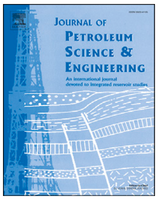
Journal of Petroleum Science and Engineering 156 (2017) 616–622

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol



Investigation of the temperature effect on rock permeability sensitivity

Xiao Guo [a], Gaofeng Zou [a,*], Yunhan Wang [a], Ying Wang [a], Tao Gao [b]

[a] *State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, 610500, China*
[b] *The Research Institute of Shanxi Yanchang Petroleum Corporation, Xian, Shanxi Province, 710075, China*

ARTICLE INFO

Keywords:
Temperature effect
Permeability
Rock permeability sensitivity
Temperature segmented effect
Positive correlation

ABSTRACT

The temperature effect on rock physical properties, including permeability, is still topical, since the available findings are quite contradictory. In the current study of temperature effect on rock permeability, the experiments have been conducted on eight rock samples of different permeability (4) and lithology (4). The results obtained strongly indicate that the temperature effect depends on the initial permeability of core samples: for low-permeability (LP) or higher-permeability (HP) rocks, the temperature-permeability dependence exhibits a negative nonlinear correlation. When the temperature increases from 20 °C to 100 °C, the permeability of LP rocks decreases by 24–70%. However, in ultra-LP rocks, a positive nonlinear correlation has been revealed between temperature and permeability: when the temperature was increased from 100 to 800 °C, the permeability of ultra-LP rocks exhibited a gradual increase within the initial range from 200 °C to 400 °C, and a sharp rise, while in the medium range from 400 to 600 °C the lithology threshold value was reached, the thermal-induced tensile stress in the rock exceeded its yield stress, which resulted in a sharp increase of permeability in the final temperature range from 600 to 800 °C. Based on the experimental data obtained in this study, a theoretical model is proposed, which implies a positive correlation between rock permeability, pressure, and temperature.

1. Introduction

For the last fifty years, the effect of temperature on rock physical properties has been in the focus of numerous researchers. Thus, Somerton et al. (1965); Homand-Etienne and Houpert (1989) and You and Kang (2009) reported a positive relationship between temperature and rock permeability: an increase in the temperature above 200 °C was shown to induce the augmentation of rock permeability. However, Yang et al. (2009) and Liu et al. (2011) found the temperature range, where the temperature and rock permeability exhibit a negative relationship: a temperature rise from 20 °C to 100 °C, would make the rock more compacted and reduce its permeability. Casse and Ramey (1979) postulated that the temperature effect on the permeability of sandstone is based of the properties of saturated fluid, and if core sample is saturated with gas, the temperature effect on permeability can be ignored. Villar and Loreto (2004) studied the temperature effect on the fluid flow behavior in a compacted bentonite and reported that the water retention capacity of rock and swelling capacity of clay decrease with the temperature increase from 20 °C to 80 °C.

Liang Bing et al. (2005); Zhang et al. (2005), and Zuo et al. (2007) reported on the existence of the threshold values for temperature and thermal cracking, while You and Kang (2009) suggested that the temperature threshold value vary with the rock lithology, ranging from 300 to 600 °C. Zeng et al. (2005); Huo and Yang (2005), and Li et al. (2009) reported that the effective stress of rock is related to the temperature effect on rock permeability. Li et al. (2009) reported that if the thermal stress in coal exceeded the effective stress, the coal body expanded outwards and its permeability exhibited a positive exponential dependence from temperature, and vice versa: when the thermal stress was below the effective stress, the coal body expanded inwards, with its permeability possessing a negative exponential relationship with temperature. Heap et al. (2009) investigated the instantaneous brittle creep for sandstone and reported that temperature is the key factor controlling the rock creep strain rate: a temperature rise during the segmented stress creep experiments resulted in the brittle creep strain rate increase by several orders of magnitude. Meng et al. (2015) studied the effect of temperature on the permeability of LP sandstone with different pressures and found that the stress sensitivity is enhanced at high temperatures.

Currently, there is no unified opinion on the mechanism of temperature effect on rock permeability sensitivity, which can be attributed to

---

* Corresponding author. Tel.: 028 83032019.
E-mail address: 854319272@qq.com (G. Zou).

http://dx.doi.org/10.1016/j.petrol.2017.06.045
Received 9 November 2016; Received in revised form 9 April 2017; Accepted 15 June 2017

Table 1
Classification of rock permeable level.

Rock permeability level	Ultra-low permeability	Extra low permeability	Low permeability	Medium permeability	High permeability
Permeability	<1 mD	1–10 mD	10–50 mD	50–500 mD	>500 mD

the following two factors. On the one hand, the errors in the experimental operation, sample ageing, pressure stable time and the loading pressure path can bias the experimental results and the respective conclusions. On the other hand, there was no account or classification for different levels of the intrinsic rock permeability in the previous studies. Therefore, in this study, rock permeability experiments are conducted at different elevated temperatures using four rock core samples with different permeability and four ones with different lithology rock samples, in order to assess the dependence between temperature and permeability for rocks with different intrinsic permeability levels. High-temperature experiments are designed to investigate the temperature effect on rock permeability sensitivity. Based on the thermal stress theory, the concept of temperature threshold value is applied to substantiate the pattern of temperature effect on rock permeability sensitivity. Experimental results are analyzed in detail to reveal the mechanism of temperature effect on rocks with different permeability levels and lithology.

