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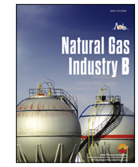

Research article

A new evaluation method for micro-fracture plugging in high-temperature deep wells and its application: A case study of the Xushen Gas Field, Songliao Basin☆

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Abstract

Micro-fractures are developed in volcanic layers of Cretaceous Yingcheng Fm in the deep part of Xujiaweizi fault depression, Songliao Basin. In the process of well drilling, various complex problems happen, such as borehole wall slabbing and collapse and serious fluid leakage. Based on conventional drilling fluid plugging evaluation methods, the real situations cannot be presented accurately, especially in fracture feature simulation and plugging effect evaluation. Therefore, a specific micro-fracture plugging evaluation method was put forward especially for high-temperature deep wells in the paper. It is a new type of micro-fracture core model with the fracture apertures in the range of 1−50 μm. It is made of aluminosilicate that is compositionally close to natural rocks. It is good in repeatability with fracture-surface roughness, pore development and fracture-surface morphology close to natural fractures. Obviously, this new model makes up for the deficiencies of the conventional methods. A new micro-fracture plugging evaluation instrument was independently designed with operating temperature of 200 °C and operating pressure of 3.5−5.0 MPa. It can be used to simulate the flow regime of downhole operating fluids, with the advantages of low drilling fluid consumption, convenient operation and low cost. The plugging capacity of the organo-silicone drilling fluid system was evaluated by using this instrument. It is shown that the grain size distribution of the drilling fluid is improved and its anti-collapse capacity is enhanced. Based on the field test in Well XSP-3, the safe drilling problems in volcanic layers with developed micro-fractures are effectively solved by using the drilling fluid formula which is optimized by means of this evaluation method. And the safe drilling is guaranteed in the deep fractured formations in this area.

Keywords: HPHT; Micro-fracture; Plugging experiment; Evaluation method; Drilling fluid; Volcanic rock; Songliao Basin; Xushen Gas Field

As exploration and development activities by the PetroChina Daqing Oilfield Company (hereinafter referred to as Daqing Oilfield) continually go deeper, volcanic gas reservoirs (i.e., the Xushen Gas Field) of the Cretaceous Yingcheng Fm in the deep part of the Xujiaweizi fault depression, Songliao Basin, have became important succeeding resources for the Daqing Oilfield in recent years. As volcanic strata are thick-bedded and broadly distributed in the Xujiaweizi fault depression with numerous fractures and broken zones, complex downhole accidents, such as borehole wall sloughing and collapse and serious lost circulation [1−5], may often occur, leading to huge economic losses in exploration and development [6]. Essentially, after a stratum is drilled, drilling fluids will physically and chemically interact with rocks, pores, fractures and fluids in it, which led to an increase in borehole wall collapse pressure and thus would further increase the risk

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of wellbore instability, especially in the case of hard and brittle formation with micro-fractures developed at its deeper part. It has been widely acknowledged in the industry that, an important approach to stabilizing the borehole is to prevent the drilling fluids and filtrates from penetrating the formation and to prevent the wellbore [7−9]. Researchers have made great efforts to work out methods for evaluating the micro-fracture plugging. Common methods applied at home and abroad are HPHT filtration loss and dynamic filtration loss, which can provide guidance in porous formation plugging. The modeling of the fractured formation focuses on macroscopic fractures that would induce lost circulation, and the evaluation method for micron-sized fractures is however relatively less studied. The core test method allows for the modeling of formation conditions using a core flow unit, but it involves a complex evaluation process, a lot of repeated tests, and a difficult control of temperature [10−12]. Therefore, it is necessary to develop a simulated plugging evaluation unit with advantages of close morphology to natural micro-fractures, precise fracture aperture, high repeatability and ease of operation, in order to establish an effective method for evaluating the plugging capacity of drilling fluid to micro-fractures and provide technical support for the safe drilling in highly fractured complex strata.

