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Perspective

Infrared thermal imaging under a macro lens empowers geo-energy exploration and development: Application scenarios and scheme conceptions

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Abstract:
This study introduces the potential applications of infrared thermal imaging under a macro lens in the realm of geo-energy. Leveraging disparities in the thermal radiation of objects, this technology captures minute thermal signals from small objects through its macro lens, offering benefits such as straightforward sample preparation, rapid testing, and non-destructive imaging. In the context of static attribute characterization of reservoirs, it facilitates the acquisition of temperature data and the identification of macroscopic geological attributes like lithology via machine learning. It also enables precise characterization of microscopic solid components and fluid distribution, based on variances in thermophysical properties, and aids in determining multidisciplinary properties of rocks. In studies concerning dynamic behavior, it allows for real-time monitoring of structural changes during reservoir heating or cooling, the design of in-situ conversion heating schemes for low-maturity shale oil, tracking of fluid-rock interactions and microbial oil extraction characteristics, and provides dynamic information to optimize extraction schemes in energy development and utilization. Although there are challenges in practical applications, innovative ideas and technological progress are expected to overcome these obstacles, supporting the efficient exploration and sustainable development of geo-energy.

1. Introduction

In recent years, the imaging characterization of reservoir components, structures, and physicochemical properties, along with their dynic behaviors across multiple dimensions and scales, has emerged as a focal point in geo-energy research. Each characterization technique comes with its unique set of strengths and weaknesses (Bera and Shah, 2021; Du and Bai, 2024). Nevertheless, the seamless progression of energy exploration and development necessitates a substantial amount of timely experimental data. It is imperative to note that if an imaging characterization technique requires intricate sample preparation, complex equipment handling, and excessive testing time, it not only escalates the research costs but also may not yield data that truly represents the rock characteristics. Consequently, the introduction of a non-destructive imaging characterization technology, characterized by straightforward sample preparation, simple equipment operation, swift testing, and non-contact methodologies, is pivotal. Such advancements

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would invariably lead to cost reductions while enhancing our expedient and precise comprehension of geo-energy reservoir characteristics.

With the advent of non-destructive characterization technology, infrared thermal imaging via a macro lens is progressively gaining prominence in sophisticated analyses across sectors such as electronics, materials, automobiles, and biomedicine. This imaging technique is facilitated by detecting the infrared radiation emitted from objects, which is subsequently converted into electrical signals to produce thermal images. The substitution of the traditional lens with a macro lens allows for enhanced focus on capturing and imaging the thermal signals from minute objects (Planinsic, 2011; Umar et al., 2024). This research posits that this approach will offer a novel perspective for delving into the microscopic intricacies of geo-energy reservoirs, potentially overcoming existing limitations and enabling swift insights spanning from millimeters to micrometers. Such advancements significantly bolster our capability and efficiency in managing the intricate mechanisms within reservoirs, thereby providing a new impetus for expediting the exploration and development of geo-energy.

2. Potential applications of infrared thermal imaging

Infrared thermal imaging primarily operates on the principle of differences in the thermal radiation emitted by objects. When an object is composed of heterogeneous materials, the resulting image will exhibit temperature gradients due to the disparate abilities of these materials to emit and absorb infrared radiation (Gade and Moeslund, 2014). The macro lens, capable of surpassing the constraints of traditional imaging, offer a novel approach to a wide array of scientific and engineering challenges inherent in geo-energy exploration and development.

The aforementioned technique was utilized to image five samples of four distinct lithologies: andesite, conglomerate, sandstone, and shale, under identical external conditions. As shown in Fig. 1, the surface temperature distribution characteristics and the statistical curves of temperature value distribution for these lithologies vary significantly. These disparities are inherently linked to their composition, structure, and the heterogeneity of their reservoirs. Notably, the two shale samples, sourced from different regions (shale-1 and shale-2), display variations in their absolute temperature values, yet their temperature distribution curves are morphologically akin (Fig. 1(f)). It is posited that these novel data, previously unattained and unexplored, will significantly empower the exploration and development of geo-energy.

2.1 Characterization on the static attributes of reservoirs

2.1.1 Identification of macro-geological attributes

The use of infrared thermal imaging in conjunction with a a macro lens facilitates the efficient identification of macroscopic geological attributes of the reservoir, including lithology, lithofacies, and sedimentary facies. The process commences by placing core samples from various strata or polished rock thin sections under the infrared thermal imager for imaging, which results in temperature distribution curve data. This data is then integrated with the previously determined lithology, lithofacies, and sedimentary facies types of each sample, ascertained through field observations and polarized light microscopy. Through the application of machine learning and other methodologies, it is possible to construct intelligent correlation models. These models link temperature distribution curve data with the aforementioned three macroscopic geological attributes. Consequently, when new samples are procured from newly drilled wells within the research area, the reservoir's lithology, lithofacies, and sedimentary facies can be swiftly determined by measuring its temperature distribution curve with the infrared thermal imager and applying it to the intelligent model. Given the instrument's capacity for rapid real-time imaging, this approach significantly enhances work efficiency.

