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Study on Temperature Rise Characteristics of Granite Irradiated by Millimeter Waves

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Abstract

To clarify the thermal response law of granite under millimeter wave irradiation, this study combines experiments with COMSOL simulations. Taking homogeneous granite standard samples as the research object, different irradiation durations are set, and surface and internal temperature data are collected by an infrared temperature measurement system to explore the effects of irradiation parameters and rock properties on temperature rise characteristics. The results show that the energy of millimeter waves attenuates sharply when propagating in granite, with the highest electric field intensity at the central point of the surface and an inverted cone-shaped uniform distribution inside. The temperature rise of granite presents a nonlinear characteristic of "rapid growth - slow stabilization", and the temperature increases with irradiation duration. The surface temperature is higher than the internal temperature, forming an inverted cone-shaped layered temperature field, and the temperature rise rate decreases with the increase of irradiation depth. Compared with sandstone, granite shows overall uniform temperature rise due to its dense structure and good thermal conductivity, while sandstone exhibits extreme local overheating. The difference between the two originates from the different thermophysical properties. The experiment and simulation are highly consistent in the temperature of characteristic points, maximum temperature and temperature field distribution, verifying the reliability of the simulation model. This study reveals the energy transfer and conversion mechanism between millimeter waves and granite, and provides key experimental basis and theoretical support for the application of millimeter wave technology in engineering fields such as rock cutting, underground drilling and oil exploration.

Keywords

Millimeter Waves; Electric Field Intensity; Temperature Rise Characteristics; Granite.

1. Introduction

Mechanical drilling is the current mainstream method for extracting deep mineral resources, and its technology has been quite mature [1-2]. During mechanical drilling, downhole tools and drill bits act directly on the rock formation. When facing deep hard rock formations, the drilling cost is high and the cycle is long due to mechanical wear and other factors. Therefore, high-energy beams such as lasers or microwaves are considered for non-contact drilling to achieve rapid rock breaking. Laser beams were first used in non-contact drilling research, but due to physical and technical factors (such as Rayleigh scattering, light source efficiency, etc.), they are still in the laboratory research stage [3]. Microwaves overcome the limitations of infrared laser technology, and their transmission is less affected by dust. Theoretically, continuous drilling can be achieved, so microwave drilling technology has gradually become a research focus [4-8].

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As a special band in the electromagnetic spectrum with strong directionality, concentrated energy and moderate penetration, millimeter waves have shown broad application prospects in industrial processing, geological exploration, disaster management and other fields. Granite, as one of the most widely distributed magmatic rocks in the earth's crust, is widely used in construction engineering, mineral development and underground space construction due to its high strength and high stability physical and mechanical properties. Its thermal response characteristics under external energy directly affect the safety and efficiency of related projects.

Since the rise of laser technology in the 1960s, experts and scholars at home and abroad have conducted research on laser drilling for more than 50 years. Although theoretical research has confirmed that laser drilling can significantly improve mechanical drilling speed and reduce drilling costs, no literature report on penetration depth exceeding 1m has been seen so far, let alone on-site application [9-14].

Millimeter wave rock breaking technology began in 2008. The Massachusetts Institute of Technology (MIT) took the lead in carrying out directional high-power millimeter wave drilling tests and found that 28GHz millimeter waves can heat granite to above 3000℃, causing it to melt and gasify, and the energy absorption rate of millimeter waves in rocks is better than that of lasers [15]. In the process of implementing the International Thermonuclear Experimental Reactor (ITER) plan, a millimeter wave gyrotron transmitter with a frequency of 110~170GHz and a power of 1MW has been successfully developed, with a power conversion efficiency exceeding 50%. In addition, a short-pulse millimeter wave gyrotron transmitter with a frequency of 200~300GHz and a power of 1MW has also been successfully developed [16-18]. In 2021, the research institute carried out research on rapid drilling technology for high-power millimeter wave energy heating and penetrating rocks based on a 140GHz high-power millimeter wave system [19].

The temperature rise of materials under millimeter wave irradiation is essentially a process of converting electromagnetic energy into thermal energy. This conversion process is mainly affected by the material’s dielectric properties, thermophysical parameters and irradiation parameters. Most studies on temperature rise of materials under millimeter wave irradiation focus on homogeneous materials such as metals and polymers. In contrast, for heterogeneous rocks composed of minerals such as feldspar, quartz and mica, the temperature rise mode, energy absorption mechanism and the influence of mineral composition on temperature rise characteristics after millimeter wave irradiation have not been systematically studied. Existing studies mostly focus on the thermal response of rocks under traditional heating methods. The instantaneous temperature rise characteristics, temperature distribution and the mechanism of key influencing factors of granite under millimeter wave irradiation have not been deeply explored, which results in the lack of theoretical basis for the application of millimeter wave technology in rock engineering.

This study takes granite as the research object, systematically explores its temperature rise characteristics under millimeter wave irradiation, focuses on analyzing the effects of irradiation parameters and the rock’s own properties on temperature rise rate, peak temperature and temperature field distribution, and reveals the energy transfer and conversion mechanism of millimeter waves in granite. The research results not only provide theoretical support for the application of millimeter wave technology in engineering scenarios such as rock cutting, breaking and underground drilling, but also improve the basic theory of interaction between millimeter waves and rocks.

2. Theoretical Basis of Millimeter Wave Heating

Millimeter waves belong to the extremely high-frequency band in the electromagnetic spectrum, between microwaves and far-infrared waves. They are a key frequency band

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connecting macro communication and micro sensing, with a wavelength range of 1 mm~10 mm and a total bandwidth of 270 GHz. Their propagation speed in vacuum is the same as the speed of light, slightly lower in air and significantly affected by the medium. Sub-bands such as 24 GHz, 60 GHz and 77 GHz are commonly used to adapt to different scenarios. In terms of technical characteristics, they have extremely strong directivity, small antennas that are easy to integrate into large-scale arrays, data transmission rates up to 10 Gbps~100 Gbps, flexible polarization and low interception probability, and also have certain thermal effects and energy concentration characteristics. The rock breaking by millimeter wave irradiation relies on its advantages of directivity, concentrated energy and thermal effect: through precise irradiation of rocks, local thermal stress, crack propagation or structural damage are generated to achieve rock breaking, providing an efficient and environmentally friendly new path for scenarios such as mineral mining and tunnel excavation. This technology not only inherits the characteristic of obvious propagation attenuation of millimeter waves, but also faces core difficulties such as high device cost, complex signal compensation, difficult heat dissipation and power consumption control, and the need for precise spectrum planning for anti-interference in the same frequency band.

