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Review article

A review on hydraulic fracturing of unconventional reservoir

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ABSTRACT

Hydraulic fracturing is widely accepted and applied to improve the gas recovery in unconventional reservoirs. Unconventional reservoirs to be addressed here are with very low permeability, complicated geological settings and in-situ stress field etc. All of these make the hydraulic fracturing process a challenging task. In order to effectively and economically recover gas from such reservoirs, the initiation and propagation of hydraulic fracturing in the heterogeneous fractured/porous media under such complicated conditions should be mastered. In this paper, some issues related to hydraulic fracturing have been reviewed, including the experimental study, field study and numerical simulation. Finally the existing problems that need to be solved on the subject of hydraulic fracturing have been proposed.

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1. Background

Unconventional gas mainly includes shale gas, tight gas and coal seam gas. Shale gas is commonly in mudstone, shale and between them the interlayers of sandstone. Tight gas often has been stored in tight sandstone or sometimes limestone. Coal bed methane is contained within coal seams. Their common attribute is that the permeability of the matrix is very low, and the permeability often has been improved by artificial or natural fractures [55]. However, the differences between them are also significant. For example, the effective shale thickness for gas production should be more than 15 m while the height of coal is generally from 0.6 m to 5.0 m [68], as coal seams to be fractured may be multiple and thin, hydraulic fracturing in coal needs to be more accurately designed and controlled. Moreover, the Young's modulus of coal is smaller than shale and tight sandstone, the permeability of coal is more sensitive to stress due to the development of cleat system, and leakoff in coal may be more severe, which can significantly affect the fracturing result. Due to the complexity of unconventional reservoirs, it is challenging to predict the initiation and propagation of hydraulic fractures [39]. For example, the complex in situ stress state and distribution of rocks of varied attributes, which may change the profile of hydraulic fractures [38]; the existence of arbitrary pre-existing interfaces may diversify or arrest hydraulic fractures [93]; the temperature effect [75]; the fluid loss and transport of proppant; the competition between hydraulic fractures, and its recession and closure [4]. Thus, it is crucial to explore how hydraulic fracturing process will happen in complex geological settings.

Firsthand materials of hydraulic fracturing come from in-door experiments, and field study. Laboratory study undergoes from small-scale rock samples with several cubic centimetres to large ones with one cubic metre or more. Since it is easy to control the stress conditions and make artificial structures within samples, hydraulic fracturing process with different stress field and rock structures can be conveniently studied. Especially in large scale experiments, it is possible to build a full size borehole, or to control the development of hydraulic fractures, and the hydraulic fracture geometries can be obtained easier and parametric study can be quite handy [7,41].

Field study is much more complex because the mechanical traits and geologic conditions and in-situ stress fields are different and unique while laboratory experiments can be

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controlled and repeated, and difficulties for hydraulic fracturing can be easily added by in situ experiences [87]. Many methods can be used to evaluate hydraulic fracturing in field study. For example, historical production data such as bottomhole pressure and near-wellbore pressure losses can be used to understand the fracturing process [45]; sonic anisotropy and radioactive tracer logs can be used to analyse hydraulic fracture geometry [76]; and both resistivity and acoustic imaging can be used to evaluate dominant fracture azimuths and borehole features [44].

2. Influences of in-situ stresses on hydraulic fracturing

In order to optimize gas production in shale, it is necessary to create as much contact area between the unconventional gas reservoir and fracture system as possible, within economical permit. Stress condition in formation is a dominating factor in creating hydraulic fractures at different locations and being able to control their propagation [51]. Warpinski and Teufel [87] showed from field results that in-situ stress was the overriding factor that influenced the fracture propagation when it was in a high-stress region compared to interfaces, modulus, strength changes, fluid pressure gradients, and most bedding planes. Near wellbore stress condition can control the initiation and propagation of hydraulic fracture, and the size of hydraulic fracture and injected fluid can also change the stress field in the reservoir. Also the real time change along the near wellbore can change the hydraulic fracture direction and affect the production greatly [3,9,90]. The differences in far-field principal stress can alter the direction of hydraulic fractures and also determine whether there is a main fracture or there are many secondary fractures, as well as the shape of fracture has also been constrained [23,88]. But Abass et al. [2] pointed out that the near wellbore stress field can control the hydraulic fracturing in its early stage, and once the fracture extended into the original stress field, its propagation will be controlled by the original stress field. Thus, the well should be perforated to bypass the near wellbore stress field in order to create oriented fractures perpendicular, angularly or longitudinal to the wellbore, as shown in Fig. 1.

