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Research Article

Research progress of symbiotic accumulation of coal measure gas in China☆,☆☆

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Abstract

Coal measure gas (CMG), referring to natural gas stored in coal measures, as well as its existence, exploration and production, has been highly concerned recently in natural gas sector in China, and pilot tests of which have been succeeded with some achievements. To provide new geological references, this paper discussed the research progress in CMG co-existence and pooling factors in the respects of the tightening mechanism of coal measure sandstone reservoirs, CMG co-existence and gas pooling assemblages, the superimposed CMG system, and so on. The following findings were obtained. (1) The particularities of CMG geological conditions are shown in three aspects: First, the occurrence and reservoir lithology of CMG are diverse, and the accumulation of sandstone gas in coal measures may be different from that of conventional sandstone gas. Second, the sedimentary environment of coal measures causes the frequent and thin interbedding with various lithologic reservoirs, strong cyclicity and complex gas–water relationship, and the Surat-type CMG is worthy of attention. And third, the sandstone reservoirs in coal measures are embedded in the wide overlying mudstones, the special source–reservoir match and composite gas reservoirs need to develop adaptive co-exploration and co-production technology. (2) The coal measures are rich in organic matters, and a large number of the organic acids are formed during gas generation from the source rocks, which are important factors for the densification of the sandstone reservoirs in coal measures. And the sandstone reservoirs in coal measures may be characteristic of self-generating and self-storing gas and adsorption to a certain extent, and their physical properties can be improved by organic detritus in the reservoirs. (3) The sedimentology of coal measures defines four generalities for favorable CMG accumulation, but effect of the gas-generating intensity, gas migration system, formation fluid energy and effective regional caprock thickness to the accumulation are variable. The natural gas generated in source rocks is re-allocated with a special migration system in a complex source–reservoir system, which is an important basis of CMG accumulation. (4) The superimposition of the gas-bearing system is one of the leading problems in CMG research. In recent years, the logging response identification technology of key strata and the superposition identification method of the gas-bearing system have been further developed. It is found that there are three typical types of fluid pressure curves in coal measures. At the same time, the CMG co-accumulation in the whole sense requires a certain threshold depth. Based on the progress above, the theory of CMG accumulation has been improved and deepened, which is helpful in providing more pertinent suggestions for the development of the joint CMG exploration and production technology.

Keywords: China; Coal measure gas; Co-generation, co-exploration and co-production; Geological condition; Coal-measure sandstone reservoir; Organic acids; Pooling factors; Gas-bearing system

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Geologists of the older generation proposed the term of "coal measure gas (CMG)" in as early as the 1980s, and presciently pointed out its important role and strategic position in future natural gas resources in China [1–3]. Strictly, CMG refers to natural gas stored in coal measures, and is defined as a mineral resource only based on the reservoir genetic type or geological carrier. CMG is mainly composed of the humic-type gas, and synoptically classified into two types, i.e. inner-generating & self-storing gas and inner-generating but storing in other places, according to the positional relationship between source rocks and reservoirs, including coalbed methane (CBM) and coal measure sandstone gas, shale gas, etc. According to the preliminary prediction results by some experts and institutions, the resource quantities of CBM, tight sandstone gas, and shale gas in CMG in local basins or areas in China account for 36.61%, 23.53% and 39.86% on average, respectively [4,5]. CMG co-existence is the geological foundation for complex accumulation of various gases in coal measures, and CMG exploration and development has expanded the previous exploration range limited to only CBM. It helps improve production and economic benefit from a simple CBM well, and provides a new technical way for efficient CMG development [6]. CBM existence, exploration and production have been highly concerned recently in natural gas sector in China [7,8], and specific studies and pilot tests have been funded nationally and invested extensively by related enterprises with some achievements in recent years. In this paper, recent CMG research achievements are reviewed to show the latest progress and to provide new geological references for the development of the joint CMG exploration and production technology.

1. Particularities of CMG geological conditions

Coal measures refer to a set of origin-related sedimentary rocks with coal beds or streaks formed in a marine-terrigenous or terrestrial environment during a certain tectonic stage, which occurred in residual basins of different tectonic natures [6]. The term "CMG" highlights the genetic relationship between different lithologic reservoirs, especially the difference between reservoirs and gas pools, which is exactly originated from the particularities of CMG geological conditions. These particularities are summarized into three aspects.

1.1. Diverse occurrence and reservoir lithology

Coal measures are the only sedimentary system for the symbiotic accumulation of adsorbed gas, free gas or CBM, shale gas, and sandstone gas. CMG is composed of adsorption state-dominated CBM, free state-dominated tight sandstone and carbonate gas, and shale gas of mixed state. Under particular conditions, CMG can be combined with water molecules to form clathrate gas hydrates [9]. In coal measures, the abundance of organic matter increases gradually from inorganic reservoirs (e.g. sandstone, and limestone), mixed reservoirs (shale) to organic reservoirs (coal seam and oil shale), forming a reservoir lithologic sequence without natural boundaries, which is considered as the root cause for the diverse states of CMG. As the production mechanism and development method are varied due to the different occurrence state, joint exploration and production technology of CMG is facing new challenges and technical difficulties.

There are numerous types of source rocks in coal measures, including coal, carbonaceous mudstone, dark mudstone and oil shale, and their large cumulative thickness, high gas-generating intensity and adequate gas supply lead to high abundance of CMG resources [10–12]. In China, new breakthroughs were achieved in CBM pilot tests for vertical wells in 2017. For example, Well Yangmeican 1 targeting at the coal bed, carbonaceous mudstone, and tight sandstone in the western Guizhou, revealed a daily gas production as high as 4656 m^3 and a stable production more than 3600 m^3/d for 50 consecutive days, recording a peak of vertical well daily production rate in Southwest China. The geological resource quantity of CMG in the Yangmeishu Syncline where Well Yangmeican 1 is located is 4.79×10^8 m^3/km^2, six times larger than the simple CBM resource quantity [13].

According to the simulation experiment results, compared with marine source rocks, coal has a relatively higher gas expulsion efficiency, which is 75% at an organic matter maturity (R_{omax}) of 1.0%, and achieves as high as 90% when R_{omax} reaches 5.5%, indicating that the majority of gas generated in coals is migrated and injected into other reservoirs and becomes the main gas source for CMG and adjacent non-CMG reservoirs [14]. It is noteworthy that coal measure sandstone often contains a certain amount of organic matters produced in the form of coal detritus, coal streak and inclusion, suggesting it has certain gas generation and adsorption capacity. As a result, sandstone gas in coal measures may be different from conventional sandstone gas in accumulation effect and even production features [15,16].

1.2. Strong cyclicity of coal measures

As deposited in a transitional environment, coal measures have lithology and thickness sensitively responsive to geological controlling factors, resulting in frequent and thin interbedding with various rocks, such as sandstone, mudstone and coal, and strong cyclicity [17,18]. Such cyclicity is the root reason for various lithologic reservoirs, and also for the occurrence diversity of CMG. It also leads to formation of multiple source–reservoir–caprock assemblages and interior seal rocks under the control of sequence framework with generally small thickness and varied structure in vertical [19], complex and varied gas–water relationships within coal measures [20], and vertical development of multiple fluid pressure systems [21–25].

Fluid pressure systems are adjacent to each other or separated with small spacing, and the dynamic energy equilibrium between them is fragile, so inter-system interference may occur due to mining disturbance [8,26–28]. The variable source–reservoir–caprock assemblages make the co-existence of source rocks, reservoir rocks and cap rocks in one coal bed or shale bed, and makes one assemblage