Microwave heating is a heating method that uses electromagnetic induction to achieve heating purposes, which can usually be called thermal radiation heating. Different from the conventional heat transfer heating where the heat source emits heat through heat conduction, convection and other heat transfer methods to heat the surface of the medium, and then transfers the heat to the inside of the medium through heat conduction, thermal radiation heating has the advantages of high efficiency and short heating time. In many cases, it can better meet people's needs and is an excellent heating method. There are many polar molecules and non-polar molecules in rock media. When these two types of molecules are in an electromagnetic field, non-polar molecules will be partially polarized, and polar molecules will rearrange with newly formed polar molecules under the action of the electromagnetic field. The process of molecular rearrangement is the process of molecular thermal motion. Molecular thermal motion must overcome the interference of the original irregular molecular motion, resulting in an effect similar to friction. Therefore, the continuous movement of molecules will release a lot of heat and generate a heating phenomenon. The heating method of thermal radiation uses this principle. When microwaves irradiate rocks, the polar molecules in the rocks will continue to move in the electromagnetic field, leading to the conversion of a large amount of microwave energy into thermal energy for release, so as to achieve the purpose of heating, which is the principle of microwave heating.

The mutual coupling of multiple physical fields is the core feature of the microwave heating process, specifically including electromagnetic field, heat transfer field, pressure field and stress field. This process is accompanied by multiple physical and chemical behaviors such as energy conversion, mass transfer, momentum transfer and phase change, and the microwave thermal effect constitutes the core premise of other associated effects. The microwave electromagnetic field equation is [20]:

$$\nabla \times \mu_{\mathrm{r}}^{-1}(\nabla \times E) - k_0^2\left(\varepsilon_r - \frac{\mathrm{j}\sigma_e}{\omega\varepsilon_0}\right)E = 0$$

Where: ∇ is the curl operator; μ_{r} is the relative permeability, V/A^2; E is the electric field intensity,N/C; ε_{r} is the relative permittivity, F/m; ε_0 is the permittivity in vacuum ,F/m ; ω is the angular frequency ,rad/s ; σ_{e} is the electrical conductivity,s/m ; k_0 is the wave number in free space,rad/m, $k_0 = \frac{\omega}{c_0}$, $c_0$is the speed of light in vacuum,taken as2.998×10^8m/s.

Based on the electromagnetic-thermal coupling model, the heating simulation study of rocks under microwave irradiation is carried out. In the electromagnetic physical field module of the

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model, the f(E, H) function is set as the core input parameter. For the setting of multi-physics field interface, electromagnetic waves are introduced in the frequency domain, the heat transfer equation is embedded in the solid interface, and the electromagnetic loss generated by electromagnetic waves is converted into a heat source term through the coupling effect of physical fields. The solid heat transfer equation is [21]:

$$\rho C_p u \cdot \nabla T + \nabla \cdot q = Q + Q_{ted}$$

Where: q is the heat flux, q=-k∇T, k is the thermal conductivity of rock, W/m·K; T is the temperature,℃; ρis the rock density, kg/ m^3 ; Cp is the constant pressure heat capacity, J/(kg·K); u is the thermal energy, J; Qis the electromagnetic heat source, W/ m^3 ; Q_{ted} is the thermoelastic damping effect in rock, W/ m^3

3. Simulation Study

3.1. Establishment of Simulation Model

Figure 2 shows a simulation model consistent with the actual experimental conditions. The model is composed of a circular waveguide, an air intermediate layer and a granite sample. The inner diameter d of the circular waveguide is 20mm, the size of the granite is 95mm×80mm×60mm, the frequency of the millimeter wave is 30GHz, and the incident power is 200W. The simulation is carried out using the multi-physics simulation software COMSOL Multiphysics.

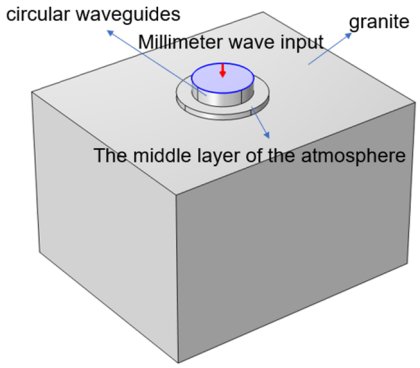


Figure 1. Three-dimensional model of millimeter-wave irradiation on granite

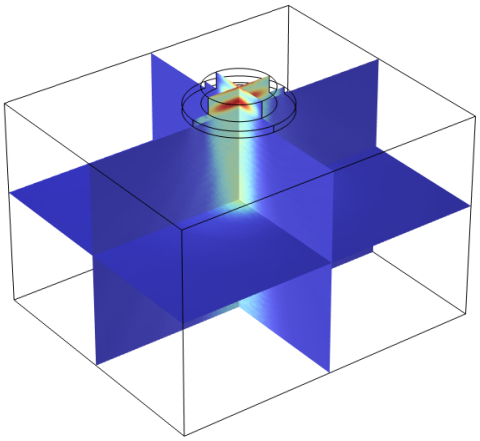
The thermoelectric parameters of the granite sample are shown in Table 1. The complete grid of the three-dimensional model includes 1,023,843 tetrahedral elements, 23,136 triangular elements and 640 edge elements.

