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Invited review

Pore structure characterization, permeability evaluation and enhanced gas recovery techniques of tight gas sandstones

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ABSTRACT

This mini review provides an overview of the recent developments in the pore structure characterization of tight gas sandstones, permeability measurement techniques, and enhanced tight gas recovery techniques. Firstly, we review the various testing techniques used for characterizing pore structures of tight gas sandstones, namely, the characteristics of pore, throat and micro-cracks in tight sandstones. These techniques can be grouped into qualitative, semi-quantitative and quantitative methods. We review the capabilities of these methods as well as their resolutions in pore-throat diameter measurement. Then the descriptive theories of pore networks of tight sandstones are overviewed, with a special attention paid to the fractal theory. Secondly, the commonly used permeability measurement techniques for tight cores are discussed; these measurements techniques are unsteady-state methods that accommodate the nature of low permeability of tight sandstones. Their merits and drawbacks are provided in this review. We next elaborate on the effect of effective stress and water saturation on the gas relative permeability in tight sandstones; a consensus is found to exist that agrees on the pronounced reduction of gas relative permeability due to increasing water presence and higher effective stress. The permeability jail concept can be used to explain some field observations where there is little water or gas production. Lastly, we move on to review the enhanced gas recovery techniques including waterless fracturing and CO_2-based enhanced gas recovery. Both lab experiments and field applications demonstrate that, due to the negative impact that water causes on gas-phase relative permeability, waterless hydraulic fracturing holds a large potential in effectively unlocking tight gas resources. It deserves further detailed experimental and numerical investigation as well as field studies. In addition, CO_2 injection into tight gas formations is an important technology that is worth of consideration by both industry and governments due to its promising potential for enhancing CH_4 recovery as well as sequestrating CO_2 into depleted tight gas formations.

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Nomenclature

b	Klinkenberg equation constant
k_g	Gas permeability, mD
k_L	Liquid permeability, mD
k_{rg}	Gas relative permeability
k_{rw}	Water relative permeability
p	Exponent in Corey's equation
P	Pressure, MPa
P_C	Confining pressure, MPa
P_P	Pore pressure, MPa
q	Exponent in Corey's equation
r_{p35}	Pore throat aperture corresponding to a mercury saturation of 35%, μm
S_{gc}	Critical gas saturation below which $k_{rg} = 0$
S_w	Water saturation
S_{wc}	Critical water saturation at and below which $k_{rw} = 0$
$S_{wc,g}$	Critical water saturation at and below which $k_{rg} = 1$
S_{wi}	Irreducible water saturation

Greek letters

χ	Effective stress coefficient for permeability
ϕ	Porosity, fraction

1. Introduction

Natural gas including conventional gas and unconventional gas is currently the third largest global energy sources (Ayodele, 2011; Leather et al., 2013). Compared to coal and crude oil, natural gas is a cleaner energy. Therefore, recent years have witnessed an increasing investment in this sector. BP's Energy Outlook 2035 (2014) noted that global energy consumption will grow by 41% before 2035. Conventional gas and unconventional gas seem likely to play a more and more important role in the global energy market. According to Economist (2012), about 45% of the world's recoverable natural gas reserves are "unconventional". International Energy Agency (IEA) (2015) stated that unconventional gas accounts for about 60% of the growth in global gas supply, but also cautioned about the uneven growth across different continents. Unconventional gas, e.g., tight gas, is distributed in many countries and regions in the world, such as USA, Canada and China (Nwaoha et al., 2014). Overall, it can be foreseen that the development of unconventional gas is having an increasing influence on both the regional and global gas markets. However, compared to conventional gas, unconventional gas is regarded as not-easy-to-tap resources due to its complex pore structure characteristics and geological features. Special recovery technologies are usually required, such as multiple hydraulic fractures created in a horizontal well, in order to deliver commercially viable quantities of gas. Unconventional gas mainly includes shale gas, tight gas, coal bed methane and natural gas hydrate (Zou et al., 2012). Significant reserves of tight gas are discovered in both tight sandstones and tight carbonates.

The earliest finding of tight gas occurred in the San Juan basin of America in 1927, and, in 1976, the large Elm Voss tight gas sandstone field was discovered in the western deep depressions of the northern Alberta basin in Canada (Liu et al., 2010). Although the development of tight gas resources dated back to 1920's, there is no unified definition on "tight gas sandstones" in the petroleum industry. Some different names such as tight gas, tight sandstone gas and tight gas sands constantly appear in the published document and literature. Table 1 chronologically lists the definition of tight gas formations from different sources over the years. The Federal Energy Regulatory Commission (1978) and Elkins (1978) stated that the in-situ permeability of tight gas formations should be less than 0.1 mD (See Table 1). Spencer (1985), Holditch (2006), and Perry and Lee (2007) agreed with such viewpoint on the definition of tight gas. Some scholars suggested that porosity should be taken into account in addition to permeability. Therefore, Sharif (2007) proposed to use cut-off permeability of 0.1 mD and cut-off porosity of 10% to define "tight gas". In addition, the air permeability of ≤1 mD and porosity of ≤12% are used to define "tight gas" by Surdam (1997). Zou et al. (2009) and Dai et al. (2012) agreed

Table 1
Definition of tight gas formations from different sources.

Upper limit of porosity, %	Upper limit of permeability, mD	Pore-throat diameter cutoff, μm	Reference
/	0.1	/	Federal Energy Regulatory Commission, 1978
/	0.1	/	Elkins, 1978
/	0.1	/	Spencer, 1985
12	1.0 (air permeability)	/	Surdam, 1997
/	0.1	/	Holditch, 2006
10	0.1	/	Sharif, 2007
/	0.1	/	Perry and Lee, 2007
10	1.0 (air permeability)	/	Zou et al., 2009
/	/	2.0	Nelson, 2009
10	1.0 (air permeability)	/	Dai et al., 2012
10	1.0 (air permeability)	1.0	Zou et al., 2015