Geomechanics and Engineering, *Vol. 17, No. 6 (2019) 535-541*
DOI: https://doi.org/10.12989/gae.2019.17.6.535

An experimental study on the hydraulic fracturing of radial horizontal wells

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(Received February 23, 2018, Revised March 9, 2019, Accepted March 17, 2019)

Abstract. Combining the radial well drilling and hydraulic fracturing technique, the production capacity of the reservoirs with low-permeability can be improved effectively. Due to the existence of radial holes, the stress around the well is redistributed, and the initiation and propagation of hydraulic fractures are different with those in traditional hydraulic fracturing. Therefore, it is necessary to study the influences of radial horizontal wells on hydraulic fracturing. The laboratory experiment was conducted to simulate the hydraulic fracturing on the physical model with radial holes. The experimental results showed that, compared with the borehole without radial holes, the sample with radial hole in the direction of maximum horizontal stress was fractured with significantly lower pressure. As the angle between direction of the horizontal hole and the maximum horizontal stress increased, the breakdown pressure grew. While when the radial hole was drilled towards the direction of the minimum horizontal stress, the breakdown pressure increased to that needed in the borehole without radial holes. When the angle between the radial hole and the maximum horizontal stress increase, the pressure required to propagate the fractures grew apparently, and the fracture become complex. Meanwhile, the deeper the radial hole drilled, the less the pressure was needed for fracturing.

Keywords: hydraulic fracturing; breakdown pressure; radial horizontal well; rock mechanics; experimental study

1. Introduction

As ultra-low permeability reservoirs are characterized by large burial depth and poor physical properties, resulting in low productivities, they have to be fractured in the reservoirs in practical engineering(Qi *et al.* 2012, Adams and Rowe 2013, Dutta *et al.* 2014, Hammond and O'Grady 2017, Ye *et al.* 2018, Ji and Li 2018, Zhu *et al.* 2019). Radial horizontal drilling technique is an effective method to improve oilfield development (Li and Shen 2005, Marbun *et al.* 2011, Chi *et al.* 2015, Kamel 2016). However, when merely using several radial horizontal wells in the low permeability reservoirs, insufficient well-drainage areas and small increase of oil and gas production are likely to occur. Therefore, a combination of radial horizontal drilling technique and hydraulic fracturing technology can largely improve the permeabilities of formations and increase well-drainage areas (Guo *et al.* 2017). The combination presents broad application prospects in the development of low permeability reservoirs. The Doelson West Oil Field in Kansas, USA, carried out hydraulic fracturing operations in radial horizontal well in 10 wells, boosted production by more than 2 times and stabilized for more than 3 years (Cinelli and Kamel 2013). After a well is drilled, stress concentration occurs around the wellbore (Yan *et al.* 2017, Moradi *et al.* 2018), and the fracture and breakout orientation of the wellbore is determined by the stress state around the well (Li *et al.* 2018, Wang *et al.* 2018, Yan *et al.* 2018, Ghasemi and Nowak, 2018). However, the presence of radial shafts leads to the redistribution of the stress fields around the well (Zhou *et al.* 2013, Zhou *et al.* 2018)and increasingly complex initiations of hydraulic fractures (Gandossi 2013, Zhu *et al.* 2014). Furthermore, traditional fracturing models are inapplicable as the expansion trajectory of hydraulic fractures may not extend along the directions of the maximum stress. As a result, the influences of radial horizontal boreholes on the initiation and extension of hydraulic fractures need to be further explored. At present, little research on the fractures of radial horizontal well has been made and most studies are carried out using numerical simulations. In this research, the influences of the radial boreholes on the hydraulic fracturing are studied by using the radial boreholes model to perform a simulation experiment in a hydraulic fracturing chamber. This study provides experimental and theoretical bases for the fractures of radial horizontal wells.