Table 1. Granite material parameters

Property	Value
Electrical Conductivity (S/m)	0.01
Relative Permittivity	5
Thermal Conductivity (W/(m·K))	2
Constant Pressure Heat Capacity (J/(kg·K))	800
Relative Permeability	1
Density (kg/m^3)	2600

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3.2. Simulation Results of Electric Field and Temperature Field



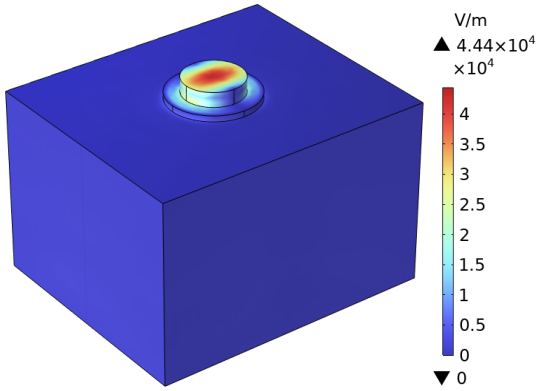


Figure 2. Multi-section electric field distribution **Figure 3.** Surface electric field distribution

The electric field intensity of millimeter waves is extremely high when propagating in air, with a maximum value of 4.44×10^4 N/C. As the millimeter waves contact the surface of granite and penetrate into the interior of granite, the intensity decreases sharply. The reason is that the absorption efficiency of granite for millimeter waves is low. After part of the millimeter waves are reflected by its surface, they either return to the waveguide or stay inside the cavity. The reflected millimeter waves staying in the cavity will continuously irradiate the surrounding area of granite with low intensity. The electric field intensity in the central point area of the granite surface is relatively high, with a value of 4.41×10^4 N/C. The internal electric field intensity is uniformly distributed on each section, and the overall intensity attenuates sharply in an inverted cone shape along the central axis.

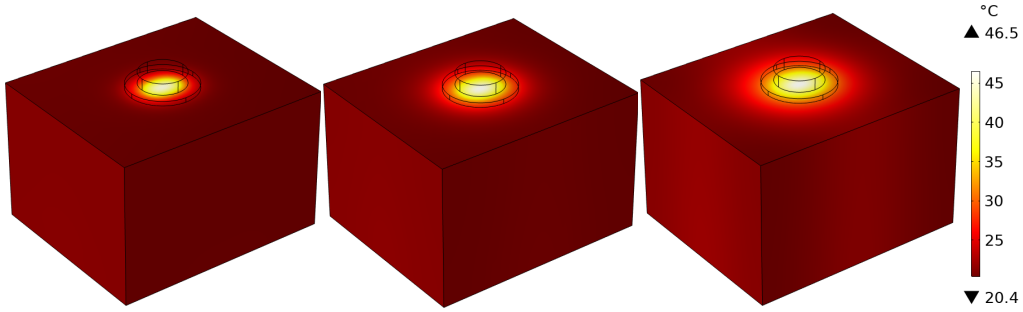


Figure 4 (a)60s Figure 4 (b)90s Figure 4 (c)120s

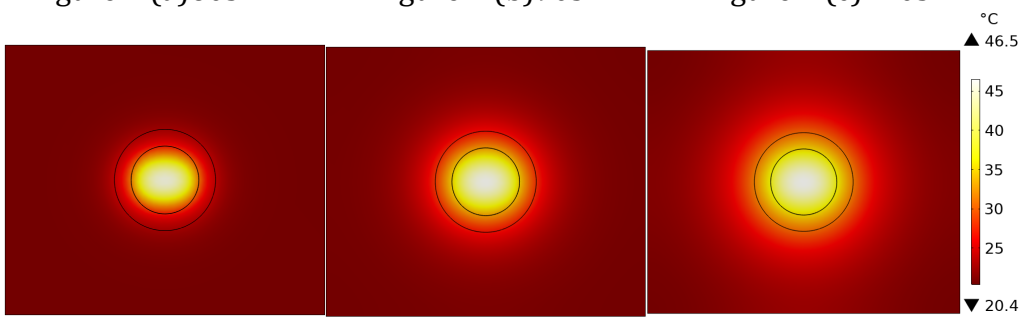


Figure 4 (d)60s Figure 4 (e)90s Figure 4 (f)120s

Figure 4. Surface temperature field distribution

After the granite is irradiated by millimeter waves, the central area of the rock becomes the core of energy absorption, forming the highest temperature point. Under the continuous irradiation of millimeter waves, the temperature of the granite gradually decreases from the center to the surrounding area, forming an obvious temperature gradient. During the entire irradiation process, the temperature of the central area of the granite increases significantly,

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and the overall temperature of the rock also shows an upward trend, as shown in Figs. 4, 5 and 6; the range of temperature rise includes the entire irradiation-affected area.

Under the irradiation of millimeter waves, the overall temperature of the granite increases significantly, forming an obvious temperature difference, which is mainly due to the complex composition structure of its minerals. Granite is mainly composed of mineral particles such as feldspar, quartz and mica. Different minerals have inherent differences in dielectric properties, leading to different absorption efficiencies of millimeter wave energy. Minerals with strong absorption capacity can quickly convert electromagnetic energy into thermal energy, making the temperature rise rapidly; while minerals with low absorption efficiency have a relatively slow temperature rise. This uneven energy absorption leads to a significant temperature gradient inside the rock, thereby causing uneven thermal expansion. Minerals with high absorption capacity expand more obviously, while minerals with low absorption capacity expand less. Under the constraint of the overall rock structure, minerals cannot expand freely, resulting in thermal stress inside the rock. With the increase of irradiation time, the temperature continues to rise, the temperature difference further expands, and the thermal stress continues to accumulate and intensify. Once the thermal stress exceeds the bonding strength inside the granite mineral particles and between the particles, microcracks will be initiated in the stress concentration area. These cracks may occur inside the mineral particles or extend along the contact interface between different minerals.