To enhance recognition accuracy, collected rock samples can be subjected to a uniform heating process on a heating plate. By measuring the temperature rise curves for various rocks and halting the heating at a consistent temperature to obtain their cooling curves, valuable data that reflects rock properties could be generated. Incorporating both the temperature rise and cooling curve data into the machine learning model training process will yield an updated intelligent recognition model, potentially significantly augmenting the recognition accuracy.

2.1.2 Microscopic characterization of solid components

The primary solid constituents of geo-energy reservoirs encompass minerals, organic matters, and biological fossils. These components exhibit distinct thermophysical properties, notably thermal conductivity and specific heat capacity. In the context of infrared thermal imaging via a microscopic lens, these disparities in thermophysical properties manifest as variations in temperature characteristics within the thermal image. For example, there exists a marked difference in thermal conductivity between quartz and clay minerals. When subjected to identical external thermal conditions, the temperature value and its temporal evolution in regions containing quartz will inherently deviate from those dominated by clay minerals. By creating a comprehensive database documenting the thermophysical attributes of microscopic solid components and integrating it with the temperature distribution data from thermal images, one can discern the component types present in the reservoir, quantify their abundance, and delineate their spatial distribution. If a thermal image indicates a zone with an elevated concentration of clay minerals, the temperature fluctuations in that region will be noticeably distinct compared to areas laden with brittle minerals. The state of such distribution holds significant implications for reservoir characteristics, especially its fragility.

Through careful statistical analysis of the original temperature distribution data and the heating and cooling curve data for each core sample (e.g., variance, standard deviation, coefficient of variation), a quantitative characterization of the

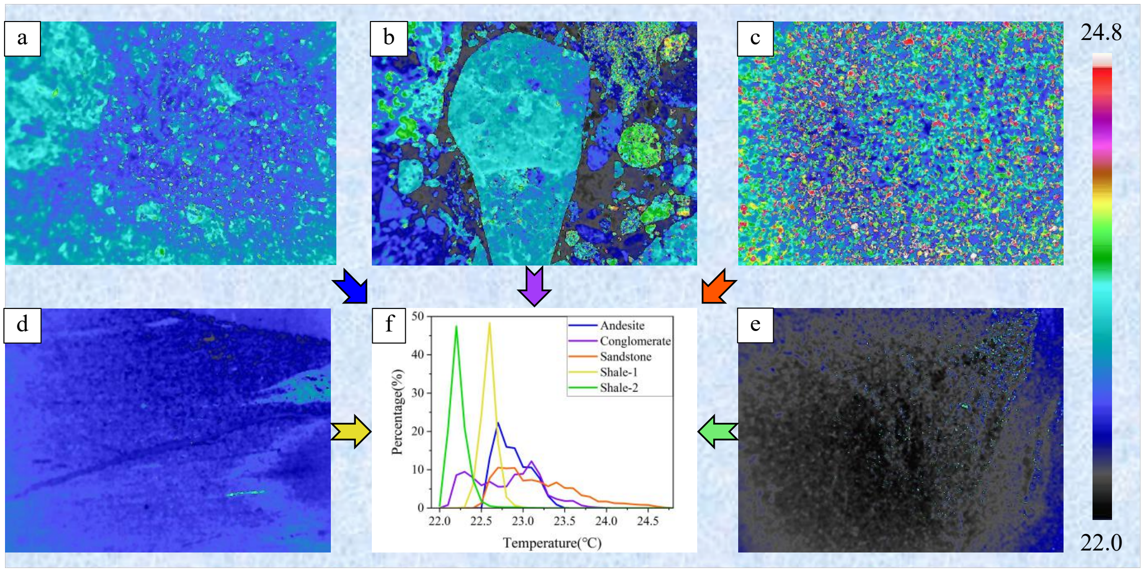

Fig. 1. Applications of infrared thermal imaging under a macro lens in typical reservoir samples. (Note: The five heatmaps were captured using the macro lens of FOTRIC 288+. The labels “a”, “b”, “c”, “d”, and “e” correspond to andesite, conglomerate, sandstone, shale-1, and shale-2, respectively.)

heterogeneity of different sample components can be achieved. For example, a larger coefficient of variation, variance, or standard deviation suggests greater reservoir heterogeneity.

2.1.3 Characterization of fluid micro-distribution state

In addition to the reservoir’s solid components, its pores, fractures, and holes house various fluids such as oil, gas, and water. Just as microscopic solid components can be identified based on their specific heat capacity and thermal conductivity, distinct fluids can also be identified by their unique properties. The contrast in specific heat capacity and thermal conductivity between oil and water, for instance, allows for their easy differentiation. By creating a comprehensive database of thermophysical properties for these fluids and correlating the database with the temperature distribution from thermal images, one can identify the fluid types present in the reservoir, quantify their content, and delineate their distribution states, be it adsorbed, free, or otherwise. It is also possible for us to ascertain the characteristics of fluid distribution in cores that have been collected at various stages. This satisfies the prerequisite for a nuanced understanding of fluid dynamics at different stages of energy exploration and development.