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2. Experimental equipment

The equipment used in this research is a tri-axial

ISSN: 2005-307X (Print), 2092-6219 (Online)

(a)

(b)

Fig. 1 The tri-axial simulation device for the hydraulic fracturing

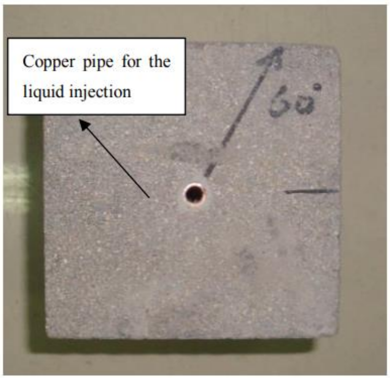


Fig. 2 Untested rock specimens after processing

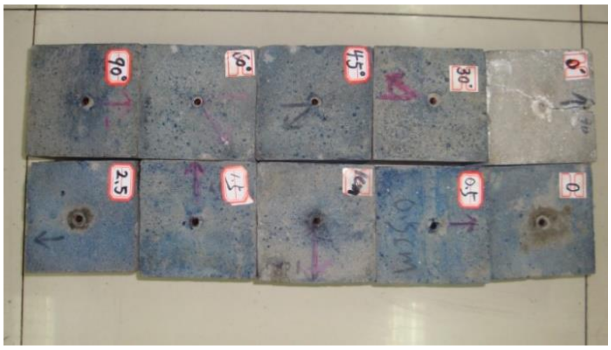


Fig. 3 The photos of the tested cores

simulation test system developed by the laboratory of rock mechanics in China University of Petroleum (East China) (Cheng *et al.* 2013). This simulation test systems can be used in researches on fracturing mechanisms and the mechanisms of wellbore instability and the failure mechanisms of rocks. The fracturing simulation test system consists of a main true triple-axis pressure chamber of, an oil pump under confining pressure, a servo-controlled injection pump, a hydraulic capsule, a data collection system and other auxiliary devices. Experiments are made under independent loading along three orthogonal directions to simulate the real states of in-situ stress. The stress loading method of the experimental system is exerting a flexible pressure on each compression plate. The compression plates are set between the rock specimens and the loading frames. The liquid injection into pressing plates results in increasing pressure, causing the expansion of pressing plates. Afterwards, to achieve the goal of simulating horizontal in-situ stress, the pressures are passed to the surfaces of the rock specimens. Compared with the loading on a rigid target using the traditional flat jacks, the flexible pressures of compression plates have an advantage - homogeneous stress loads. However, owing to expanded compression plates materials has the characteristics of non-retraction, they has a shortfall as well: a limitation in the number of repeated use.

3. The experimental program

Artificial rock specimens made of cement and sand are used in the experiments, because the underground natural rock specimens are difficult to meet the dimension requirements of experiments (Jia *et al.* 2013, Zhu *et al.* 2014, Yilmaz *et al.* 2017). The tested physical and mechanical properties of rock specimens are shown as follows: The porosity is 17%-20%, the Young's modulus is 6.2GPa-6.9 GPa, the Poisson's ratio is 0.23-0.26, the uniaxial compressive strength is 34.3MPa-37.5MPa, the tensile strength is 3.6MPa-4.1MPa, and the internal friction angle is 20.1°-23.5°.

Table 1 The experimental program

Sample No.	Vertical stress (MPa)	Maximum horizontal stress (MPa)	Minimum horizontal stress (MPa)	Radical hole direction* (°)	Radical hole depth (cm)
I	30	20	10	---	---
II-1	30	20	10	0	2.0
II-2	30	20	10	30	2.0
II-3	30	20	10	45	2.0
II-4	30	20	10	60	2.0
II-5	30	20	10	90	2.0
III-1	30	20	10	0	0.5
III-2	30	20	10	0	1.0
III-3	30	20	10	0	1.5
III-4	30	20	10	0	2.5

*Radical hole direction: The angle between the radial holes and the direction of the maximum horizontal stress

In addition, the dimension of the specimens is 105 mm×105 mm×93 mm, the depth of simulated borehole is 65 mm, the borehole diameter is 8 mm, and the diameter of the radical hole is 2.5 mm. The simulated borehole is located at the center of the samples, and the fracturing fluid is pumped into the borehole using a high-pressure pump. A method of applying prefabricated boreholes is used in the rock specimens with radial holes. Before conducting the experiments, the rock specimens made of cement are processed on the mill to planish the end surfaces. In this way, the dimensions of rock specimens can perfectly match with the experimental molds. Moreover, the copper pipe with 30 mm in length used for the injection of fracturing fluid is buried in the central borehole to be fixed and sealed by using strong adhesive. On this basis, the rock specimens can be obtained.

