Original Research Article

Study on heat transfer law of rock strata under different temperature conditions

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Abstract: To reveal the heat transfer evolution law and internal influence mechanism of rock strata under different temperature conditions, and clarify the effects of temperature gradient, lithological characteristics and rock stratum structure on the heat transfer process, this paper systematically studied the variation characteristics of thermophysical parameters of rock strata with different lithologies and under different temperature gradients in the temperature range from normal temperature to 800℃, analyzed the heat transfer laws of single-layer homogeneous rock strata and multi-layer interbedded rock strata, discussed the influence mechanisms of porosity, water content, mineral composition and other factors on the heat transfer of rock strata, and established an unsteady heat transfer mathematical model of rock strata under different temperature conditions.
Keywords: temperature condition; rock stratum; heat transfer law; thermophysical parameter; thermal resistance effect; influence mechanism

1. Research significance

As an important carrier of heat transfer, the heat transfer process of rock strata is affected by the coupling of multiple factors such as temperature conditions, lithological characteristics and microscopic structure. The thermophysical parameters of rock strata under different temperature conditions change regularly, thus altering the rate and mode of heat transfer. At present, most studies on rock stratum heat transfer focus on normal temperature or specific high-temperature conditions, with insufficient systematic research on the heat transfer law of rock strata in a wide temperature range, and the discussion on the action mechanisms of key factors such as temperature gradient and rock stratum structure is not in-depth enough. Therefore, carrying out systematic research on the heat transfer law of rock strata under different temperature conditions, revealing the internal correlation between temperature and the thermophysical parameters and heat transfer characteristics of rock strata, clarifying the effects of various influencing factors, and establishing a rock stratum heat transfer model suitable for different temperature conditions can not only enrich the theoretical system of rock thermal engineering, but also provide important theoretical support for the design of underground engineering, resource development and disaster prevention and control under high-temperature environments, which has significant theoretical research value and engineering application significance.

2. Research methods

The main equipment adopted in this test includes a high-temperature thermophysical parameter tester, a vacuum drying oven, an electronic balance, a constant temperature and humidity box, etc. Among them, the high-temperature thermophysical parameter tester has a temperature control range from normal temperature to 1000℃ with a temperature control accuracy of ±1℃, and can simultaneously determine the thermal conductivity, specific heat capacity and thermal diffusivity of rocks. The transient plane source method was used for the test, which has the advantages of fast testing speed, high accuracy and low sample loss, and is suitable for the determination of rock thermophysical parameters in a wide temperature range.

3. Temperature evolution law of thermal conductivity

Thermal conductivity is the core parameter characterizing the heat transfer capacity of rock strata, reflecting the heat flux density of rock strata under a unit temperature gradient, and its value is closely related to temperature, lithology, microscopic structure and other factors. The thermal conductivity of rock strata with different lithologies in the range from normal temperature to 800℃ all presents a nonlinear evolution characteristic of "stable at low temperature and decreasing at high temperature", and there are obvious differences in the critical temperature of thermal conductivity of rock strata with different lithologies.

In the low-temperature stage from normal temperature to 300℃, the thermal conductivity of all rock strata remains basically stable with a fluctuation range of less than 5%. This is because under low-temperature conditions, the thermal expansion effect of mineral particles inside the rock strata is weak, the microscopic pore structure does not change significantly, and the main mode of heat transfer is lattice thermal conduction between mineral particles with the heat conduction path remaining intact, thus the thermal conductivity is basically stable. Among them, magmatic rocks have the highest thermal conductivity: the thermal conductivity of granite at normal temperature is 2.8~3.2 W/(m·K), and that of basalt is 3.0~3.4 W/(m·K), mainly due to the dense mineral structure and low porosity of magmatic rocks leading to high lattice thermal conduction efficiency. For sedimentary rocks, the thermal conductivity of sandstone at normal temperature is 2.0~2.4 W/(m·K), and that of shale is 1.2~1.6 W/(m·K). The low thermal conductivity of shale is due to its developed bedding structure and high content of clay minerals, which cause many barriers to lattice thermal conduction. For metamorphic rocks, the thermal conductivity of marble at normal temperature is 2.2~2.6 W/(m·K), and that of gneiss is 1.8~2.2 W/(m·K). The gneissic structure of gneiss results in discontinuous heat conduction paths, making its thermal conductivity lower than that of marble.

