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Liquid nitrogen gasification fracturing technology for shale gas development

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A B S T R A C T

Shale gas, as an important source of non-conventional energy, has only been successfully exploited for commercial use in the United States, Canada and China. The successful commercial exploitation of shale gas depends primarily on the development of horizontal drilling and fracturing technology. Currently, hydraulic fracturing is the main approach used in exploiting shale gas; in addition, there are alternative approaches to high energy gas fracturing and CO_2, N_2 foam fracturing. However, there are some shortcomings of each of the existing fracturing technologies. For example, hydraulic fracturing can realize large-scale fracturing but cannot avoid the problem of clay hydration swelling. The influence of fracture orientation via ground stress is also larger. Moreover, hydraulic fracturing consumes a large amount of water. As a result, hydraulic fracturing is not applicable to western China. For resource and environmental reasons, the French government has proposed legislation to ban hydraulic fracturing for the exploitation of shale gas (2012). Based on the survey and study of existing fracturing technologies, the author proposes a new technology: liquid nitrogen gasification fracturing technology. This novel fracturing approach involves liquid nitrogen pressure fracturing, rock contraction fracturing, rock embrittlement fracturing and nitrogen expansion fracturing. The proposed approach can realize large-scale fracturing, does not suffer the problem of clay hydration swelling, has no water resource limitation and does not produce environmental pollution. In short, the proposed approach may better guide shale gas development practices.

1. Introduction

With the development of the global economy and scientific technologies, oil and gas resources are in short supply. Shale gas, as an unconventional gas resource, has attracted the full attention of senior managers, scholars and investors (Yan et al., 2009; Beckwith, 2011; Selley, 2011). The exploration and development of shale gas have been very successful in North America in recent decades and is currently expanding throughout the world. The acceleration of the development of shale gas resources has become a common activity in countries and regions around the world (Zhang and Tan, 2009).

Shale gas resources are abundant around the world but have not been widely developed until now. It is difficult to exploit shale gas due to low porosity pressure, low porosity, low permeability and high clay concentration (Zhang et al., 2008). Over 90% of the wells must be fractured to achieve commercial gas flow after drilling (Xue, 2011; Wang et al., 2011).

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Currently, hydraulic fracturing is the main method used in the exploitation of shale gas. Although hydraulic fracturing could realize large-scale fracturing, it cannot avoid the problem of clay hydration swelling, and it consumes a large amount of water. The high consumption of water is not applicable in western China. For resource and environmental reasons, the French government has proposed legislation to ban hydraulic fracturing for the exploitation of shale gas (2012). Accordingly, the author proposes a new technology: liquid nitrogen gasification fracturing technology (LNGF) (Li, 2011), which has many advantages in the development of shale gas, such as large-scale fracturing and the lack of a water resource limitation.

2. The current status of shale gas fracturing

Various fracturing measures have been used in shale gas wells. In the 1970s, open-hole completion and nitroglycerine explosions were used to enhance the recovery ratio in American shale gas development. In the 1980s, high energy gas fracturing and CO_2, N_2 foam fracturing were developed. Since 1985, hydraulic fracturing has been used in shale gas stimulation. After entering the 21st

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century, increasing numbers of new fracturing technologies, such as hydrojet fracturing, re-fracturing, and so on, have been developed, promoting shale gas development (Li et al., 2007; Leonard et al., 2007).

2.1. Hydraulic fracturing technology

Hydraulic fracturing technology, the main method used in shale gas exploitation, includes multi-stage fracturing, water fracturing, simultaneous fracturing, hydrojet fracturing, and re-fracturing.

Hydraulic fracturing technology has been continuously developing and improving (Rahm, 2011; Ding et al., 2012). From the original massive hydraulic fracturing to the current water fracturing with a drag reducer, the cost of hydraulic fracturing technologies has been greatly decreased, and production has increased significantly (Tang et al., 2010, 2011).

Multi-stage fracturing involves segment fracturing in different formation positions of a wellbore. This mature technique is applicable to horizontal wells with more production layers and long horizontal section (Dusseault et al., 2011). The fracturing fluid of water with a small amount of additives (drag reducer, stabilizer, surfactants, and so on) is suitable for water fracturing because it can achieve an even better production-increasing effect at a lower cost. Simultaneous fracturing is a common technology in the middle-later development period in shale gas. By making full use of the advantage of offset wells, simultaneous fracturing can increase the width of cracks and connect natural cracks at maximum. Hydrojet fracturing completes hydraulic perforation, fracturing and segregation as a whole. Hydrojet fracturing solves the difficulty of fracturing in open-hole completion (Tian et al., 2008). The flow conductivity of a fractured shale gas well will decline during production and must be restored by re-fracturing. Table 1 shows the characteristics and adaptabilities of hydraulic fracturing technologies in exploiting shale gas.