During the experiment, the simulated fracturing fluid medium was 0.5% melon gum solution. In order to facilitate the observation, blue ink was added as the tracer in the fracturing fluid, so as to observe the development of the fractures in the process of hydraulic fracturing more clearly. The fracturing fluid volume remained constant at 9.0 ml/min.

By using artificial cores, ten sets of hydraulic fracturing experiments for true triple-axis are made. Through the experiments, the influences of the radical hole orientation and the depths of radial hole on the initiation and the propagated morphology of the fractures induced by hydraulic fracturing are studied under the conditions of certain in-situ stresses. The experimental program is shown in Table 1. The rock specimens tested are demonstrated in Fig. 3.

4. Experimental results

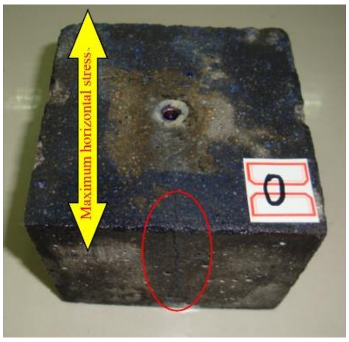
The obtained breakdown pressures under each experimental condition are shown in Table 2.

Fig. 4 shows the photos of the Sample I after the test, we can see that a crack along the maximum stress direction is fractured. According to the fracturing simulation curve in Fig. 5, the breakdown pressure of this sample is 26.3 MPa, the fracture extension pressure is 10.7 MPa.

The radical hoe depth of Sample II-3 is 2 cm, and the angle between radial hole and the maximum horizontal principal stress is 45°. Fig. 6 is the photos of Sample II-3 after the test, and Fig. 7 is the fracture simulation curve. The breakdown pressure of this sample is 24.1MPa and the fracture extension pressure is 17.1MPa. It is noteworthy that the fracture extension pressure of Sample II-3 is much higher than that of samples II-1 and II-2, which may be because of the presence of radial holes, the borehole is firstly fractured along the radial hole at the time of initial fracturing, but the extension orientation of the crack away from the wellbore will eventually be along the maximum horizontal principal stress, so that the shape of the cracks become more complex, crack extension pressure increases. Although the presence of radial holes in samples II-1 and II-2 also reduced the breakdown pressure, due to the radial hole orientations are along the maximum horizontal principal stress orientation or near the maximum horizontal principal stress orientation. So that the wellbore basically fractured at the maximum principal stress direction, cracks almost have no specific, so the extension of the pressure is small.

Table 2 The experimental results

Sample No.	Breakdown pressure (MPa)	Fracture extension pressure (MPa)
I	26.3	10.7
II-1	21.3	11.0
II-2	23.9	11.4
II-3	24.1	17.1
II-4	22.9	20.0
II-5	25.8	13.2
III-1	24.2	11.0
III-2	25.0	11.2
III-3	24.5	10.7
III-4	15.3	10.0



(a)

(b)

Fig. 4 Crack morphology of Sample I after the test

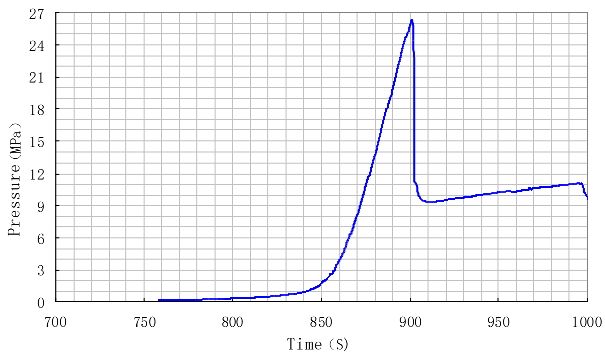
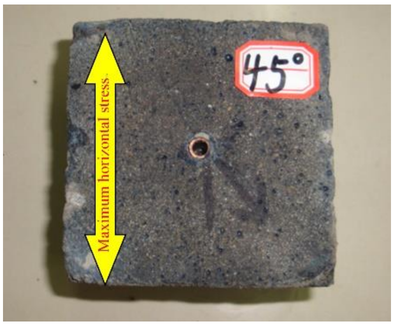


Fig. 5 Fracturing simulation curve of Sample I

The radical hoe depth of Sample II-5 is 2cm, and the angle between radial hole and the maximum horizontal principal stress is 90°. Fig. 8 is the photos of Sample II-5 after the test, and Fig. 9 is the fracture simulation curve.

