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A NOVEL SELF-DIVERTING FRACTURING TECHNOLOGY BASED ON INVERSE PHASE TRANSFORMATION

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A self-diverting fracturing technology is proposed in the study as a way of effectively creating a stimulated reservoir volume. The technology, which is based on the use of a novel self-diverting fracturing fluid, can create and extend fractures to design shapes, is strong enough to effectively plug fractures and can then be effectively removed from fractures and form a branched network of highly permeable fractures. It can also greatly enlarge the stimulated reservoir volume, possesses excellent injecting and plugging capacity, effective diversion and complete self-plugging ability, produces little reservoir damage, and is simple and practical. Gelling and gel-breaking macro-phenomena, temporary plugging, diversion, and fluid loss are described in detail. All the test results demonstrate that the present self-diverting fluid fracturing technology possesses many advantages.
Key words: *hydraulic fracturing, self-diverting fracturing, temporary plugging, fracturing, unconventional reservoirs, stimulated reservoir volume.*

Hydraulic fracturing, the most effective method of increasing oil recovery in the development of unconventional reservoirs (low-permeable oil and gas reservoirs, deposits of shale gas, and coalbed methane deposits), is widely used today [1]. In conventional hydraulic fracturing, a high-viscosity fracturing fluid is

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pumped into a reservoir to create and enlarge a fracture, after which liquid containing proppant is pumped into the fracture to maintain it in the open state [2, 3]. The conventional hydraulic fracturing technology substantially increases the productivity of sand reservoirs [4].

However, in ultra-low permeability reservoirs the productivity achieved with simple “wing-like” fractures does not meet production demands [5]. Dingwei [6] and Tingxue [7] proposed the creation of a branched network of fractures to exploit extremely low permeable gas shale. Mayerhofer [5] suggested that ultra-low permeable shale reservoirs require a large network of fractures to maximize production, since the permeability achieved with individual wing-like fractures is not sufficient for the development of a reservoir. Multi-stage and volume fracturing are effective methods of increasing well productivity and developing unconventional reservoirs [8–11].

Researchers have also discovered shortcomings in these methods. Mayerhoffer et al. [5] and Cipolla et al. [12] suggested that there are many elements that directly influence the volume of a reservoir affected by hydraulic fracturing (referred to as the stimulated reservoir volume [SRV]). First, many of the parameters cannot be controlled directly, such as the thickness of a shale reservoir, the direction and magnitude of the stresses in a reservoir, the presence of preexisting open or “healed” natural fractures, barriers to the development of fractures, and the brittleness of rock and geological features, such as faults and karsts. Second, engineering measures adopted to increase a stimulated reservoir volume and the uniformity of fracture spacing (lengthwise extent and orientation, treatment magnitude, number of stages, perforation clusters, diversion techniques, and/or open hole packer completion system) are also limited. Finally, the volume fracturing technology has a great demand for fracturing fluid and entails special requirements on the properties of the fluid and the volume and concentration of proppant. These methods also involve high technological costs, which limit their use. The great risk of environmental pollution also restricts the use of these technologies [13, 14].

In [15] Gomaa argued that the primary challenge in the design of the volume fracturing technology in shale reservoirs is to increase the resultant geometry of a fracture and that near-wellbore diversion technologies are effective methods of increasing the permeability of the wellbore zone. Stanojcic and Rispler [16] found that successful development and exploitation of unconventional reservoirs depends on the use of innovative multi-stage hydraulic fracturing technologies. Operations to stimulate influx of shale gases from reservoirs depends on the existence of an interconnected network of fractures of moderate permeability (“finning” fractures).

Warpinski [17] found that successful exploitation of reservoirs of shale gases and low-permeability sand reservoirs for the purpose of attaining economic objectives entails such steps as horizontal drilling, multi-stage completion, innovative hydraulic fracturing, and mapping of fractures. Diversion of fracturing fluid is realized by temporary plugging of fractures. This leads to a growth in the pressure in the wellbore or in the fracture and the formation of new fractures. Such a technology, which increases the number of fractures and enlarges the stimulated reservoir volume, is widely used today [18–23]. However, there are many problems associated with the technology of temporary plugging of fractures in hydraulic fracturing, such as the limited efficiency of plugging mechanisms, the fact that diverting materials with poor injectivity are employed, incomplete plugging, poor cleaning of fractures, and damage to the reservoir.