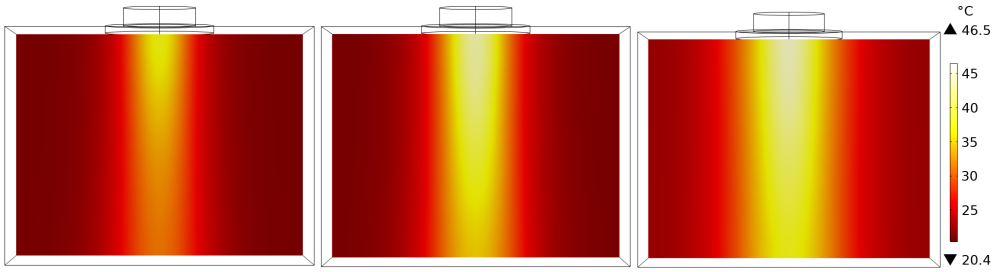


Figure 5(a)60s Figure 5(b)90s Figure 5(c)120s

Figure 5. Internal temperature field distribution

During the millimeter wave irradiation process, the millimeter wave energy absorption area of granite is concentrated on the upper surface, and it is difficult to directly characterize the dynamic change of its internal temperature in the experimental level. Relying on numerical simulation technology, the distribution characteristics of the internal temperature field of granite can be intuitively obtained (as shown in the above figures). From the analysis of the temperature field cloud map, the internal temperature of granite gradually decreases from the surface to the inside, and the isotherms are overall in an inverted cone-shaped distribution. The essential reason for this phenomenon is that the energy intensity of millimeter waves attenuates sharply when propagating into the interior of granite, and the corresponding difference in energy loss leads to a gradual decrease in the temperature change range from the surface to the inside.

Numerical simulation constructs a physical model matching the experimental conditions, incorporates variables such as granite texture and millimeter wave irradiation parameters, which can not only accurately reproduce the temperature dynamics inside the rock during the irradiation process without damaging the natural state of the sample, but also intuitively present the complete distribution characteristics of the temperature field, as shown in Figs. 7, 8 and 9. This method intuitively shows the gradient distribution, morphological characteristics and evolution law of the internal temperature, providing key support for the analysis of the temperature change mechanism. The analysis of the temperature field cloud map of the

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numerical simulation shows that the temperature of the granite decreases from the surface to the interior: the surface temperature is the highest, and the temperature decreases continuously with the increase of depth.

As a high-frequency electromagnetic wave, millimeter waves attenuate sharply when propagating due to dielectric loss, mineral particle scattering and absorption. When propagating in the surface layer, the energy attenuation is small, and it is absorbed by the granite and converted into thermal energy, so the surface temperature rises. With the increase of depth, the energy continues to weaken, and the energy absorbed by the granite decreases.

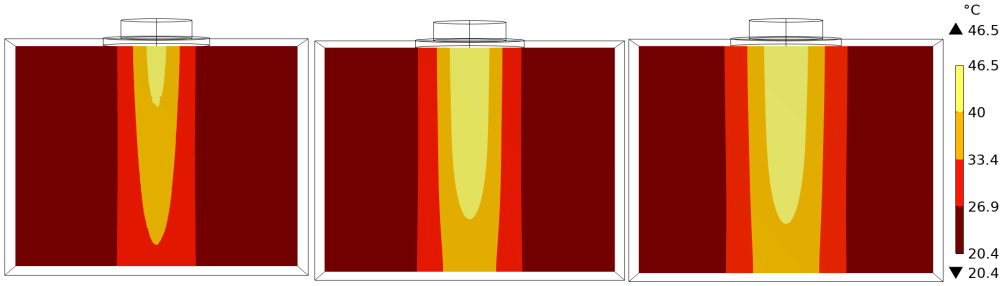


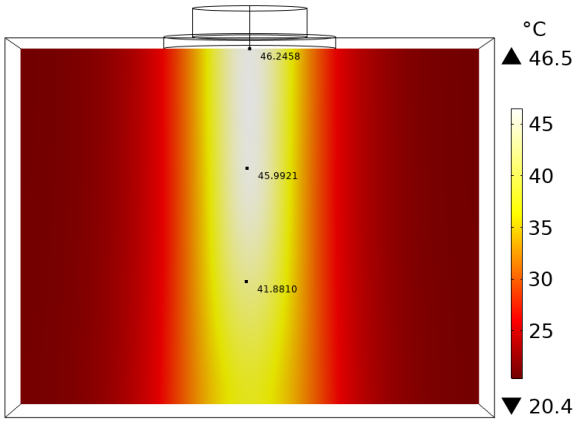
Figure 6(a)60s Figure 6(b)90s Figure 6(c)120s

Figure 6. Temperature field stratification characteristics

The temperature field distribution of granite irradiated by millimeter waves shows obvious layered characteristics:

High-temperature zone: This zone is located at the core center of the temperature field, corresponding to the area where the millimeter wave beam is incident vertically. It appears bright yellow, as shown in Fig. 12, and is the core area where millimeter wave energy is concentrated. The granite molecules undergo intense thermal motion under the action of millimeter waves, resulting in the temperature of this zone reaching the maximum value of the entire temperature field and becoming the zone with the most significant thermal effect.

High-temperature thermal action zone: This zone is located on the periphery of the high-temperature zone and appears orange, as shown in Fig. 12. The temperature rise in this zone is caused by the temperature conduction from the high-temperature zone and the millimeter wave irradiation. A temperature gradient is formed with the high-temperature zone; heat is quickly diffused from the high-temperature zone to this zone through molecular thermal conduction. The temperature is lower than that of the high-temperature zone, but it also has an impact on the local physical state of the material.



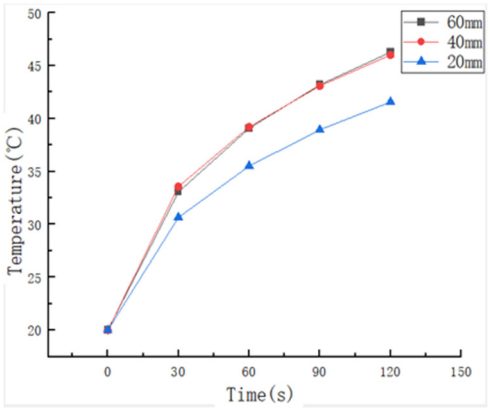


Figure 7. The highest temperature at three points **Figure 8.** The temperature at three points over time

High-temperature thermal influence zone: This zone is located at the outermost periphery of the high-temperature thermal action zone and appears red, as shown in Fig. 12. The

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temperature rise in this zone is due to the heat conduction from the high-temperature thermal action zone, and it is an area indirectly affected by high temperature. The temperature rise in this zone is relatively limited and does not reach the level of significantly changing the properties of the granite material.

