspectives: design, experiments, and theoretical calculations, yielding the following findings:

(1) Under the same experimental conditions, the conventional drill bit sintering process requires 41 min of sintering time and consumes 15.2 kW-h of electrical energy. In contrast, the low-carbon, energy-saving sintering process with uniform temperature only needs 32 min of sintering time and has an average electrical energy consumption of 6.63 kW-h. Compared to the conventional process, the low-carbon, energy-saving sintering process reduces the sintering time by 21.95% and decreases electrical energy consumption by 56.38%. This reduction in sintering time improves drill production efficiency, while energy savings contribute to cost reduction and increased efficiency;

(2) Under the same sintering parameters, the average circumferential temperature difference between the mold at insulation temperatures of 900 °C and 1080 °C is 47.3 °C and 48 °C, respectively, in the conventional drill sintering process. In contrast, the low-carbon, energy-saving sintering process with uniform temperature exhibits average circumferential temperature differences of 8.7 °C and 11.3 °C at the same insulation temperatures. Compared to the conventional process, the low-carbon, energy-saving sintering process reduces the average circumferential temperature difference of the mold at 900 °C by 81.61% and at 1080 °C by 76.46%;

(3) Through calculations, it is determined that the energy output of the medium frequency furnace for sintering 76/49 mm drill bits is 12.7 kW-h in the conventional drill bit sintering process, with an energy loss of 8.84 kW-h. In the low-carbon, energy-saving sintering process with uniform temperature, the energy output is 4.2 kW-h, with an energy loss of 0.26 kW-h. The energy utilization rates for sintered drill bits in the two processes are 30.4% and 93.8%, respectively. The low-carbon, energy-saving sintering process with uniform temperature exhibits significantly higher energy utilization compared to the conventional drill bit sintering process.

(4) In summary, this paper takes the diameter of the 76/49 mm impregnated diamond drill bit as an example and elaborates on the low-carbon, energy-saving sintering process with uniform temperature of low-carbon, energy-saving, high-efficiency features; with the increase in the diameter of the drill bit and insulation time, the energy utilization will be higher, and the circumferential temperature difference of the drill bit will be more uniform. For China’s annual consumption of 700,000 diamond drill bits, drill sintering energy savings of at least 1,799,700,000 kW-h—equivalent to 539,900 tons of standard coal power generation, reducing carbon dioxide emissions by 68,259,000 tons—has good application prospects in the field of drill preparation. However, the effect of drill sintering temperature uniformity on drill quality is difficult to be quantitatively detected with experiments, so further in-depth research on the effect of sintering temperature uniformity on drill quality is needed to determine the quantitative relationship between circumferential temperature difference and drill quality.

Author Contributions: Conceptualization, K.G.; Data curation, J.W.; Formal analysis, J.W.; Investigation, J.W. and P.L.; Methodology, J.W. and P.L.; Project administration, Y.Z.; Resources, J.W.; Supervision, K.G.; Writing—Original Draft, J.W.; Writing—Review and Editing, Y.Z. and K.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Technology Innovation Center for Directional Drilling Engineering, Ministry of Natural Resources, Innovation Base for Directional Drilling Engineering, Geological Society of China (Grant No. KF202304 and No. KF202307), the National Key R&D Program of China (Grant No. 2022YFC3005903–2), the National Natural Science Foundation of China (Grant No. 41972324 and No. 42172345), and the Engineering Research Center of Geothermal Resources Development Technology and Equipment, Ministry of Education, Jilin University (Grant No. 23021 and No. 23022).

Data Availability Statement: Data are available upon request from the authors.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.