Stress difference not only influences the direction of hydraulic fractures, but also the quantity. Zhou et al. [96] found that within the scope of high horizontal stress difference, hydraulic fracture was a dominating fracture with random multiple branches, while within the scope of low horizontal stress difference the hydraulic fracture was partly vertical, planar fracture with branches. Moreover, they related the pressure profile to natural network conditions. For example, a high frequency of pressure

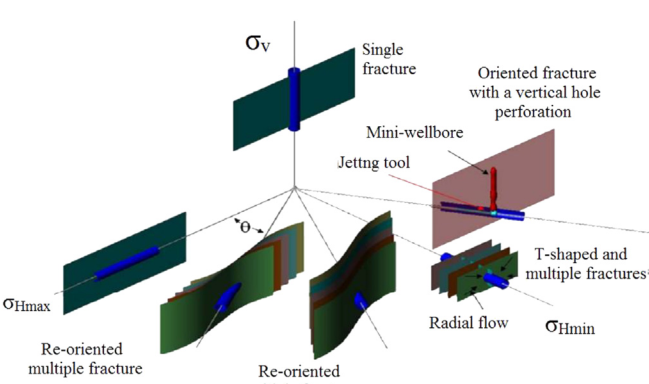

Fig. 1. Fracture geometry with different wellbore orientations relative to in-situ stress field [2].

fluctuation during fracture propagation could mean the existence of small natural fractures while the smooth pressure could mean the existence of natural fractures with strong network. Stress field will be changed during or after hydraulic fracturing process, thus, hydraulic fractures may mutually affect each other. Rabaa [30] found that because the stress field was changed after the fracture was created, subsequent created fracture would be affected by the new stress field and would not be parallel to the first fracture. Moreover, stress field with other factors, such as fluid viscosity and flow rate, may be together affect hydraulic fracturing process. For example Weijers et al. [89], experimented on hydraulic fractures induced from horizontal wellbores. They found that transverse fractures happened with low flow rate, viscosity and high horizontal stress contrast, while axial fracture initiated with higher flow rate and viscosity. Especially, multiple fractures occurred when the wellbore was oblique to the preferred plan.

The intersection angle between in-situ stress and wellbore direction directly affects the orientation of hydraulic fracture, and due to the geological structure and stress condition, the expected initiation and propagation of hydraulic fracture will reversely determine the spacing of wells and fractures, and orientation of wells [49,57]. Thus, in order to effectively perforate strata and develop dominant fractures and maximize fracture complexity, it is important to master the stress condition in the reservoir and also know how it will evolve with hydraulic fracturing process [14,52]. However, the initiation locations of hydraulic fractures are usually equally spaced, which is a waste of fracturing capital because the formation is heterogeneous [73]. Thus, in order to properly select locations for hydraulic fractures, factors such as near wellbore stress condition, wellbore direction, direction of principal stress etc. should be considered with cautious [21]. Horizontal well is popular in unconventional gas stimulation because it can greatly increase the contact area between fracture and reservoir. Experiments on horizontal wells from Ref. [1] showed that hydraulic fracturing was significantly influenced by its deviate angle from the direction of maximum horizontal stress. They found that the initiation pressure was related to the angle; if the angle was not 0, crack would be reorientated into the direction perpendicular to the minimum in-situ stress, during which shear failure would occur but followed immediately by tensile failure; if the angle is 45°, multiple parallel fractures happened, which would cause screenouts and high treating pressure; besides, T-shaped crack would be generated due to the near wellbore stress field if the overburden stress was the highest among the three principal in-situ stresses.

In shale gas reservoirs horizontal wells that can reach 1600 m long are predominant [12,26], multiple hydraulic fractures are placed along horizontal wells and multi-stage fracture often has been performed [18]. Earth deformation is significant because of the leakoff, anelastic deformation, enlarged fracture width when hydraulic fracturing has been performed in a large area, or residual fracture width is common after hydraulic fracturing due to rough fracture surface and/or sliding [86]. Stages of hydraulic fracturing process will be performed on a single well or on multiple wells, moreover, simultaneous and sequential fracking has been adopted to lead the orientation of hydraulic fracture [13,85]. Previous hydraulic fractures impacts on later fracking work and simultaneous fracking will influence each other by reforming the stress field and transfiguring the formation [46,64,88]. Different spacing will lead to different stress condition which can prevent/enhance secondary hydraulic fractures [88]. Moreover, contact area between hydraulic fracture and rock matrix has been enlarged by increase the fracture complexity or networking [59,66]. Even in some cases, bottomhole pressures

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