The initial breakdown pressure of the sample was 25.8 MPa and the fracture extension pressure was 13.2 MPa. The breakdown pressure is essentially the same as that of the non-radial hole. The initiation and extension of fracture both along the maximum horizontal stress direction, which indicates that the presence of radial horizontal hole in this direction has no significant effect on the expansion of the fracture.



(a)

(b)

Fig. 6 Crack morphology of Sample II-3 after the test

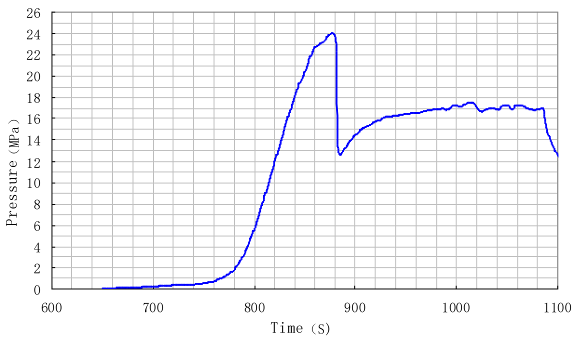
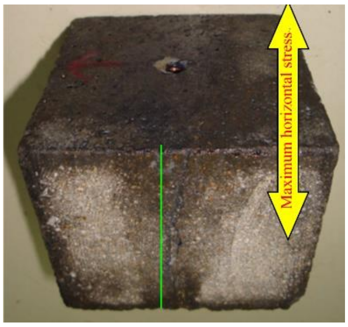


Fig. 7 Fracturing simulation curve of Sample II-3

(a)

Fig. 8 Crack morphology of Sample II-5 after the test



(b)

Fig. 8 Continued

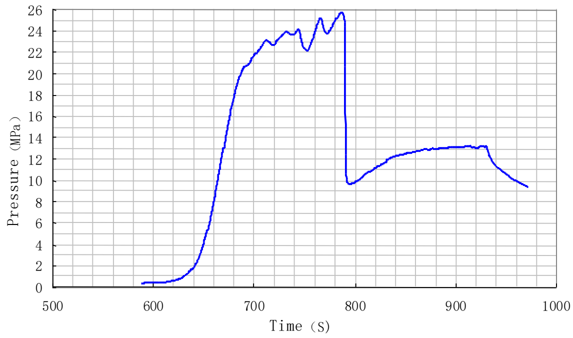


Fig. 9 Fracturing simulation curve of Sample II-5

5. Interpretations and discussions

5.1 The influences of the orientation for the radial borehole on hydraulic fracturing

Fig. 10 shows the relationships between the breakdown pressures and the radical hole orientations. As seen from the figure, compared with the breakdown pressures of boreholes without radial holes, the breakdown pressures of the samples with radial holes along the directions of the maximum horizontal principal stress presents a more apparent decrease. Moreover, with the increasing angle between the borehole orientation and the maximum horizontal principal stress, the breakdown pressure tends to increase. (The lower breakdown pressures of samples at 60°may be related with the heterogeneity of the samples). However, when the radial borehole is located toward the orientation of the minimum horizontal principal stress, the breakdown pressures increase to the same level as intact boreholes without radial holes.

The relationships between the fracture extension pressures and the orientation of radial hole are demonstrated in Fig. 11. As the figure indicates that when there is no radial hole or radial hole approaches the orientation of maximum horizontal principle stress, the fracture extension pressure is about 11 MPa with little change. Nevertheless, when there is a large angle between the radial borehole and the orientation of maximum horizontal principle stress, the fracture extension pressures increase significantly.