In order to solve problems associated with the hydraulic fracturing technology, the present article proposes a hydraulic fracturing technology with the use of a self-diverting liquid. It is implemented in the following way:

1. The self-diverting fracturing fluid is pumped in at high pressures and high flow rates to create fractures in the reservoir.

2. As the self-diverting fracturing fluid is gradually heated up by the reservoir, it first reaches the gelling temperature at the fracture tip, at which point the fracture is completely plugged.
3. The self-diverting fracturing fluid continues to be pumped in and once a fracture is completely plugged, the pressure in the fracture again grows to the breakdown pressure, forming and enlarging a succeeding fracture.
4. The heat energy of a stratum is practically inexhaustible, hence the heating function of the cold self-diverting fracturing fluid pumped from the surface is also realized continuously, which means that fractures may be created more than once.
5. Finally, all the gelling fracturing fluid in all the fractures is heated to the gel-breaking temperature; all the fractures may be cleared automatically.

Hydraulic fracturing can be performed highly efficiently with the use of this technology. The present article considers a new type of heat-sensitive, self-diverting fracturing fluid capable of opening up fractures and plugging fractures and which can also be removed independently from fractures (self-unplug fractures). The fluid does not contain any free water and has good injectivity.

The following substances are used in the experiments: PC410 system (self-diverting fracturing fluid); sandstone core; deionizing water; KCl (analytically pure); carbon tetrachloride (analytically pure).

A diagram of the experimental plant is presented in Fig. 1.

To determine the sol–gel–sol transformation, the PC410 system is hermetically sealed in a test tube and heated with the use of oil baths. All possible variations, including variations in transparency and in the sol–gel–sol transformation (estimated by a laser pointer) accompanying the gradual and continuous growth in temperature were recorded.

To determine the temporary plugging capacity, the cores were collected from a lithologically screened reservoir, then cut down to a diameter of 2.54 cm and length 5 cm. The cores are cleaned using carbon tetrachloride and then dried, and then broken, leading to the formation of fractures throughout the length of the cores.

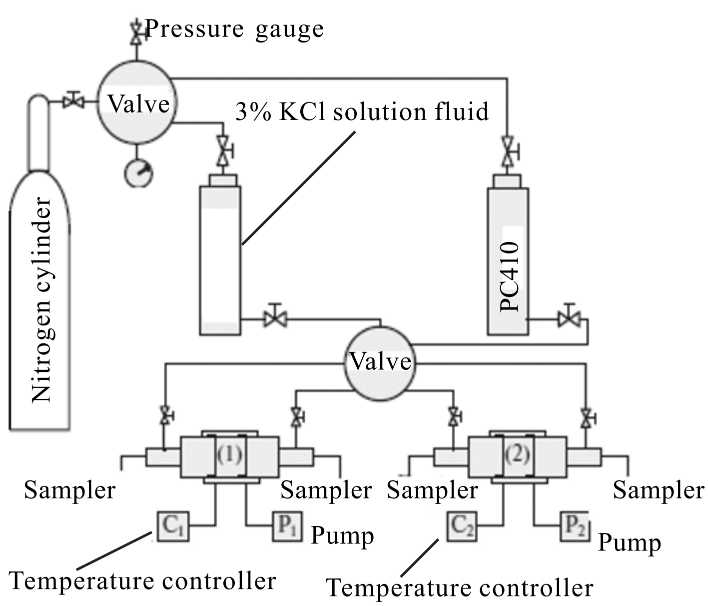


Fig. 1. Experimental plant for studying hydraulic fracturing with self-diverting fluid.