Three points of 20mm, 40mm and 60mm were taken from the bottom to the top on the YZ section of granite, and the maximum temperature values of the three points were compared as shown in Figure 13. In the process of irradiating granite with millimeter waves, as the irradiation depth of millimeter waves increases, the temperature rise rate of granite shows a decreasing trend, as shown in Figure 14. This is because when millimeter waves propagate into the interior of granite, they will have complex interactions with mineral crystals, micropores and various impurities inside the granite. On the one hand, the dielectric properties of granite will affect the energy propagation of millimeter waves. With the increase of propagation depth, the energy density of millimeter waves continues to decrease; on the other hand, the heat conduction process inside the granite will also affect the temperature rise. The surface layer obtains sufficient millimeter wave energy, and the thermal motion of mineral molecules is intense, leading to rapid temperature rise. When the depth increases, the energy propagation of millimeter waves is greatly reduced, and the efficiency of heat conduction from the surface to the interior of granite is also limited due to the characteristics of rock thermal conductivity. As a result, the energy obtained by the deep granite per unit time cannot achieve rapid temperature rise, and finally the temperature rise rate of granite slows down with the continuous increase of irradiation depth.

4. Experimental Study

4.1. Experimental Equipment

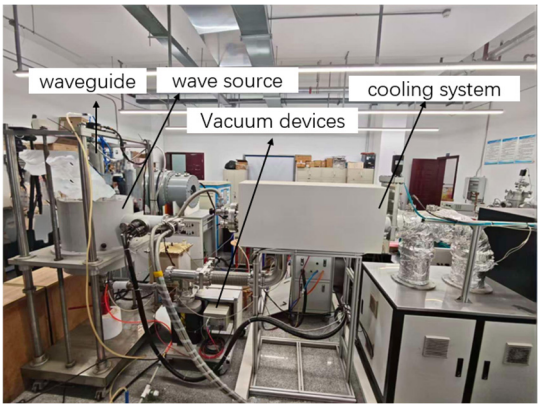


Figure 9. Test Equipment

The experimental equipment is a millimeter wave experimental platform built by the University of Electronic Science and Technology of China, which is composed of four parts: waveguide, wave source, vacuum device and cooling system. The fast-wave device converts electronic kinetic energy into millimeter wave energy through the synchronous interaction between high-speed electron beam and fast-wave electromagnetic field. The millimeter wave is transmitted to the platform through the waveguide to act on the granite. The cooling system cools the wave source and vacuum device throughout the process to avoid component damage or experimental data distortion caused by high temperature, which is divided into two major cooling circuits: wave source cooling and vacuum device cooling.

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4.2. Experimental Results

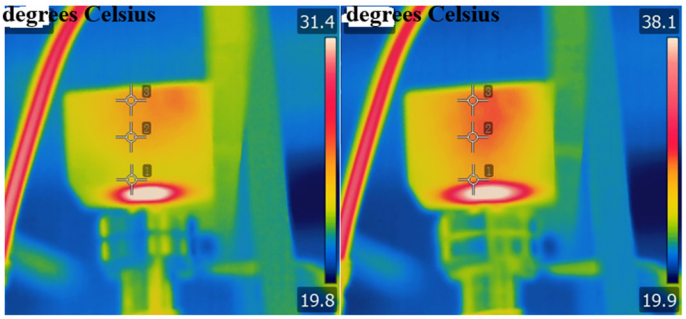


Figure 10(a)30s Figure 10(b)60s

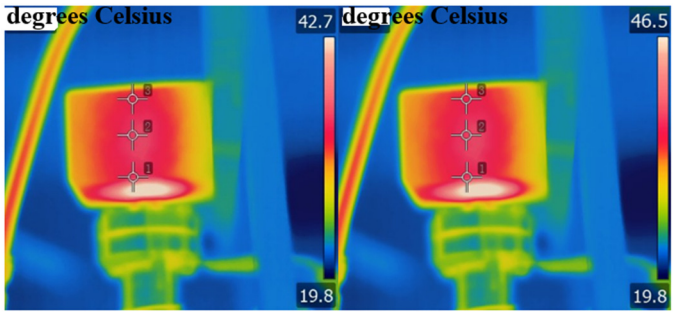


Figure 10(c)90s Figure 10(d)120s

Figure 10. Infrared image of granite after millimeter-wave irradiation



Figure 11. Test Diagram of Millimeter Wave Exposure on Granite

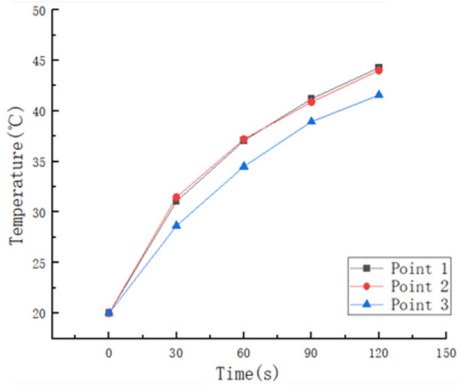


Figure 12. Graph showing the temperature changes at points 1, 2, and 3 over time

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In the initial ambient temperature environment, the surface temperature of the granite remains stable at approximately 24 °C. At this time, no millimeter wave irradiation occurs, and no special temperature anomalies are shown in the infrared image, as shown in Fig. 16(a). When the millimeter waves start to act on the granite surface, their energy is gradually absorbed by the surface, and "hot spots" with alternating red and white colors first appear in specific areas. These hot spots form a distinguishable temperature difference with the surrounding non-irradiated areas, and the temperature gradient is gradually formed.