2.2. High energy gas fracturing technology

High energy gas fracturing (HEGF) was developed on the basis of detonation fracturing. With powder or propellant rapidly burning in wellbore, a great quantity of high temperature and high pressure gases can be generated under control in a very short time. The high energy gases are squeezed into the strata along the perforation and create several radial cracks without earth stress restrictions. As a result, natural cracks are connected. Thus, the gas conductivity can be effectively improved. Moreover, the pollution and blockage of the pores near the wellbore caused by drilling, perforating and cementing can be effectively eliminated. HEGF has been successfully used in the shale gas reservoirs of Devonian in eastern American since the 1980s (Ji and Li, 1994).

HEGF has the following advantages:

Table 1
The characteristics and adaptabilities of hydraulic fracturing technologies for shale gas.

Technology	Characteristic	Adaptability
Multi-stage fracturing	Maturity, universality, segment fracturing	Wells with more production layers
Water fracturing	Low cost, low sand-carrying capability	Wells of many natural cracks
Simultaneous fracturing	Simultaneousness, low cost, short operation time	Offset or short distance wells
Hydro jet fracturing	Accurate and fast locating, without packer	Wells of open-hole completion
Re-fracturing	Open cracks again	Old or declined production wells

(1) It creates radial cracks without earth stress restrictions.
(2) The process of energy release is under control.
(3) It does not pollute the formation and environment.
(4) This technique has the advantages of short period, low cost, simple equipment, and no topography and water limitations.
(5) It is suitable for the fracturing operation of water or an acid sensitive formation.

2.3. CO_2, N_2 foam fracturing technology

Foam fracturing began in the 1970s and has been widely used in America and Canada since the 1980s (Zhang and Zhang, 1991; Xu et al., 2002). The fracturing fluid is a liquid mixture including liquid nitrogen (or liquid carbon dioxide), a thickener and other chemical additives. After fracturing fluids with propping agents enter the formation, liquid nitrogen/liquid carbon dioxide will be transformed into the gas state with the temperature increase of the wellbore and formation; thus, a gas–liquid two-phase flow forms.

Foam fracturing is especially suitable for the fracturing operation with low pressure, low permeability and water-sensitive formation. Compared with other technologies, only small amounts of propping agents and fluid enter into the formation; the formation damage can be minor; and low filtration, high backflow and good compatibility with formation fluids are obtained.

3. Shortage of existing shale gas fracturing

Although there are many types of fracturing technologies, each of them has flaws. Hydraulic fracturing can realize large-scale fracturing, but it cannot avoid clay hydration swelling. The influence of fracture orientation by ground stress is also larger. Moreover, hydraulic fracturing consumes a large amount of water; take as an example the Barnett shale gas field—the average water consumption in drilling is 182 t per well, while 13,650 t are consumed in fracturing, and the well number of shale gas development is ten times that in convention. Moreover, the amount of wastewater used in shale gas exploitation is very high. This wastewater puts a large amount of pressure on the resources and environment. The French government has proposed legislation to ban hydraulic fracturing in the exploitation of shale gas.

HEGF can fill the gaps caused by hydraulic fracturing, but it just creates short cracks around wells and is not applicable to wells of poor cementing quality. The operational conditions of HEGF are also very strict. HEGF is suitable for brittle formations but not plastic formations, and it is suitable for limestone, dolomite, and sandstone with low shale content but not mudstone, marl, or sandy mudstone.

Foam fracturing is especially appropriate for the fracturing operation of low pressure, low permeability and water-sensitive formations and results in low formation damage. Foam fracturing can only be used for shale gas reservoirs of low pressure or shallow depth (less than 1500 m).

Based on the above, to better guide the practice of shale gas development, it is necessary to continually study and develop new fracturing technologies.

4. Liquid nitrogen gasification fracturing technology

Shale gas wells must be fractured to achieve commercial gas flow. To address the shortcomings of existing technology, inspired by magma splits into pieces after contacting sea water (Fig. 1), magma cools into hexagonal prisms (Fig. 2) and the crack in the surface in winter (Fig. 3), and at the same time Cha et al. (2014)