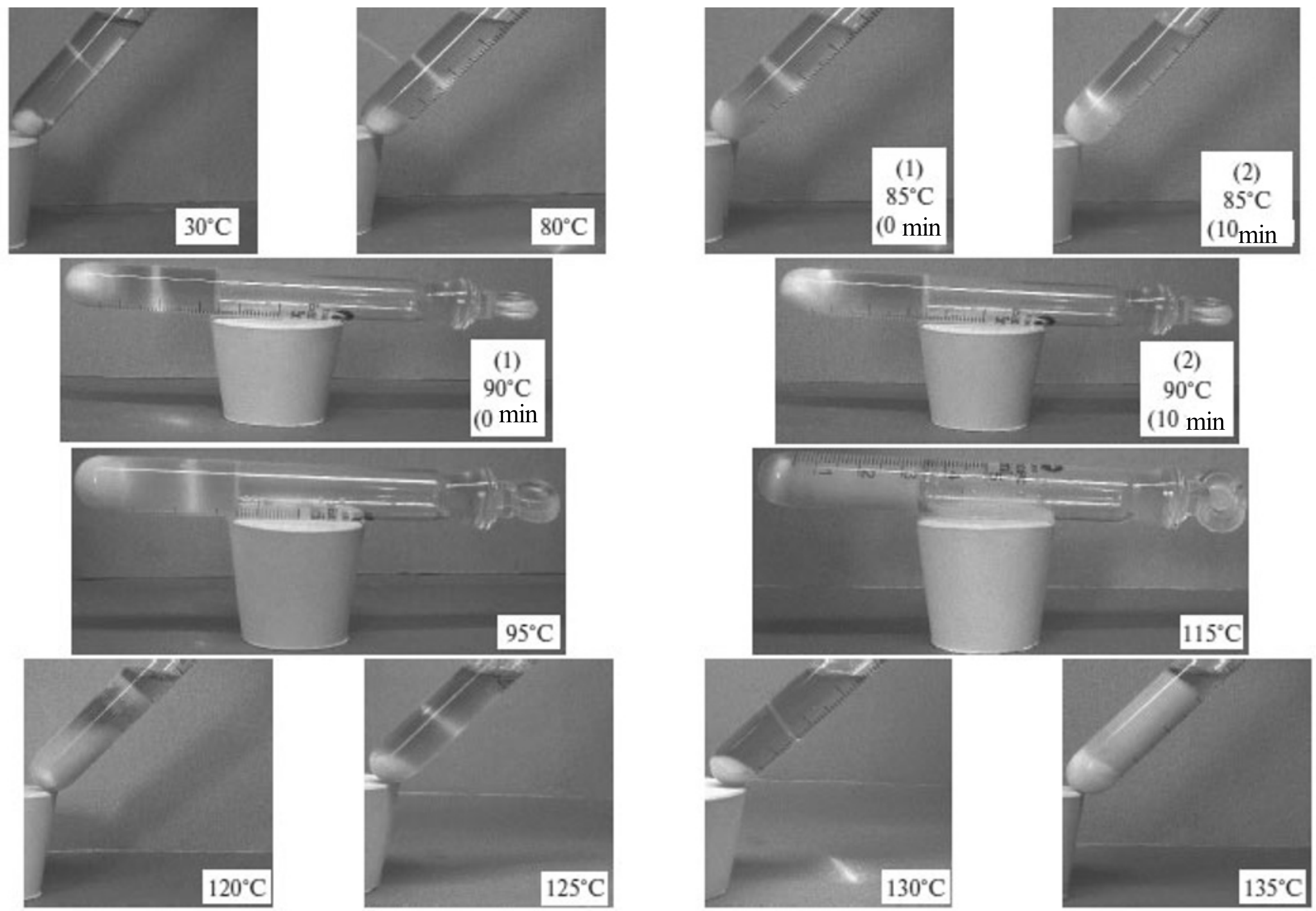


Fig. 2. Variation of phase of agent for temporary plugging.

Cores with fractures were placed in a core holder, the gradual flow-pumping rate set at 5 ml/min with temperature in the core holder 100°C, and the pressure held at a range above the displacement pressure (2 MPa). A 3% KCl aqueous solution was used to estimate the fluidity. The PC410 system was pumped in at the same pumping rate. The temperature in the core holder was set at 120°C and 3% KCl was injected.

To determine the diverting capacity, two cores containing fractures were placed in core holders connected in parallel. Both inlet and outlet are equipped with switching devices (selector switches) to enable easy control of the displacement directions and selection of the core holder to be opened. Both core holders were equipped with confining pressure pumps and temperature control devices.