With the increase of millimeter wave irradiation time, energy continues to accumulate on the surface and shallow layer of the granite without obvious energy dissipation. Due to the accumulation of millimeter wave energy, the surface temperature of the granite enters a rapid rise stage. In the infrared image, the originally limited warm-colored area begins to expand significantly, and the brightness of the high-temperature hot spots formed initially increases gradually, with the coverage area also expanding continuously, making the boundaries between the high-temperature zone, transition zone and low-temperature zone more obvious. Compared with the initial stage, the gradient of temperature distribution becomes more significant.

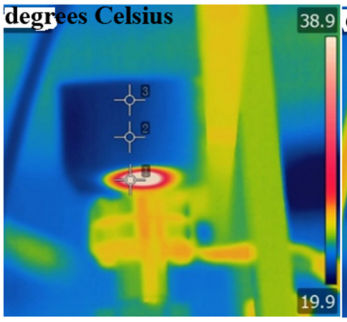


Figure 13(a)30s

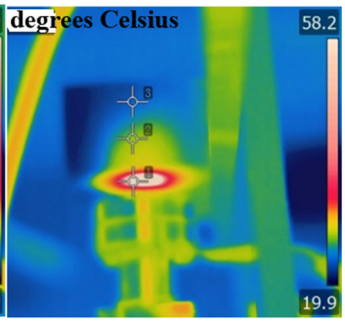


Figure 13(b)60s

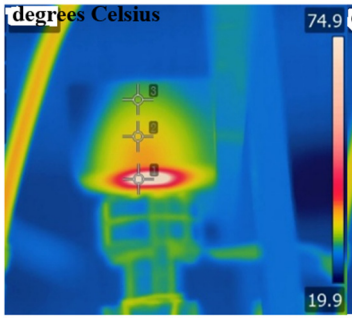


Figure 13(c)90s

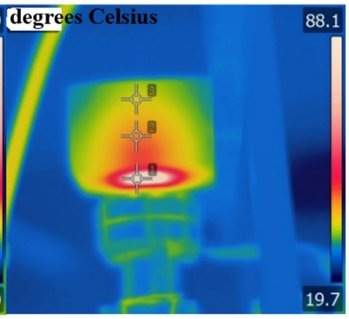


Figure 13(d)120s

Figure 13. Infrared view of sandstone under millimeter-wave irradiation



Figure 14. Test Diagram of Millimeter Wave Exposure on Sandstone

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As the millimeter wave irradiation continues, the surface temperature of the granite becomes higher, and the red high-temperature area in the infrared image continues to expand, covering most of the irradiated surface of the granite. The temperature distribution is no longer limited to the hot spot area on the surface, but gradually develops from the initial concentrated hot spots to an overall uniform state. The temperature difference between the high-temperature area on the surface of the granite and the internal area continues to decrease. After 120 seconds of continuous millimeter wave irradiation, the infrared image is mainly composed of a large-area red area, which visually shows that under continuous irradiation, the surface temperature of the granite further increases, and the thermal radiation intensity of the entire irradiated area remains uniform and at a relatively high level.

Millimeter waves themselves have penetrating properties and can act on the granite surface. Granite is a typical dielectric material and has a good absorption capacity for microwave energy. The absorbed microwave energy is directly converted into thermal energy, causing the local area on the surface to heat up first and form hot spots. Over time, heat will naturally flow from the hot spots with higher temperature to the non-hot spot areas with lower temperature, gradually eliminating the local temperature difference, and finally making the temperature distribution of the entire irradiated surface change from "local concentration" to "overall uniformity".

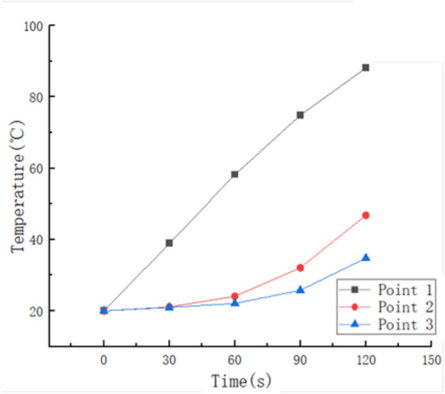


Figure 15. Graph showing the temperature changes at points 1, 2, and 3 over time

Compared with granite, the temperature rise characteristics of sandstone under millimeter wave irradiation are more concentrated and uneven: the millimeter wave energy is highly concentrated in the central part of the millimeter wave irradiation area, with high energy density. A clear and concentrated "hot spot" is quickly formed. Compared with the relatively uniform energy distribution of granite under millimeter wave irradiation, the energy distribution of millimeter waves on the sandstone surface is more concentrated and the effect is stronger, making the hot spot area the core area of energy absorption and temperature rise.

The first point in this hot spot core area undergoes an extremely intense temperature change: the temperature rises rapidly from the initial 20 °C to 88.1 °C, with a temperature increase of 68.1 °C, and the temperature rises rapidly in a short time. The temperature in the unexposed area around the hot spot rises at a relatively slow rate; most areas only rise from room temperature to approximately 25 °C, resulting in a significant temperature difference of more than 40 °C between the hot spot core area and the surrounding areas. This temperature difference is much larger than the temperature gradient of granite when exposed to radiation, highlighting the uneven temperature rise of sandstone.

Sandstone has large internal pores and discontinuous heat conduction paths between mineral particles. This structural characteristic directly leads to a significant reduction in heat conduction efficiency, laying a physical foundation for subsequent heat accumulation. A large amount of heat accumulated in the hot spot area is difficult to diffuse to the surrounding and

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internal areas quickly through conduction; even during the entire test period, the heat remains concentrated in the irradiation center, making it difficult to form a uniform temperature distribution in the entire area. The hot spot on the sandstone surface emits a bright and strong thermal radiation signal, which is mostly circular or elliptical, and its brightness increases continuously with the increase of irradiation time; while the area around the hot spot maintains a low-brightness and low-temperature signal, with a clear boundary between the two. The diffusion of heat inside the sandstone is very slow, only penetrating a few millimeters to the surface; during the entire test period, the deep temperature has almost no obvious fluctuation, which further confirms the uneven heating of sandstone and the lag of heat conduction.

