Fuel 186 (2016) 293–304

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Experimental investigation of shale gas production with different pressure depletion schemes

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HIGHLIGHTS

- Gas production in shale with different pressure depletion schemes is investigated.
- Pressure depletion scheme affects not only gas production rate but also ultimate gas recovery.
- Permeability reduction is the major reason for the decrease in ultimate gas recovery.

ARTICLE INFO

Article history:
Received 11 April 2016
Received in revised form 10 August 2016
Accepted 12 August 2016
Available online 29 August 2016

Keywords:
Shale gas
Gas production
Pressure depletion
Linear pressure decline
Step-wise pressure decline

ABSTRACT

A matrix pressure depletion scheme can result in pore structure deformation and permeability reduction in shale, which affects the process of gas production in shale. Shale gas production tests were carried out with four core samples and with two crushed samples to investigate the effects of three different pressure depletion schemes on gas production rate and on ultimate gas recovery. The three pressure depletion schemes tested include constant production pressure, linear pressure decline, and step-wise pressure decline. Results of the gas production tests show that, for shale core samples, a production pressure depletion scheme affects not only gas production rate but also ultimate gas recovery. Pressure sensitivity tests of the four shale core samples were also performed, and the results show that permeability reduction of shale cores due to rapid pressure depletion caused the decrease in ultimate gas recovery. The gas production tests with crushed shale samples which were under zero effective stress show that a pressure depletion scheme only affects the gas production rate; that is, the same ultimate gas recovery was obtained for different pressure depletion schemes. The experimental results also show that the linear pressure decline and step-wise pressure decline depletion schemes delay the permeability reduction of the shale matrix, thereby resulting in a greater ultimate gas recovery than the constant production pressure scheme in which the production pressure was dropped immediately to an end value. In a step-wise pressure decline depletion scheme, in which gas diffusion and desorption were allowed to reach equilibrium at each pressure step, the ultimate gas recovery increases with a decrease in the size of the pressure step. However, in a linear pressure decline depletion scheme, the maximum ultimate gas recovery is obtained with that optimum pressure decline rate which causes the best match between the permeability reduction rate and the gas diffusion and desorption rates.

1. Introduction

Shale is considered to be both the source rock and the reservoir, and the shale gas resource is expected to contribute significantly to future gas reserves and production. It is also therefore expected that the production of gas from organic rich shale will increase worldwide [1,2]. China is estimated to have the world's largest shale gas reserves. Shale gas formations are complex and heterogeneous systems, with both organic and inorganic contents [3,4]. Compared to conventional gas reservoir rocks, shale gas reservoirs generally have much smaller pores and pore throats [5], and their effective permeability may often be in the range of 10^{-3}–10^{-6} mD. Porosity is normally in the range of 2–8%, and the amount of total organic content is between 1% and 14% [6]. Shale gas production character is determined by the complex and heterogeneous

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http://dx.doi.org/10.1016/j.fuel.2016.08.057
0016-2361/

structure of shale. Although horizontal wells with multiple transverse fractures (MTFHW) have been applied for economic shale gas production, many factors of an exploitation scheme have impacts on gas production from shale gas reservoirs, and currently the most prominent one is the pressure depletion scheme.

The gas contained in shale gas reservoirs includes compressed gas in pores, adsorbed gas on the surface of pore walls, and dissolved gas in kerogen [7–9]. A significant reservoir pressure drawdown is required to promote free gas expansion and adsorbed gas desorption. Many studies have been performed to determine the production characteristics of the free gas and adsorbed gas of shale gas reservoirs [10–13], especially the production of the adsorbed gas [14–20]. Recent studies [21,22] indicated that the desorption process of the adsorbed gas has a significant effect on the shale gas production behavior and on the pressure transient behavior. Gas desorption is one of the major production mechanisms and can be an important factor for ultimate gas recovery. Desorption plays an important role in both defining the longevity and rate of the gas supply. Because the release of adsorbed gas is pressure dependent, a matrix pressure depletion scheme can affect the adsorbed gas production process.