When the temperature exceeds 300℃, the thermal conductivity of rock strata begins to decrease gradually, and the higher the temperature, the faster the decrease rate, with significant differences in the decrease range of rock strata with different lithologies. Among them, the thermal conductivity of metamorphic rocks decreases the most obviously: at 800℃, the thermal conductivity of gneiss decreases by 45%~50% compared with normal temperature, and that of marble decreases by 35%~40%; sedimentary rocks take the second place: the thermal conductivity of shale decreases by 40%~45% at 800℃, and that of sandstone decreases by 25%~30%; magmatic rocks have the optimal thermal stability: the thermal conductivity of basalt decreases by 20%~25% at 800℃, and that of granite decreases by 15%~20%. The main reasons for the decrease of rock stratum thermal conductivity under high-temperature conditions are as follows: on the one hand, mineral particles expand when heated, and the difference in thermal expansion coefficients of different minerals leads to microcracks between particles, which destroys the continuity of lattice thermal conduction and increases thermal resistance; on the other hand, the primary pores inside the rock strata expand when heated, the pore volume increases, and there are more pore thermal resistances in the heat transfer process, which further reduces the heat conduction efficiency. Magmatic rocks have high mineral crystallinity and dense structure, and the evolution degree of microcracks and pores at high temperature is low, so the decrease range of thermal conductivity is the smallest and the thermal stability is the best.

4. Analysis of heat transfer law of rock strata under different temperature conditions

4.1. Heat transfer law of single-layer homogeneous rock strata

Under the same temperature condition, the larger the temperature gradient, the higher the heat flux density inside the rock strata and the faster the heat transfer rate. Taking basalt at 800°C as an example, when the temperature gradient is 50°C/m, it takes about 8 hours for heat to transfer 1 meter; when the temperature gradient increases to 200°C/m, it takes about 2 hours for heat to transfer 1 meter, with the heat transfer rate increased by 75%. This is because the temperature gradient is the driving force of heat transfer; the larger the temperature gradient, the more significant the difference in molecular thermal motion inside the rock strata, the higher the heat flux density, and the faster the heat transfer rate. In addition, the increase of temperature gradient will lead to an increase in the thermal stress inside the rock strata, which may induce the generation and propagation of microcracks, thereby changing the thermophysical parameters of the rock strata and forming a coupling effect between the temperature gradient and the heat transfer process.

4.2. Heat transfer law of multi-layer interbedded rock strata

In actual engineering, rock strata mostly exist in the form of multi-layer interbedding. The thermophysical parameters of different rock strata are different, and interfacial thermal resistance is generated at the rock stratum interface. Therefore, the heat transfer law of multi-layer interbedded rock strata is more complex than that of single-layer homogeneous rock strata, and its heat transfer process is controlled by both low thermal conductivity rock strata and interfacial thermal resistance.

The overall heat transfer rate of multi-layer interbedded rock strata is mainly determined by the rock stratum with the lowest thermal conductivity, that is, the "short board effect". The rock stratum with low thermal conductivity will become a bottleneck of heat transfer, significantly reducing the overall heat transfer efficiency. For example, in the interbedded rock strata of granite and shale, granite has high thermal conductivity and shale has low thermal conductivity. During heat transfer, when passing through the shale layer, the heat flux density decreases significantly, and the overall heat transfer rate is determined by the thermal conductivity of shale. Even if the thickness of the granite layer is increased, the improvement of the overall heat transfer rate is very limited. Under different temperature conditions, the thermal conductivity of low thermal conductivity rock strata has higher temperature sensitivity, and the decrease range of thermal conductivity at high temperature is larger. Therefore, the increase range of the overall heat transfer rate of multi-layer interbedded rock strata with the rise of temperature is smaller than that of single-layer homogeneous rock strata.