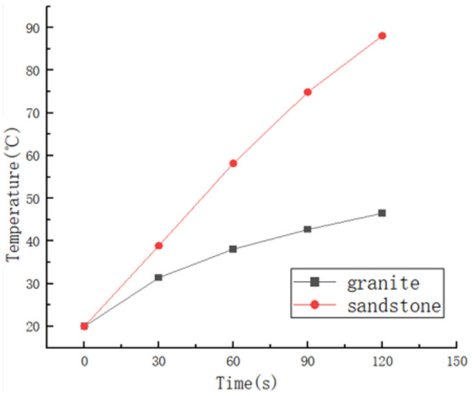


Figure 16. Comparison Chart of Granite and Sandstone Temperatures

Under the action of millimeter waves, the temperature response characteristics of granite and sandstone are significantly different: the overall temperature rise of granite under millimeter wave irradiation is uniform, the temperature difference between various points is small, the internal heat conduction homogenization speed is fast, and the surface temperature in the infrared image quickly tends to be uniform; sandstone undergoes extreme local overheating after millimeter wave irradiation, with energy highly concentrated at the radiation center point, forming a strong temperature gradient of more than 40 °C with the surrounding area. The thermal conductivity of sandstone is extremely low, making it difficult for heat to diffuse outward, and the infrared image shows a scene where bright hot spots coexist with surrounding dark areas.

The core of this difference lies in their different thermophysical properties: granite has a dense structure and good thermal conductivity, while sandstone is porous and has weak thermal conductivity, and may contain strong wave-absorbing components inside. This finding also provides key theoretical support for formulating millimeter wave application strategies for different lithologies.

4.3. Comparison between Experimental and Simulation Results

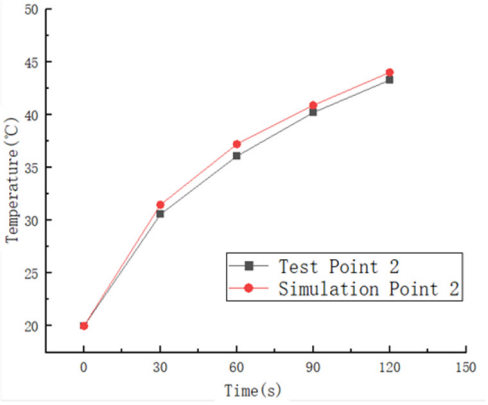


Figure 17. Comparison of temperatures at Test Point 2 and Simulation Point 2

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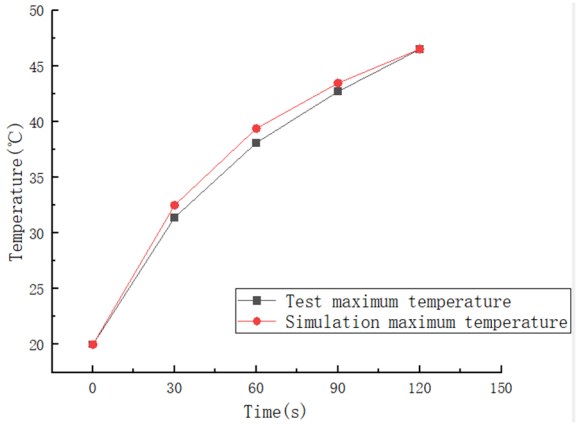
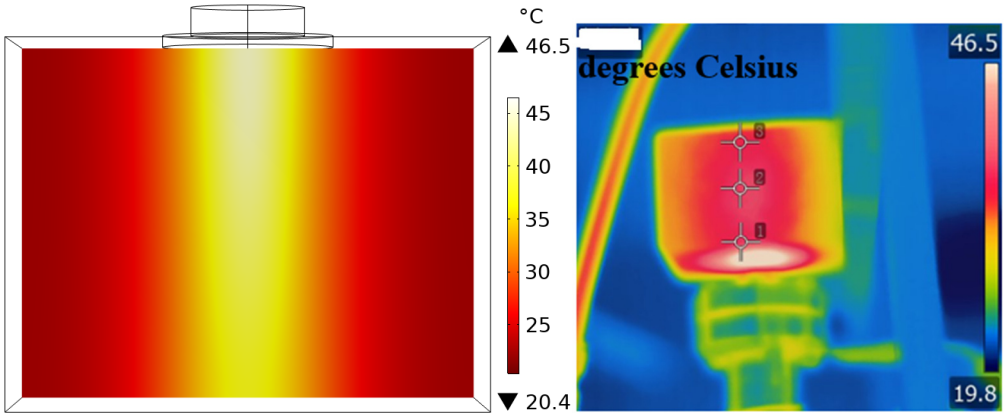


Figure 18. Comparison of the highest temperatures in the test and simulation



(a)Simulation temperature cloud map (b)Test infrared view

Figure 19. Comparison of simulated temperature cloud map and test infrared image

In terms of the quantitative accuracy of temperature data, the temperature errors between Experimental Point 2 and Simulation Point 2 at key time points such as 0s, 30s and 60s are all ≤2%. The error between the experimental and simulation maximum temperatures at 120s is only about 1.1%, and the temperature rise rates are basically synchronized; in terms of the spatial distribution of the temperature field, the gradient distribution of high temperature in the center and low temperature at the edge of granite (19.8°C~42.7°C) in the experimental infrared view is completely consistent with the gradient shape of red in the center and yellow at the edge of the simulation temperature field; at the same time, both show a continuous and stable linear temperature rise trend without abnormal fluctuations. This multi-dimensional performance of "minimal quantitative error of characteristic points/maximum temperature, consistent spatial gradient shape of temperature field, and complete synchronization of thermal response time law" not only verifies that the simulation model has high accuracy in describing the heat transfer process (the error is much lower than the engineering acceptable threshold), but also lays a reliable numerical foundation for subsequent engineering applications such as irradiation parameter optimization and thermal stress mechanism research based on simulation.

5. Conclusion and Suggestions

The energy of millimeter waves attenuates sharply when propagating in granite, with higher electric field intensity at the central point of the surface and uniform inverted cone-shaped distribution inside. After being irradiated, the center temperature of granite is the highest and

diffuses to the surrounding area. The difference in the absorption of millimeter waves by minerals forms a temperature difference, which in turn generates thermal stress and causes microcracks, ultimately realizing rock weakening, and the temperature continues to rise with the irradiation time.