1. Geological setting of deep volcanic rocks

The Xujiaweizi fault depression is a large deep fault depression developed in the northern part of the Songliao Basin, in which the deeply buried Cretaceous Yingcheng Fm strata host well-developed volcanic lithologic traps and are dominated by rhyolite, followed by tuff and breccia. Core data and well log interpretation indicate that, volcanic rocks in this formation mainly contains structural fractures and dissolution fractures with a width of 1−50 μm and a density of 1−5 fractures per meter. Chemical composition analysis, X-ray diffraction, scanning electron microscope (SEM) and casting thin section analysis were performed with volcanic samples from the Yingcheng Fm to determine their chemical composition, mineral type and content, pore structure, and fracture development (Table 1, Figs. 1 and 2) for a targeted research.

SiO_2 is the dominating chemical composition of the Cretaceous Yingcheng Fm volcanic rock (Table 1), followed by Al_2O_3, K_2O+Na_2O, Fe_2O_3, CaO and MgO. Content of clay minerals is low, which are mainly chlorite (with absolute content ranging from 1.99% to 8.06% and relative content ranging from 46% to 72%) and a small amount of illite (with absolute content ranging from 0.29% to 1.60% and relative content ranging from 2% to 8%). Both illite and chlorite exhibit low hydration degree. Volcanic rocks are often tight and hard, and contain mosaic grains and poorly developed and connected pores. These pores are mainly fissure pores with illites attached to the surface and a small amount of locally present cement dissolved pores with few chlorites filled in intergranular pores. Volcanic rocks exhibit textures of porphyritic trachytic, granular, massive, and tuffaceous. Of 22 samples observed microscopically, 20 samples show linear or tubular micro-fractures with a width of 1−50 μm, irregular shapes and varying lengths.

Table 1
Chemical composition of the Yingcheng Fm volcanic rocks.

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O+Na_2O
Average content	67.96%	13.52%	1.08%	1.09%	0.63%	8.10%

2. Preparation of a micro-fractured core model and plugging experiments

2.1. Preparation of a micro-fractured core model

In the preparation of a physical model of micro-fractured core that is similar to a volcanic rock formation, a superfine aluminosilicate gelling material, which has close chemical compositions to volcanic rocks and will no longer be hydrated once solidified, was selected in the lab. Chemical compositions are given in Table 2. The micro-fractured core model is prepared in the following procedures. ① Prepare the slurry of gelling material at a certain water-cement ratio and pour it into a core mould. ② Put a metal foil into the gelling material and place them into the water bath for conservation. ③ Remove the foil gently at an appropriate time before initial gelling to make fractures formed with a certain width. ④ Place the mould again in the water bath for conservation and control the final aperture range of micro-fractures by adjusting temperature and time based on a fact that gelling material can resume the hardening (i.e., it can grow).

For comparing the natural core and the micro-fractured core model, a microscopic scanning analysis was performed of micro-fractures in natural core, metal fracture board and core model to determine the fracture surface morphology, using scanning electron microscope and high-resolution full-automatic metalloscope (Fig. 3). In comparison to traditional scanning electron microscope, the use of scientific-grade, high-end, full-automatic DSX500 metalloscope allows for an analysis of a sample without any damage or specific processing. The test is easy to operate, the magnification factor ranges from 139 to 5000, and the resolution can reach up to 0.01 μm, meeting the requirement of a microscopic analysis of rocks. Microscopic analysis indicates that, natural core exhibits a rough surface and contains well-developed pores; metal fracture board has a smooth and flat surface with very few carbonizations, but exhibits a distinctly different fracture surface shape features from natural micro-fractures; and the modeled core, in comparison to the metal fracture board, has irregular textures and well-developed pores, shows a similar fracture shape to the natural core, and is made up of aluminosilicate matrix that is compositionally close to formation rocks.

2.2. Validation of effective micro-fracture width

Effective micro-fracture aperture of core model provides an important parameter for an evaluation test and determines the