A temperature of 105°C, volumetric confining pressure 3 MPa, and displacement pressure 1 MPa were set in both core holders. The permeability of each of the two cores was measured by means of a 3% KCl solution. The forward switch of core holder (1) was then opened (the backward switch being closed), both switches of core holder (2) were closed and the PC410 system was pumped in at a pressure of 1 MPa. The forward switch of core holder (2) was opened (the backward injection switch being closed), and injection of the PC410 system performed at a pressure of 1 MPa. Both of the backward switches of core holders (1) and (2) were then opened (the forward injection switches of core holders (1) and (2) kept closed) and injection of the PC410 system continued at a pressure of 1 MPa. A 3% KCl solution was pumped in at a pressure of 1 MPa. The temperature in both core holders was increased to 120°C and injection of the 3% KCl solution continued at a pressure of 1 MPa.

To determine the degree of fluid seepage into the rock, the cores were placed in a filter press and heated to 105°C, with pressure drop between the inlet and outlet roughly 1.5 MPa. PC410 was then injected from the inlet to the outlet and the instantaneous flow continuously recorded.

The variation in the phase state of the temporary plugging agent is represented in Fig. 2. The figure shows that the temporary plugging agent is transparent and clear until 80°C. Once the plugging agent has been heated to 80°C the solution began to turn opaque. When the temperature reached 85°C, the transparency of the solution dropped markedly and the viscosity began to grow. When the temperature reached 95°C, the entire solution lost transparency and mobility, which indicated gelling. Gelling was amplified as the temperature of the plugging agent continued to grow. However, when the temperature reaches 115°C, the gelatinuous substance began to turn back into a solution. The solution was now as clear and transparent as it had been at room temperature.

In view of the fact that the sol–gel–sol transformation depends on temperature, we wish to suggest that it may be used for temporary plugging, employing all the advantages of the phase transformations induced by heating. Thus, the formation and break-up of gels without the introduction of a cross-linker or gel breaker may be easily implemented. Unlike a conventional plugging agent, the present hydraulic fracturing fluid may be controlled, which produces a minimum level of damage to the stratum.

We investigated the plugging capacity of the PC410 system with constant flow rate of 5 ml/min (Fig. 3). The permeability of a core with fractures was verified by a 3% KCl solution (0.2 MPa). Upon input of the self-diverting fracturing fluid, the displacement pressure grew gradually until it had reached its ultimate level (18 MPa). Once the 3% KCl solution was injected, the core was still completed plugged. When the temperature of the core holder had been gradually increased to 115°C, the 3% KCl solution began to flow out of the core and the displacement pressure dropped gradually to 0.19 MPa.

The results of temporary plugging showed that a self-diverging fluid is capable of strongly plugging a core containing fractures and that the plugging strength reaches 18 MPa. As the temperature in the core holder increased, the rheology of the fluid could be restored to the initial level.

