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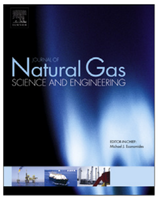

Experimental study on the pressure-depleted flow of natural gas in a cluster of combined tight cores with a certain water saturation

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ABSTRACT

A novel experiment on gas flow in a cluster of combined tight cores was designed to study the degree of reserve recovery of tight gas reservoirs. The composition of the experimental apparatuses and the function of each apparatus are described in detail. An important apparatus was a clamping device that was 50 cm in length. Five pressure gauges were distributed at five different positions on the clamping device to monitor the gas flow pressure. Ten basic operation steps and a formula to determine pressure depletion degree are provided. We conducted 7 experiments using 30 core specimens and real natural gas collected from a tight reservoir in the Ordos basin of China. We categorized the specimens into three groups and designed low, middle and high water saturations and gas flow rates to study the influences of the physical properties, water saturation and gas rate on the degree of reserve recovery. We plotted dynamic pressure curves and calculated the pressure depletion degree, which quantitatively reflected the degree of reserve recovery of the example reservoir. We comparatively analysed the pressure depletion characteristics among different measurement points and experimental conditions. The research results showed that our designed experiment was useful and valuable.

1. Introduction

In recent years, natural gas, especially unconventional gas, has had an increasingly important role in meeting the world's energy needs (Ahmed and Mckinney, 2005). Tight gas, as an important unconventional energy resource, has aroused great public concern, but has a rapidly growing market because its deposits account for much of the world's remaining reserves (Islam, 2015; Dusterhoft and Sharma, 2015; Mcglade et al., 2013). Experts estimate that tight gas has the potential to add anywhere from 60 to 250% to the global proven gas reserves over the next two decades (Ahmed and Mckinney, 2005; Khlaifat et al., 2010).

Tight gas reservoirs have the traits of low porosity and low permeability, as demonstrated in many previous publications. In 1988, Luffel et al. (1988) conducted laboratory measurements of core porosity for a tight gas sandstone reservoir; Higgs et al. (2007) described the characteristics of porosity evolution from a tight gas reservoir in Taranaki basin, New Zealand; Spain et al. (2011) used the nuclear magnetic resonance method to measure the porosity of sample cores from the Cotton Valley Formation, East Texas; Duan et al. (2014a) studied an optimization log interpretation method to calculate the porosity of tight sand gas reservoirs. As for reservoir permeability, Walls et al. (1982), Li et al. (2004) and Cui et al. (2009) performed experiments to determine the gas permeability of tight reservoir cores; Evans (1990) analysed the water-gas relative permeability relationship of some tight gas sands of the North American Continent; Pittman (1992) and Amann-Hildenbrand et al. (2015) researched the approach of using capillary pressure to derive the effective gas permeability of tight gas sandstones; Civan (2010) and Yuan et al. (2016) studied apparent gas permeability for tight porous media; and Bennion et al. (2004) and Baziar et al. (2014) investigated a computational approach of in-situ gas permeability for tight porous reservoirs. All of the above publications indicated that the porosity of tight gas reservoirs is less than 10% and the permeability is less than 0.1mD.

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The pore structure of tight gas reservoirs and tight gas flow characteristics have also been extensively researched. Regarding pore structure, as early as in the 1980s, Soeder et al. (1987) analysed the pore structure of tight Mesaverde sandstone, Piceance basin; Desbois et al. (2011) combined argon beam cross-sectioning and SEM imaging to investigate microstructures from mm-to nm-scale for a tight gas sandstone reservoir; and Clarkson et al. (2012) performed small-angle and ultra-small-angle neutron scattering (SANS and USANS) measurements on samples from the Triassic Monthey tight gas reservoir to determine its pore structure characteristics. Sakhaee-Pour and Bryant (2014) classified the pore spaces of rocks into intergranular dominant, intermediate, and intragranular dominant to describe the effect of pore structure on the producibility of tight-gas sandstones; Mehmani et al. (2015) explored tracer breakthrough profiles (TBP) to reveal the pore structure of tight gas sandstone. Concerning tight gas flow characteristics, Wu et al. (1988) presented a set of new analytical solutions that were developed to analyse steady-state and transient gas flow through porous media, including Klinkenberg effects; Li et al. (2009) designed an experiment to study the gas slip behaviour of tight cores by applying a backpressure at the outlet of the test sample; Yue et al. (2010) conducted a low pressure experiment to reveal the flow characteristics in ultra-low permeability porous media; and Freeman et al. (2011) and Amann-Hildenbrand et al. (2012) simulated gas flow behaviour in a tight gas reservoir system using a mathematical model. In general, tight gas reservoirs and tight gas flow characteristics are rich represented in publications on pore structure.