The internal temperature of granite gradually decreases from the surface to the inside, showing an inverted cone-shaped layered distribution (high temperature zone, high temperature action zone, high temperature affected zone). The temperature rise rate decreases significantly with the increase of irradiation depth, which is related to the exponential attenuation of millimeter wave energy and the limited rock heat conduction; compared with sandstone, granite shows overall uniform temperature rise due to its dense structure and good thermal conductivity, while sandstone shows extreme local overheating due to its loose and porous structure and poor thermal conductivity. The difference between the two originates from different thermophysical properties.

The experiment and simulation have minimal quantitative errors (≤2%) in the temperature of characteristic points and maximum temperature (the error is about 1.1% at 120s), the spatial gradient shape of the temperature field is completely consistent, and the thermal response time law is synchronized. This consistency not only proves that the simulation model can accurately describe the heat transfer process, but also provides a reliable numerical foundation for subsequent engineering applications such as irradiation parameter optimization and thermal stress mechanism research.

This study mainly focuses on the temperature characteristics of granite irradiated by millimeter waves. In the future, the power and frequency of millimeter waves will be increased, the scope of lithology research will be expanded, and rocks with different thermophysical properties such as limestone and shale will be selected to systematically analyze the differences in millimeter wave irradiation response and construct the corresponding relationship of "lithological characteristics - irradiation parameters - weakening effect".

References

[1] Li, W. P. (2014). Several drilling methods for geological drilling. Heilongjiang Science, 5(10), 143. (in Chinese)

[2] Sun, W. G. (2013). Analysis on technical problems of geothermal energy mining. China Science and Technology Expo, (28), 530. (in Chinese)

[3] Graves, R. M., & O'Brien, D. G. (1998). Star Wars laser technology applied to drilling and completing gas wells. In SPE Annual Technical Conference Proceedings (pp. 761–770). New Orleans, USA. https://doi.org/10.2118/49259-MS.

[4] Hassani, F., Nekoovaght, P., Radziszewski, P., & Nour, S. (2011). Microwave assisted mechanical rock breaking. In 12th ISRM Congress. Beijing, China.

[5] Odhiambo, J., Odulaja, A., Poole, J., & Grieves, B. (2013). Investigating microwave assisted rock breakage for possible space mining applications. Mining Technology, 115(1), 34–40. https://doi.org/10.1179/174328606X101902.

[6] Nekoovaght, P., Gharib, N., & Hassani, F. (2014). Microwave assisted rock breakage for space mining. In Earth and Space 2014 (pp. 414–423). St. Louis, USA.

[7] Li, Y., Qu, J. L., & Qin, L. K. (2016). Analysis of temperature distribution and influential factors of rock particle under microwave irradiation. Coal Technology, 35(10), 103–106. (in Chinese)

[8] Lu, G., Li, Y., Hassani, F., & Zhang, X. (2016). Review of theoretical and experimental studies on mechanical rock fragmentation using microwave-assisted approach. Chinese Journal of Geotechnical Engineering, 38(8), 1497–1506. https://doi.org/10.11779/CJGE201608018 (in Chinese)

[9] Maurer, W. C. (1968). Novel drilling techniques. Pergamon Press.

[10] Maurer, W. C. (1980). Advanced drilling techniques. Petroleum Publishing Company.

[11] Moavenzadeh, F., Ma, G. F. J., & Williamson, R. B. (1968). Use of laser and surface active agents for excavation in hard rocks (SPE 2240). Society of Petroleum Engineers.

[12] Graves, R. M., & O'Brien, D. G. (1998). Star Wars laser technology applied to drilling and completing gas wells (SPE 49259). Society of Petroleum Engineers. https://doi.org/10.2118/49259-MS.

[13] Sinha, P., & Gour, A. (2006). Laser drilling research and application: an update (SPE 102017). Society of Petroleum Engineers. https://doi.org/10.2118/102017-MS.

[14] Dou, H. E. (2004). Laser drilling technology in the 21st century. Petroleum Science and Technology Forum, (2), 59–62. (in Chinese)

[15] Kenneth, O., Paul, W., Herbert, E., & Mardis, J. (2014). Deep geothermal drilling using millimeter wave technology (Final Technical Research Report). U.S. Department of Energy.

[16] Sakamoto, K., Kasugai, A., Takahashi, K., Kikunaga, K., Idei, H., & Shimozuma, T. (2007). Achievement of robust high-efficiency 1MW oscillation in the hard-self excited region by a 170GHz continuous-wave gyrotron. Nature Physics, 3(4), 411–414. https://doi.org/10.1038/nphys584.

[17] Choi, E. M., Marchewka, C. D., Mastovsky, I., Shapiro, M. A., Sirigiri, G., & Temkin, R. J. (2006). Experimental results for a 1.5 MW, 110GHz gyrotron oscillator with reduced mode competition. Physics of Plasmas, 13(2), 1–7. https://doi.org/10.1063/1.2168102.

[18] Grimm, T. L., Kreischer, K. E., & Temkin, R. J. (1993). Experimental Study of a megawatt 200-300GHz gyrotron oscillator. Physics of Fluids B, 5(4), 4135–4143. https://doi.org/10.1063/1.860404.

[19] Wang, X. C., Wang, X. J., Wu, D. J., Zhang, L. Y., & Tang, Y. Y. (2021). Research on 140GHz millimeter wave rock drilling technology. Journal of Microwaves, 37(3), 85–91. (in Chinese)

[20] Song, Y. (1979). Maxwell and electromagnetic theory. Chinese Journal of Nature, 2(11), 665. (in Chinese)

[21] Hong, Y. D., Lin, B. Q., Li, H., Dai, H., Zhu, C., Hao, Y., & Zhang, J. (2016). Three-dimensional simulation of microwave heating coal sample with varying parameters. Applied Thermal Engineering, 93, 1145–1154. https://doi.org/10.1016/j.applthermaleng.2015.10.071.