5. Analysis of influence mechanism of rock stratum heat transfer law

5.1. Influence mechanism of mineral composition

Mineral composition is the internal factor determining the thermophysical parameters and heat transfer law of rock strata. The thermophysical properties of different minerals are significantly different, and the parameters such as thermal conductivity and specific heat capacity of rock strata are all the weighted average of the thermophysical parameters of each internal mineral. The difference in mineral composition directly leads to the different heat transfer laws of rock strata with different lithologies.

In terms of thermal conductivity, rock-forming minerals such as quartz and feldspar have high thermal conductivity: the thermal conductivity of quartz at normal temperature is 7.0~8.0 W/(m·K), and that of feldspar is 5.0~6.0 W/(m·K); while minerals such as clay minerals and mica have low thermal conductivity: the thermal conductivity of clay minerals at normal temperature is 1.0~2.0 W/(m·K), and that of mica is 2.0~3.0 W/(m·K). Therefore, rock strata with high content of quartz and feldspar, such as granite and sandstone, have high thermal conductivity and strong heat transfer capacity; rock strata with high content of clay minerals and mica, such as shale and gneiss, have low thermal conductivity and weak heat transfer capacity. Under high-temperature conditions, the difference in thermal expansion coefficients of different minerals is the main reason for the generation of microcracks in rock strata. The thermal expansion coefficient of quartz is much higher than that of feldspar, calcite and other minerals. Rock strata with high quartz content have more significant development of microcracks at high temperature, and the decrease range of thermal conductivity is relatively large.

5.2. Influence mechanism of porosity

Porosity is an important microscopic structural factor affecting the heat transfer law of rock strata. The pores inside the rock strata include primary pores and secondary pores, which are usually filled with air or water. The thermophysical parameters of air and water are significantly different from those of rock minerals. Therefore, the size of porosity directly changes the overall thermophysical properties of rock strata, thereby affecting the heat transfer process.

For dry rock strata, the pores are filled with air, and the thermal conductivity of air is much lower than that of rock minerals (the thermal conductivity of air at normal temperature is only 0.026 W/(m·K)). Therefore, the increase of porosity will lead to a decrease in the overall thermal conductivity of rock strata and a weakening of heat transfer capacity. For every 1% increase in porosity, the thermal conductivity of dry rock strata decreases by about 3%~5%. When the porosity exceeds 10%, the decrease range of thermal conductivity is more obvious. At this time, the pores are interconnected to form continuous pore channels, and the thermal resistance increases significantly. Under high-temperature conditions, the air in the pores expands when heated, the thermal conductivity increases slightly, and the mineral particles of the rock strata expand when heated, filling some small pores and slightly reducing the porosity. Therefore, the influence of porosity on the thermal conductivity of rock strata under high-temperature conditions is slightly weakened, but the overall trend is still that the larger the porosity, the lower the thermal conductivity.

6. Suggestions for engineering application

Based on the research results of the heat transfer law of rock strata under different temperature conditions in this paper, combined with the actual engineering needs of deep geothermal resource development, underground nuclear waste disposal, deep mine mining and other fields, the following engineering application suggestions are put forward:

Deep geothermal resource development: In the exploitation of hot dry rock geothermal resources, magmatic rocks such as granite and basalt should be prioritized as reservoirs, which have high thermal conductivity, good thermal stability and high heat transfer efficiency at high temperature. In reservoir reconstruction, artificial fracturing can be used to increase the porosity and permeability of rock strata, but the fracturing scale should be controlled to avoid a sharp decrease in rock stratum thermal conductivity caused by excessive fracturing. At the same time, the spacing of heat exchange wells should be reasonably set according to the temperature distribution of the reservoir, and the influence of temperature gradient on the heat transfer rate should be fully considered to improve the geothermal heat exchange efficiency.