Furthermore, many studies have reported the related theoretical method of gas reservoir engineering and its applications in tight gas reservoirs. Payne (1996) proposed a reservoir (CR) model to perform material balance calculations in tight reservoirs; Kupchenko et al. (2008) and Xu et al. (2013) developed rate decline type curves for tight gas production performance analysis; Cheng et al. (2009) introduced a practical approach for the optimization of infill well placement in tight gas reservoirs; Khan et al. (2011) discussed the main effect factors of the dynamic production rate of tight gas reservoirs; Elliot and Celia (2012) studied the influence of tight gas production on carbon dioxide sequestration; and Duan et al. (2014b) experimentally characterized the petro-physical properties of a set of sandstones originating from different depths from a single tight gas field to evaluate the gas recovery potential. Generally speaking, the objective of these studies related to gas reservoir engineering was to maximize the their production potential.

Despite the copious literature on tight gas reservoirs, as described above, to our knowledge, little research has focused on the pressure-depleted flow of natural gas through a cluster of combined tight cores. In reality, the pressure-depleted development mode is usually adopted for most tight gas reservoirs. The estimated degree of reserve recovery by pressure-depleted development is one of the most significant properties of tight-gas sandstone reservoirs, however, it remains difficult to predict (Sakhaee-Pour and Bryant, 2014). Therefore, this paper designed combined core experiments to estimate the degree of reserve recovery. In our experiments, we placed 10 short tight cores that were 2.5 cm in diameter and 5 cm in length as a long combined core into a clamping device that was 50 cm in length, and we also placed 5 pressure gauges at different locations of the clamping device to monitor the pressure change caused by natural gas exhaustion. One gauge was located at the inlet of the clamping device, another gauge was located at the outlet of the clamping device, and the other three gauges were dispersed between the inlet and the outlet. To perform the pressure-depleted experiment, we chose core samples from a tight sandstone gas reservoir in the Ordos basin of China. An important procedure of our experiments was to compress natural gas into the long combined core using a pressurizer until the core pressure was equal to the initial reservoir pressure. When the outlet pressure was equal to 1 MPa, we terminated the experiments, and at this moment, the average pressure of the five gauges was deemed to be the “abandonment pressure”. Using the recording data from the gauges, we calculated the pressure depletion degree, which was defined as the percentage of pressure drop between the initial pressure and the “abandonment pressure” out of the initial pressure. The outlet pressure could be compared with the bottom-hole flowing pressure of the gas well and the “abandonment pressure” could be compared with the abandonment pressure of the tight gas reservoir. Therefore, the pressure depletion degree obtained by the pressure-depleted experiment was regarded as the degree of reserve recovery by pressure-depleted development. Generally speaking, the experimental results could provide a reference value for the development of an example tight gas reservoir in the Ordos basin of China; in addition, the proposed experiments in this paper are operable and repeatable for other researchers.

Although many tight reservoirs contain some fractures (Sun and Schechter, 2015a; 2015b), there are no fractures in our experimental cores. In addition, we did not perform repeated experiments, nor did we realize the visualization techniques through the use of CT-scanning for our experimental devices. Therefore, the work conducted in this paper still has some deficiencies: (1) the contribution of fractures to the reservoirs was not studied in our experiments; (2) error control and analysis were not evaluated using the repeated experiments; and (3) the distribution of gas in the core specimens was not visualized in a timely manner. It is suggested that these issues should be addressed in future experimental work.

2. Experimental design and procedure

2.1. Experimental design

The pressure-depleted flow experiment was originally created and designed by the use of a long core-clamping device. The experimental design scheme is shown as Fig. 1. The experimental apparatuses mainly consisted of a compressor, a long core-clamping device, a confining pressure controller, a water separator, a flow meter, four valves, five pressure gauges and a data acquisition system. The compressor is used to pressurize the natural gas gathered from a tight gas reservoir into the long core-clamping device. The long core-clamping device is a cylinder that is 50 cm in length that can sequentially clamp 10 short core specimens that are 2.5 cm in diameter and 5 cm in length. The confining pressure controller can control the confining pressure of the long core-clamping device. The water separator is used to separate water from natural gas. The flow meter records the gas flow rate. The five pressure gauges monitor the gas pressure at five different positions (see points T_1~T_5 in Fig. 1). The first and fifth pressure gauges must be located at the left and right endpoints of the long core-clamping device, respectively. The other three pressure gauges need to include some space intervals between the first measurement point (T_1) and the measurement fifth point (T_5), and the intervals are not necessarily deliberately designed to be an exact distance. The intervals between T_1 and T_2, T_2 and T_3, T_3 and T_4, T_4 and T_5 are noted as d_1, d_2, d_3 and d_4, respectively, as shown in Fig. 1. In our pressure-depleted flow experiments of tight gas, $d_1 = 17.5$ cm, $d_2 = 15$ cm, $d_3 = 10$ cm, and $d_4 = 7.5$ cm. The data acquisition system can collect and save dynamic pressure data. To obtain more accurate experimental data, it is suggested to choose high-accuracy apparatuses. The flow meter, with an accuracy of