2.1.4 Determination of the multidisciplinary reservoir attributes

Through the application of theoretical derivation, statistical analysis, and various other methodologies, it is feasible to develop a series of theoretical equations or empirical calculation formulas. These equations correlate the thermal physical properties of rocks with their multidisciplinary attributes, including permeability, mechanical properties, and more. Not only does this approach enrich the theory of rock physics, but it also provides a valuable supplementary method for determining the aforementioned multidisciplinary properties.

2.2 Characterization on the dynamic behaviors of reservoirs

2.2.1 Characteristics of reservoir structure and composition changes

During the heating or cooling process of a reservoir, new micro-cracks may emerge due to thermal expansion and contraction, while existing potential micro-cracks may further extend or close. A comparative analysis of thermal images at different times can elucidate the dynamic behavior of these micro-cracks, thereby achieving the objective of monitoring changes in the reservoir structure.

Furthermore, some components within the reservoir undergo transformations, dissolutions, or precipitations at specific temperatures. Infrared thermal imaging can indirectly illuminate these component alterations by manifesting temperature differentials. For instance, different mineral types will absorb or emit heat during their transformation, resulting in detectable abnormal temperature fluctuations within the thermal image. This facilitates the exploration of the diagenetic evolution process within the reservoir.

2.2.2 Design of heating schemes in the in-situ transformation of low-maturity shale oil

The urgent need for the transformation of China’s terrestrial low-maturity shale oil into large-scale, economically viable mature shale oil resources necessitates the application of in-situ heating to facilitate the pyrolysis of its organic matter (Zhao et al., 2024). Infrared thermal imaging, when combined with the macro lens, can significantly contribute to the design of effective in-situ transformation strategies. The initial step involves collecting a series of low-maturity shale oil reservoir samples and creating multiple identical samples from each. Subsequently, various control groups are established for each identical sample, each subjected to different heating schemes. By scrutinizing the continuous change characteristics of the thermal images under diverse heating schemes, the optimal temperature and heating strategy for encouraging the pyrolysis of organic matter can be determined. This provides crucial laboratory evidence to support field practice.

2.2.3 Fluid-rock interaction and flowing process tracking

Infrared thermal imaging, when combined with a macro lens, enables real-time observation of the dynamic interactions between fracturing fluid and acid as they contact the reservoir. This allows for the precise determination of the evolutionary characteristics of pores and fractures at various temporal stages during these fluid-rock interactions.

Similarly, this technology can be employed to investigate the preferred outflow position of fluids during the reservoir imbibition process, monitor fluid flow paths in real-time throughout the displacement process, or track the instantaneous position of tracers while injecting them. Such applications can significantly aid in optimizing the extraction strategy.

2.2.4 Characteristics of microbial oil recovery

The use of microorganisms to augment oil extraction is a novel technology in the field of oil recovery. Once these microorganisms are introduced into the reservoir, their activity generates heat (Ke et al., 2024). Utilizing infrared thermal imaging in conjunction with a a macro lens, it is expected that temperature anomalies in areas of microbial activity can be identified. This will provide insight into the distribution and activity of microorganisms within the reservoir, thereby aiding in the analysis of the microbial oil extraction mechanism.

Furthermore, microorganisms could establish biofilms on reservoir surfaces, altering the rock surface's physicochemical attributes and thermal conductivity. Leveraging this technology, it is feasible to monitor the growth boundaries and thickness variations of the biofilm, facilitating an in-depth analysis of its influence on reservoir fluid dynamics and rock physical properties.

It is important to note that the implementation of the eight aspects outlined above may encounter technical challenges and interference factors that will require resolution in practical application. Some may not even yield satisfactory results. However, it is crucial to recognize that this is a common issue for any emerging technology in the geothermal energy sector. With technological advancements and innovative approaches, infrared thermal imaging under the macro lens will undoubtedly play a significant role in the geothermal energy field.

3. Conclusions

Infrared thermal imaging under a macro lens presents itself as an innovative and promising technique. Although faced with certain challenges, this method unveils novel opportunities for exploration and development, demonstrating potential across multiple facets. Static property analysis is capable of identifying macroscopic geological features, characterizing microscopic components and fluid distributions, and establishing relationships with multidisciplinary properties. This provides valuable insights for understanding reservoirs. In the study of dynamic behavior, it is capable of monitoring changes in reservoirs, designing heating schemes for shale oil, tracking fluid-rock interactions, and microbial activities.

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Conflict of interest

The authors declare no competing interest.

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