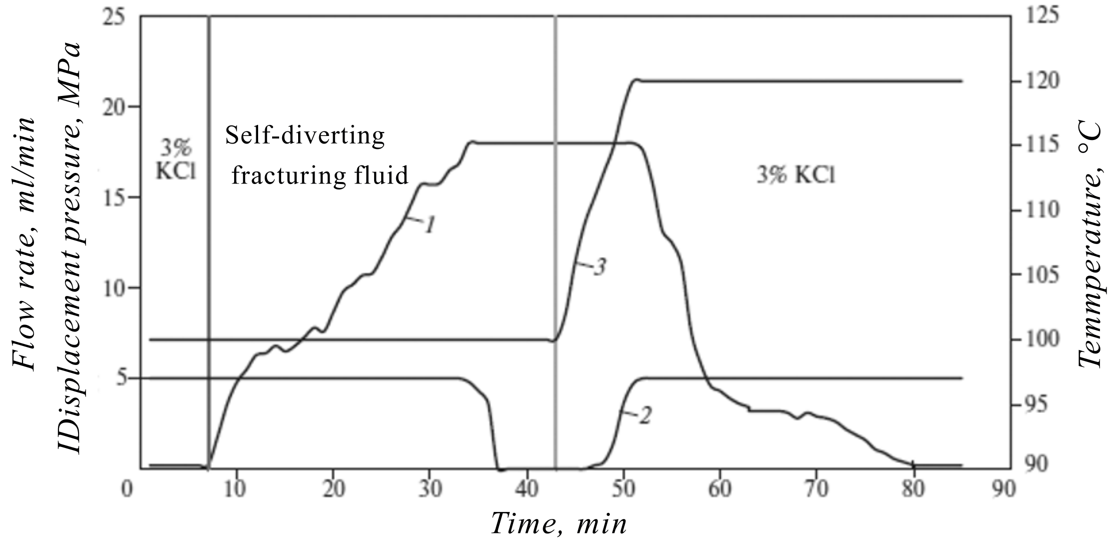


Fig. 3. Results of temporary plugging of self-diverting fracturing fluid. *1* – displacement pressure; *2* – flow rate; *3* – temperature in core holder.

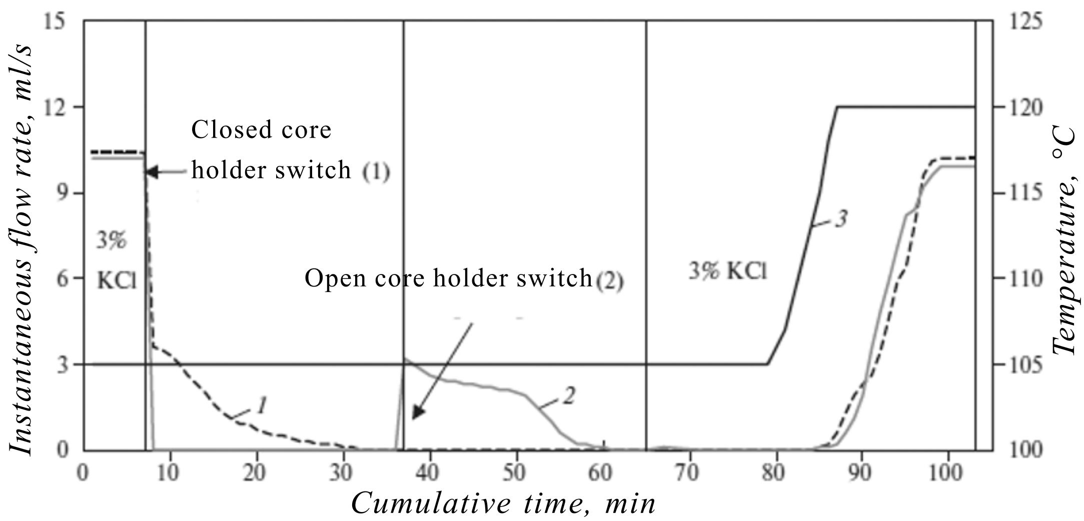


Fig. 4. Results of a study of diversion capacity: *1*, *2* – cores with fractures (core 1, core 2); *3* – temperature in core holder.

As shown in Fig. 4, with a displacement pressure of 1 MPa the instantaneous flow rate upon injection of fluid into core 1 was 10.4 ml/s and into core 2, 10.2 ml/s. Once the PC410 fluid had been pumped into core 1, the core became quickly plugged up. Then, when the switch in core holder 2 was opened, both cores also completely became plugged up. We then begin to pump in the 3% KCl solution and both cores were still plugged. However, once the two holders had been heated to 115°C, the flow rate through both of the cores began to recover. As the temperature in the core holder increases, the flow rate through both cores simultaneously grew quickly. Finally, the flow rate recovered, reaching 10.2 ml/s (core 1) and 9.9 ml/s (core 2), the degree of recovery of the flow rate amounting to 98% and 97%, respectively.

As shown in Table 1, once both cores had been plugged, a gelatinuous substance is present at the inlet and outlet and in the profiles of both cores. Once the cores had been unplugged and the temperatures increased to the gel-breaking temperature, the gelatinous substance had been completely expelled.

Table 1.