When the samples with radial boreholes are fractured, there are two potential positions where shafts tend to occur initiations: the orientation of maximum horizontal principle stress of main shafts and radial boreholes. Of the two, the

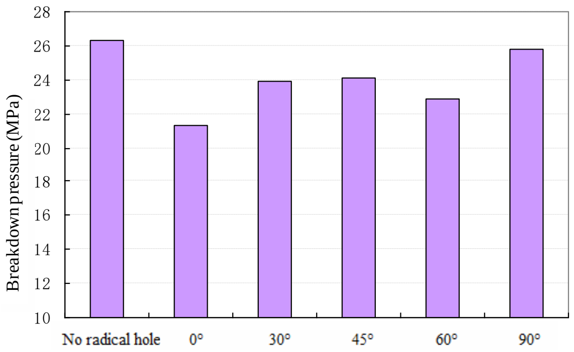


Fig. 10 The relationships between the breakdown pressures and radical hole orientations

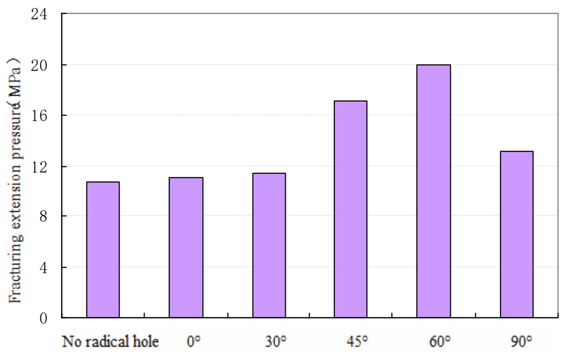


Fig. 11 The relationships between the pressures of fracture extension and radical hole orientations

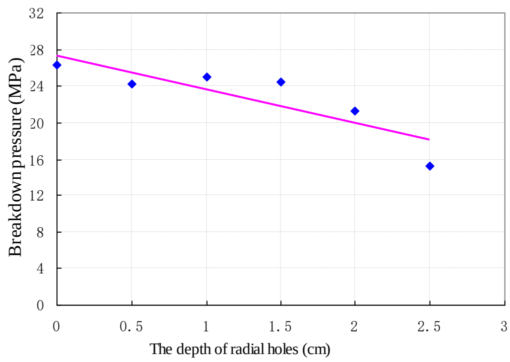


Fig. 12 The relationships between the breakdown pressures and the depth of radical holes

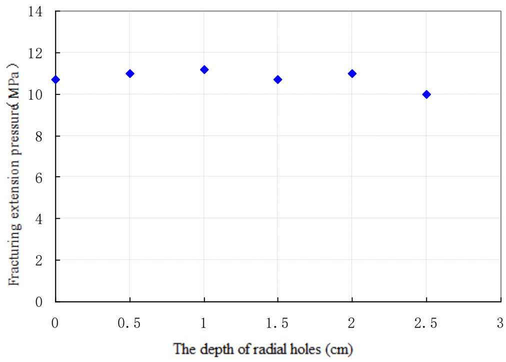


Fig. 13 The relationship between the pressures of fracture extension and the depth of radical holes

one with lower breakdown pressure happen initiations earlier than the other, but the fractures which are far away from the shaft's positions eventually extends towards the orientation of maximum horizontal principle stress. If the radial boreholes approach to the orientation of maximum horizontal principle stress, both the positions of initiation proneness are basically the same. After fracturing, the cracks fracture and extend along with the maximum horizontal principal stresses with simple crack shapes and low extension pressures. When there is a large angle between radial boreholes and maximum horizontal principal stresses, the initiation fracture occurs along the radial boreholes and finally turns to the orientation of maximum horizontal principle stress. Afterwards, radial boreholes interact with the main shafts, so the cracks change the direction in the middle process, resulting in high extension pressures. When the radial boreholes is proceeded toward the orientation of minimum horizontal principle stress, the breakdown pressure of the radial boreholes is larger than that of the main shafts and shaft initiations happen in the orientation of maximum horizontal principle stresses. Through the comparison with the breakdown pressure of original formation, it is found that using radial horizontal well to make boreholes can effectively reduce the breakdown pressure of formation and make the crack shapes more complex.

Because the in-situ stress used in this experiment is small, the fracture pressure of the sample is low. Although the difference of the breakdown pressures with the injection hole in different orientations is about 4 MPa, the breakdown pressures of the sample with 0° radical hole is 21% lower than the sample with 90° radical hole, which is a big change in the engineering practice. There is also significant difference between the crack extension pressures of the samples with different injection hole orientations and the fracture position of the outer surface of the samples, which indicates that the existence of the radial hole affects the fracture initiation and extension.