2. Experimental

2.1. Core samples and experimental setup

Rock permeability values can be subdivided/classified into five levels, as shown in Table 1.

Four core samples were selected for this study, including one medium-permeability (MP) shale core, as well as three sandstone (MP, LP and ultra-LP) cores. The rock permeability sensitivity tests were performed at different elevated temperatures from 100 °C to 800 °C. The fluid with a purity of 99.99% nitrogen was applied. The HA-III water relative permeability of oil and gas test device with a high resistance to H_2S and CO_2 was used for simulating the high-temperature and high-pressure environment (the highest temperature reaching 200 °C, the highest pressure reaching 75 MPa). Parameters of the tested core samples are listed in Table 2.

2.2. Experimental procedures and methods

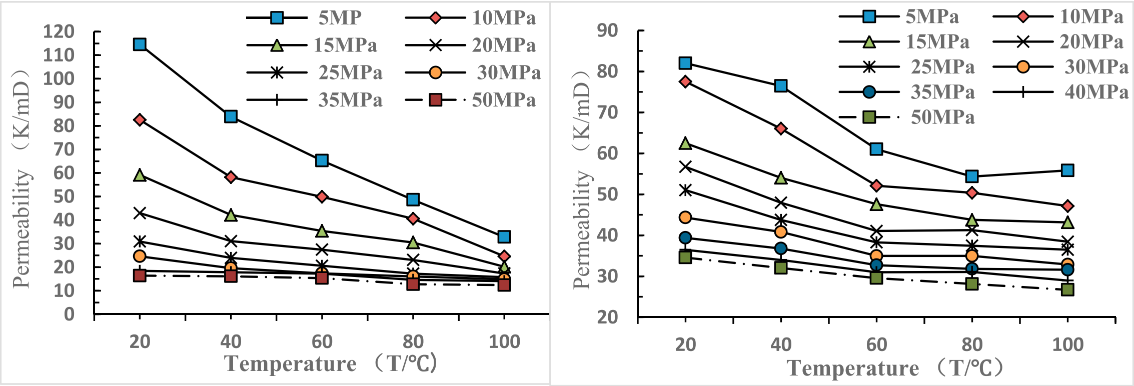
2.2.1. Rock permeability sensitivity tests

In the experiments, the major factors controlling the accuracy of rock permeability sensitivity include the rock aging treatment, pressure loading type, pressure holding time and rubber sleeve aging problems. Core samples, extracted from the underground to the surface, are in the state of stress relief, and thus require aging treatment prior to testing, in order to improve the accuracy of experimental results. Therefore, core samples are subjected to the maximal confining pressure (also referred to as lithostatic pressure, since it corresponds to the pressure imposed on a layer of soil or rock by the weight of overlying material), which is then reduced to the minimum value, and this procedure is repeated 3 times. At first, the initial confining pressure of 2 MPa is exerted via the core holder, providing a gradual and simultaneous increase of the core input and output pressures and keep a constant difference between the input and output pressure values. Once a stable pressure is achieved, the confining pressure is gradually increased together with corresponding input and output pressures. The above operation is repeated, until the input and output pressures produce the real reservoir formation pressure, while the confining pressure level reaches the overlying rock pressure value. The core samples are aged with the in-situ stress for 24 h to simulate the in-situ stressed state.

After the sample aging treatment, keeping constant the input and output pressures on the core holder, the effective stress values are set to 5, 10, 15, 20, 25, 30, 35, 40, and 50 MPa. This loading method with a constant confining pressure and variable internal pressure is widely used by researchers. Usually, the internal pressure is increased after a holding time period of 30 min for each of the above pressure levels. However, for the fractured rock samples, the loading time of the effective stress has a great impact on the stress sensitivity. Therefore, in this study, a holding time of 60 min is used for each pressure level. Once the latter is stable, the gas flow volume is measured by using soap film flow meter, wherein a flat soap bubble (film) is interposed into the flow path in the flow meter volumetric glass tube. As the gas flow causes the film to move up the volume marks, travel time is measured using a stopwatch. Flow rate is

Table 2
Parameters of Core samples.

Core number	Diameter/cm	Length/cm	Porosity/%	Permeability/mD	Type
1	2.52	4.036	24.674	114.246	Fractured medium permeable sandstone
2	2.53	4.134	16.942	81.991	Fractured medium permeable shale
3	2.50	5.034	25.38	50.605	Unfractured low permeable sandstone
4	2.53	5.084	23.57	4.893	Unfractured extra low permeable sandstone



Core1 Fractured Sandstone Core 2 Fractured Shale

Fig. 1. Temperature-permeability dependences for MP rocks at different effective stress levels.