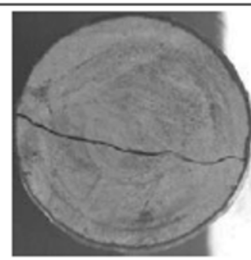
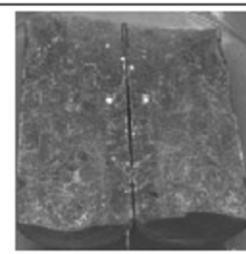
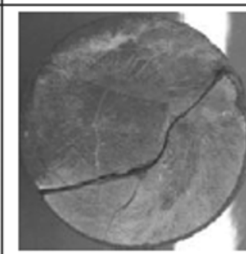
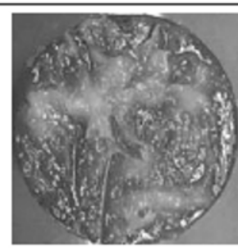
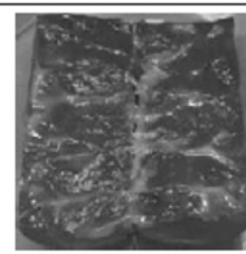
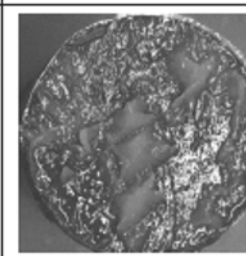
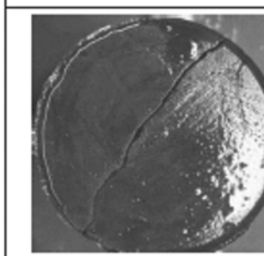
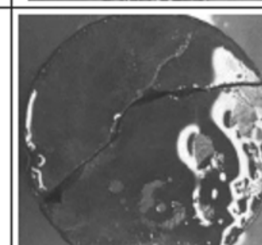
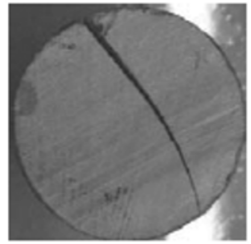
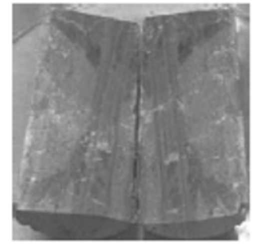
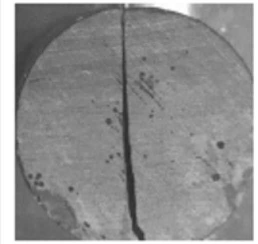
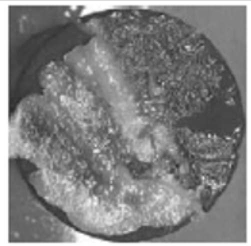
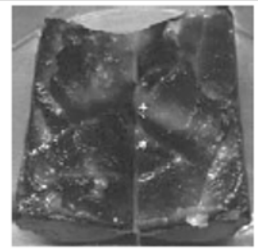
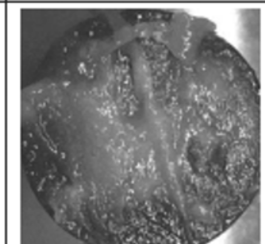
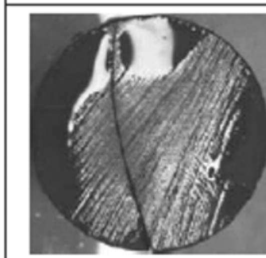
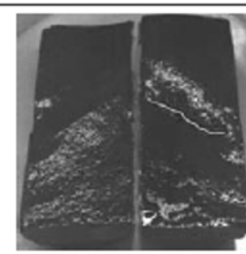
	Inlet	Core profile	Outlet	
Core (1)				Prior to injection
				Temporary plugging
				Unplugging

Table 1(continued)