5.2 The influences of the depth for the radial borehole on hydraulic fracturing

Fig. 12 indicates the relationships between the breakdown pressure and the depth of radical holes. According to the figure, with the increase of radical hole depth, the breakdown pressure decrease gradually. It can be inferred that when the length of radial holes is too long to exceed the influencing ranges of the borehole, the stress state of the radial boreholes are no longer affected by main shafts. Thus the breakdown pressures do not vary with the depth of radial boreholes. Fig. 13 represents the relationships of the fracture extension pressures and the depth of radical holes. From the figure, it can be seen that the pressure of fracture extension is about 11 MPa with little change, because the fracture initation and final extension orientations advance to the orientation of maximum horizontal principle stresses.

6. Conclusions

Compared with the breakdown pressures of intact boreholes without radial horizontal boreholes, the breakdown pressures of the samples with radial boreholes along the directions of the maximum horizontal principal stress presents a more apparent decrease. Moreover, with the increasing angle between the radical borehole orientation and the maximum horizontal principal stress, the breakdown pressure tends to increase. When the radial hole is along the minimum horizontal principal stress direction, the breakdown pressure increases to the same level as intact boreholes without radial hole.

When there is no radial borehole or radial borehole approaches the orientation of maximum horizontal principle stress, the fracture extension pressure is about 11 MPa with little change. Nevertheless, when there is a large angle between the radial borehole and the orientation of maximum horizontal principle stress, the fracture extension pressures increase significantly.

With the increase of radical hole depth, the breakdown pressure decrease gradually. It can be inferred that when the length of radial boreholes is too long to exceed the influencing ranges of the boreholes, the stress states of the radial boreholes are no longer affected by main shafts. Thus the fraturing pressures do not vary with the depth of radial boreholes.

Acknowledgements

This work is financially supported by the National Natural Science Foundation Project of China (51604225, 51704311, 51574270 and 51504280), the Qingdao National Laboratory for Marine Science and Technology (QNLM2016ORP0212), the Changjiang Scholars and Innovative Research Team in University (IRT_14R58), the Natural Science Basic Research Plan in Shaanxi Province of China (2018JQ5068).

References

Adams, J. and Rowe, C. (2013), "Differentiating applications of hydraulic fracturing", *Proceedings of the ISRM International Conference for Effective and Sustainable Hydraulic Fracturing*, Brisbane, Australia, May.

Cheng, Y., Xu, T., Wu, B.L.N. and Sun, Y. (2013), "Experimental study on the hydraulic fractures' morphology of coal bed", *Nat. Gas. Geosci.*, **24**(1), 134-137.

Chi, H., Li, G., Huang, Z., Tian, S. and Song, X. (2015), "Maximum drillable length of the radial horizontal micro-hole drilled with multiple high-pressure water jets", *J. Nat. Gas Sci. Eng.*, **26**, 1042-1049.

Cinelli, S.D. and Kamel, A.H. (2013), "Novel technique to drill horizontal laterals revitalizes aging field", *Proceedings of the SPE/IADC Drilling Conference*, Amsterdam, The Netherlands, March.

Dutta, R., Lee, C.H., Odumabo, S., Ye, P., Walker, S.C., Karpyn, Z.T. and Luis, F. (2014), "Experimental investigation of fracturing-fluid migration caused by spontaneous imbibition in fractured low-permeability sands", *SPE Reserv. Eval. Eng.*, **17**(1), 74-81.

Gandossi, L. (2013), "An overview of hydraulic fracturing and other formation stimulation technologies for shale gas production", *Eur. Commisison Jt. Res. Cent. Tech. Reports*, 26347.

Ghasemi, S.H. and Nowak, A.S. (2018), "Reliability analysis of circular tunnel with consideration of the strength limit state", *Geomech. Eng.*, **15**(3), 879-888.

Guo, T., Liu, B., Qu, Z., Gong, D. and Xin, L. (2017), "Study on Initiation Mechanisms of Hydraulic Fracture Guided by Vertical Multi-radial Boreholes". *Rock Mech. Rock Eng.*, **50**(7), 1767-1785.

Hammond, G.P. and O'Grady, Á. (2017), "Indicative energy technology assessment of UK shale gas extraction", *Appl. Energy*, **185**, 1907-1918.

Ji, Y. and Li, X. (2018), "Analysis on Geo-stress and casing damage based on fluid-solid coupling for Q9G3 block in Jibei oil field", *Geomech. Eng.*, **15**(1), 677-686.