Deep mine mining: In the high-temperature control of deep mines, cooling measures should be formulated according to the heat transfer law of rock strata. For rock strata with high thermal conductivity, ventilation cooling can be adopted to accelerate the heat exchange between rock strata and air; for rock strata with low thermal conductivity and high temperature sensitivity, water injection cooling can be adopted to increase the water content of rock strata, improve thermal conductivity and accelerate heat transfer. At the same time, underground temperature measurement points should be reasonably set according to the evolution law of the rock stratum temperature field to timely grasp the temperature change trend.

Temperature field control of underground engineering: In the construction of underground tunnels, subways and other projects, the heat transfer law and thermal hysteresis effect of rock strata should be fully considered, and reasonable heat preservation or cooling measures should be set. For multi-layer interbedded rock strata, the thermal insulation effect of low thermal conductivity rock strata should be focused on, and its thermal resistance effect should be used to reduce the influence of external temperature on the inside of the project. In underground projects in high-temperature areas, materials with low thermal conductivity can be used to protect the surrounding rock, reduce the heat transfer rate of rock strata and improve underground working conditions.

Engineering monitoring and prediction: Based on the rock stratum heat transfer mathematical model established in this paper, combined with the actual geological and temperature conditions of the project, the accurate prediction of the evolution of the rock stratum temperature field can be realized. In the process of project operation, a long-term monitoring system should be established to monitor the temperature, heat flux density and other parameters of rock strata in real time, and engineering measures should be adjusted in a timely manner to ensure the safety and stability of the project.

7.Conclusions

Taking three typical types of rock strata (magmatic rocks, sedimentary rocks and metamorphic rocks) as the research objects, this paper systematically studied the evolution laws of thermophysical parameters and heat transfer characteristics of rock strata under different temperature conditions in the range from normal temperature to 800℃ by combining laboratory tests, theoretical analysis and numerical simulation, discussed the influence mechanisms of mineral composition, porosity, water content and other factors, and established unsteady heat transfer mathematical models of single-layer and multi-layer rock strata. The main conclusions are as follows:

The thermophysical parameters of rock strata with different lithologies all show regular temperature evolution characteristics in the range from normal temperature to 800℃: the thermal conductivity presents a trend of "stable at low temperature and decreasing at high temperature" with 300℃ as the critical temperature, magmatic rocks have the optimal thermal stability, followed by sedimentary rocks, and metamorphic rocks are the weakest; the specific heat capacity shows a slow rising trend with little influence of lithology, increasing by 30%~45% at 800℃ compared with normal temperature; the thermal diffusivity is jointly controlled by thermal conductivity and specific heat capacity, presenting a trend of "stable at low temperature and increasing at high temperature", and the diffusion rate of the rock stratum temperature field accelerates at high temperature.

The heat transfer rate of single-layer homogeneous rock strata is jointly controlled by temperature and temperature gradient. The higher the temperature and the larger the temperature gradient, the faster the heat transfer rate, and there is an obvious thermal hysteresis effect, which is weakened at high temperature. The heat transfer of multi-layer interbedded rock strata has the "short board effect" and interfacial thermal resistance effect. The overall heat transfer rate is controlled by low thermal conductivity rock strata, and the interfacial thermal resistance leads to temperature mutation during heat transfer, with the temperature field evolution showing obvious layered characteristics.

The heat transfer law of rock strata is affected by the coupling of mineral composition, porosity, water content and other factors: mineral composition is the internal factor, and rock strata with high content of quartz and feldspar have high thermal conductivity and strong heat transfer capacity; the increase of porosity will reduce the thermal conductivity and increase the specific heat capacity of rock strata, thereby slowing down the heat transfer rate; water content has the most significant influence on the heat transfer law. The increase of water content in the low water content stage will accelerate the heat transfer rate, while it will slow down the heat transfer rate in the high water content stage, and there is an optimal water content for rock strata to maximize the heat transfer rate.

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