Core (2)				Prior to injection
				Temporary plugging
				Unplugging

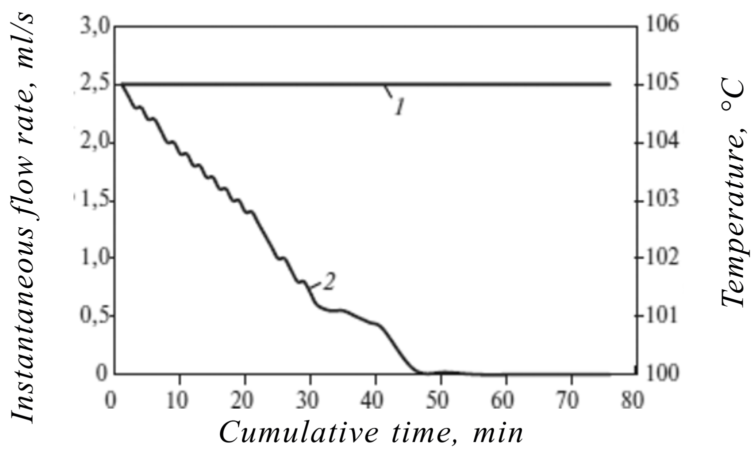


Fig. 5. Results of a filtration test in a filter press: *1* – temperature; *2* – instantaneous flow rate of diverted fracturing fluid.

The data of Fig. 4 and Table 1 show that a hydraulic fracturing self-diverting fluid is able to completely plug a core containing fractures, deflect the core in the lateral direction, form new fractures, and plugging these fractures as well. Once the effect of plugging is no longer needed, the gel completely breaks up at the gel-breaking temperature.

It is shown in Fig. 5 that the flow rate of the PC410 fluid is reduced at 105°C and that filtration halts after 46 min. This means that the fluid is able to create a high pressure in a reservoir, thus promoting the formation of fractures.

The following conclusions may be made on the basis of the results of these studies.

The self-diverting fracturing technology makes it possible to create interrelated fractures in a single operation and ensures the exploitation of all fractures.

The self-diverting fracturing fluid (which lacks a solid phase) is able to create phase transitions at different temperatures. At room temperature the self-diverting fracturing fluid is in a liquid state and turns into a gel at the gelling temperature with gel break-up occurring at still higher temperatures.

Once the self-diverting fracturing fluid has filtered into a rock matrix, the gel properties make possible the formation of a filter cake automatically, which stops further filtration. Minimum filtration delivery helps to increase the pressure to levels at which fractures form and serves as persuasive evidence of the effectiveness of the present fluid.

Gelling and gel breaking produced by the self-diverting fracturing fluid occur under the effect of temperature without the introduction of a cross-linking agent or gel-breaker. For this reason, by comparison with a conventional agent for temporary plugging, the self-diverting fracturing fluid breaks the structure of the gel independently, thus limiting damage to the reservoir and the fractures.

The self-diverting hydraulic fracturing technology makes it possible to create a branched network of fractures and this may lead to a decrease in the volume of fluid needed for fracturing. The technology is an effective means of intensifying inflow in the exploitation of unconventional hydrocarbon deposits and is an easy and convenient method of enlarging the volume of a stimulated reservoir.