Jia, L., Chen, M., Sun, L., Sun, Z., Zhang, W. and Jin, Y. (2013), "Experimental study on propagation of hydraulic fracture in volcanic rocks using industrial CT technology", *Petrol. Explor. Dev.*, **40**(3), 405-408.

Kamel, A. H. (2016), "RJD: A cost effective frackless solution for production enhancement in marginal fields", *Proceedings of the SPE Eastern Regional Meeting*, Canton, Ohio, U.S.A., September.

Li, G. and Shen, Z. (2005), "Advances in researches and applications of water jet theory in petroleum engineering", *Petrol. Explor. Dev.*, **32**(1), 96-99.

Li, X., Jaffal, H., Feng, Y., El Mohtar, C. and Gray, K.E. (2018), "Wellbore breakouts: Mohr-Coulomb plastic rock deformation, fluid seepage, and time-dependent mudcake buildup", *J. Nat. Gas Sci. Eng.*, **52**, 515-528.

Marbun, B.T.H., Zulkhifly, S., Arliyando, L. and Putra, S.K. (2011), "Review of ultrashort-radius radial system (URRS)", *Proceedings of the International Petroleum Technology Conference*, Bangkok, Thailand, November.

Moradi, S.S.T., Nikolaev, N., Chudinova, I. and Martel, A.S. (2018), "Geomechanical study of well stability in high-pressure, high-temperature conditions", *Geomech. Eng.*, **16**(3), 331-339.

Qi, W., Yun, X., Xiaoquan, W., Tengfei, W. and Zhang, S. (2012), "Volume fracturing technology of unconventional reservoirs: Connotation, design optimization and implementation", *Petrol. Explor. Dev.*, **39**(3), 377-384.

Saberhosseini, S.E., Keshavarzi, R. and Ahangari, K. (2014), "A new geomechanical approach to investigate the role of in-situ stresses and pore pressure on hydraulic fracture pressure profile in vertical and horizontal oil wells", *Geomech. Eng.*, **7**(3), 233-246.

Wang, Z., Liao, Y., Zhang, W., Sun, B., Sun, X. and Deng, X. (2018), "Coupled temperature field model of gas-hydrate formation for thermal fluid fracturing", *Appl. Therm. Eng.*, **133**, 160-169.

Yan, C., Deng, J., Cheng, Y., Yan, X., Yuan, J. and Deng, F. (2017), "Rock mechanics and wellbore stability in Dongfang 1-1 Gas Field in South China Sea", *Geomech. Eng.*, **12**(3), 465-481.

Yan, C., Li, Y., Cheng, Y., Wang, W., Song, B. and Deng, F. (2018), "Sand production evaluation during gas production from natural gas hydrates", *J. Nat. Gas Sci. Eng.*, **57**, 77-88.

Ye, Z., Sesetty, V. and Ghassemi, A. (2018), "Experimental and numerical investigation of shear stimulation and permeability evolution in shales", *Proceedings of the SPE Hydraulic Fracturing Technology Conference and Exhibition*, Muscat, Oman, October.

Yilmaz, Y., Cetin, B. and Kahnemouei, V.B. (2017), "Compressive strength characteristics of cement treated sand prepared by static compaction method", *Geomech. Eng.*, **12**(6), 935-948.

Zhou, L., Zhu, Z., Liu, B. and Fan, Y. (2018), "The effect of radial cracks on tunnel stability", *Geomech. Eng.*, **15**(2), 721-728.

Zhou, W., Banerjee, R., Poe, B. D., Spath, J. and Thambynayagam, M. (2013), "Semianalytical production simulation of complex hydraulic-fracture networks", *SPE J*., **19**(1), 6-18.

Zhu, H., Shen, J. and Zhang, F. (2019), "A fracture conductivity model for channel fracturing and its implementation with discrete element method", *J. Petrol*. *Sci*. *Eng*., **172**, 149-161.

Zhu, H.Y., Deng, J.G., Liu, S.J., Wen, M., Peng, C.Y., Li, J.R. and Dong, G. (2014), "Hydraulic fracturing experiments of highly deviated well with oriented perforation technique", *Geomech*. *Eng*., **6**(2), 153-172.

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