A matrix pressure depletion scheme will affect the rate of free gas release [23]. With the compressed gas of the matrix expanding and vacating the pores during pressure depletion, a great decrease in the matrix permeability may occur due to the increase in the effective stress resulting from drawdown of the pore pressure, depending on shale properties and the stress field during production [24]. However, the permeability decline can potentially be offset by the permeability enhancement caused by kerogen shrinkage associated with methane desorption [25]. The net reduction or enhancement of permeability accompanying gas production is thus controlled by the competition of the two opposing effects. This has been conclusively shown in field tests in some coal seams and shale reservoirs. The matrix pressure depletion can also cause the deformation of the pore structure in shale, and the pore structure deformation can have a significant impact on the process of gas production. Mckernan et al. [26] indicated that substantial overestimation of gas flow rate and original gas in place will occur from well tests unless the effective pressure-dependent permeability is taken into account. Different permeability changes may occur with different pressure depletion schemes. Hence, a detailed and systematic study of production pressure depletion schemes for shale gas is necessary.

The constant-rate pressure drawdown scheme is a common pressure depletion scheme for shale gas production. However, the available literature on optimization of pressure depletion schemes for shale gas production is limited. In modelling and numerical simulation of shale gas production, models for long term rate decline behavior at a constant pressure and for pressure drawdown at a constant production rate have been developed [27,28]. However, experimental studies comparing constant production pressure and declining production pressure have been rarely reported.

In this paper, shale gas production tests were carried out with four core samples and with two crushed samples to investigate the effects of three different pressure depletion schemes on gas production rate and ultimate gas recovery. The three pressure depletion schemes tested in this paper include constant production pressure, linear pressure decline, and step-wise pressure decline. Results of cumulative gas production and gas production rate under the three depletion schemes were compared and analyzed. Pressure sensitivity tests of the four shale core samples were also performed and the results were used to explain the dependency of the ultimate gas recoveries on the pressure depletion schemes.

2. Experimental

2.1. Core samples and characterization

The shale cores and crushed samples used in this study were collected from well HF-1 in the Jiannan shale play in the Sichuan Basin (Sichuan, China). The shale gas play was found within the stone pillar synclinorium, located on the upper Yangzi block in the eastern Sichuan fold belt. Fig. 1 shows the geologic map of the Jiannan shale play, and the subject location is depicted in light cinnamon in the center. The lithology of the shale core plugs is mixed limestone, shale, and siltstone. The dimensions, mass, porosity, and total organic carbon (TOC) mass fractions are shown in Table 1. The total organic carbon content of the shale samples #1 to #4 analyzed in this study were 3.23 wt.%, 2.91 wt.%, 1.32 wt.%, and 0.49 wt.%, respectively.

2.2. Permeability measurements using pressure pulse decay method

All permeability measurements were made using the pressure pulse decay method [5]. Helium was used as the test gas. Shale plugs were initially cut to a length of approximately 2 cm and a diameter of approximately 2.5 cm. The plugs were placed in a vacuum oven at 60 °C to remove any water and/or residual hydrocarbons from the core until constant mass was achieved. Before a core sample was installed in the core holder, the core sample was wrapped with copper foil to prevent helium gas (test gas) from diffusing through the rubber sleeve to the confining chamber. The temperature of the permeability tests was kept constant at 25.5 °C. A pump was used to apply confining pressure on the sample. The core holder was connected to an upstream gas chamber and to a downstream gas chamber. The test procedure is as follows. Initially, the pressure exerted is the same everywhere in the system. A closed (main) valve separates the upstream chamber from the core sample and the downstream chamber. The downstream pressure is decreased to a value less than the initial pressure that exists in the downstream chamber. After that, the gas flows from the upstream chamber to the core sample and the downstream chamber with a "pressure pulse." The pressure difference (Δp) across the sample is monitored with time. The Δp versus time data series can then be analyzed to determine the sample permeability based on an analytical solution of the equations describing the pressure change during the experiment with known parameters of sample pore volume and gas properties [5]. The permeabilities of core plugs at different pressures which were consistent with the gas production tests were measured.

2.3. Gas production tests of core samples

Fig. 2 shows a schematic of the gas production test of core samples. The experimental setup consisted of a high pressure core holder with two polytetrafluoroethylene pads to seal the end faces of the core sample, a high pressure helium cylinder, a high pressure methane cylinder, a backpressure regulator (BPR), and a gas-flow meter.

The two end faces of the core plug are sealed in the experiments to allow gas to be produced only along the radial direction, as illustrated schematically in Fig. 3. The high pressure pump was connected to the polytetrafluoroethylene pad to provide a constant confining pressure. The annulus between the core sample and core holder wall represents a fracture that provided a gas flow channel. A confining pressure of 26 MPa was applied for experiments with different core samples. The BPR was used to control the production pressure. The fracture pressure was measured using a digital