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REFERENCES

1. P. M. Saldungaray, T. Palisch, and R. Shelley, Hydraulic fracturing critical design parameters in unconventional reservoirs, in: *SPE Unconventional Gas Conference and Exhibition*, Society of Petroleum Engineers (2013).
2. H. K. Van Poollen, Theories of hydraulic fracturing, in: *Second US Symposium on Rock* Mechanics (USRMS), American Rock Mechanics Association (January, 1957).
3. G. C. Howard and C. R. Fast, *Hydraulic Fracturing,* Society of Petroleum Engineers, New York (1970), 210 pp.
4. R. G. Agarwal, R. D. Carter, and C. B. Pollock, Evaluation and performance prediction of low-permeability gas wells stimulated by massive hydraulic fracturing. *J. Petroleum Technology*, 31, No. 3, 362–372 (1979).
5. M. J. Mayerhofer, E. Lolon, N. R. Warpinski, C. L. Cipolla, D. W. Walser, and C. M. Rightmire, What is stimulated reservoir volume? *SPE Production and Operations*, 25, No. 1, 89–98 (2010).
6. W. Dingwei, L. Qun, X. U. Yun, L. Yang, L. Deqi, and W. Weixu, Network fracturing techniques and its application in the field, Acta Petrolei Sinica, 32, No. 2, 280–284 (2011).
7. J. Tingxue, J. Changgui, W. Haitao, and S. Haicheng, Study of network fracturing design method in shale gas, *Petroleum Drilling Techniques*, 39, No. 3, 36–40 (2011).
8. C.H. E. N. Zuo, X. Chengjin, J. Tingxue, and Q. Yuming, Proposals for the application of fracturing by stimulated reservoir volume (SRV) in shale gas wells in China, *Natural Gas Industry*, 30, No. 10, 30–32 (2010).
9. W. Qi, X. Yun, W. Tengfei, and W. Xiaoquan, The revolution of reservoir stimulation: Introduction to volume fracturing, *Natural Gas Industry*, 31, No. 4, 7–12 (2011).
10. J. Changgui, L. Shuangming, W. Haitao, W., and J. Tingxue, Shale reservoir network fracturing technology research and experiment, *Engineering Sciences*, 14, No. 6, 107–111 (2012).
11. W. Qi, X. Yun, W. Xiaoquan, W. Tengfei, and S. Zhang, Volume fracturing technology of unconventional reservoirs: Connotation, design optimization and implementation, *Petroleum Exploration and Development*, 39, No. 3, 377–384 (2012).
12. C. L. Cipolla, N. R. Warpinski, M. J. Mayerhofer, E. Lolon, and M. C. Vincent, The relationship between fracture complexity, reservoir properties, and fracture treatment design, in*: SPE Annual Technical Conference and Exhibition*, Society of Petroleum Engineers (January, 2008).
13. A. Vengosh, R. B. Jackson, N. Warner, T. H. Darrah, and A. Kondash, A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States, *Environmental Science and Technology*, 48, No. 15, 8334–8348 (2014).
14. A. Bergmann, F. A. Weber, H. G. Meiners, and F. Mьller, Potential water-related environmental risks of hydraulic fracturing employed in exploration and exploitation of unconventional natural gas reservoirs in Germany, *Environmental Sciences Europe*, 26, No. 1, 1 (2014).
15. A. M. Gomaa, A. Nino-Penaloza, E. McCartney, and J. Mayor, Engineering solid particulate diverter to control fracture complexity: Experimental Study, in: *SPE Hydraulic Fracturing Technology Conference*. Society of Petroleum Engineers (February, 2016).

16. M. Stanojcic and K. A. Rispler, How to achieve and control branch fracturing for unconventional reservoirs: Two novel multistage stimulation processes, in: *Canadian Unconventional Resources and International Petroleum Conference*, Society of Petroleum Engineers (January, 2010).
17. N. R. Warpinski, M. J. Mayerhofer, M. C. Vincent, C. L. Cipolla, and E. P. Lolon, SPE 114173: Stimulating unconventional reservoirs: Maximizing network growth while optimizing fracture conductivity, in: *Proc. SPE Unconventional Gas Conference*, Keystone, Colorado (February 10–12, 2008).
18. C. L. Smith, J. L. Anderson, and P. G. Roberts, New diverting techniques for acidizing and fracturing, *J. Petroleum Technology*, 21 (1969).
19. D. Wang, F. Zhou, H. Ge, Y. Shi, X. Yi, C. Xiong, C., An experimental study of the mechanism of degradable fiber-assisted diverting fracturing and its influencing factors, *J. Natural Gas Science and Engineering*, 27, 260–273 (2015).
20. D. Wang, D., F. Zhou, W. Ding, H. Ge, X. Jia, Y. Shi, et al., A numerical simulation study of fracture reorientation with a degradable fiber-diverting agent, *J. Natural Gas Science and Engineering*, 25, 215–225 (2015).
21. N. W. Harrison, Diverting agents – history and application, *J. Petroleum Technology*, 24, No. 5, 593–598 (2013).
22. H. Hou, W. Xiong, X. Zhang, D. Song, G. Tang, and Q. Hu, *The application of in-fissure divert fracturing technology in ultra-low permeability oil field* (2009); Downloads.hindawi.com.
23. S. Xue, Z. Zhang, G. Wu, Y. Wang, J. Wu, and J. Xu, (2015, Application of a novel temporary blocking agent in refracturing, in: *SPE Asia Pacific Unconventional Resources Conference and Exhibition*, Society of Petroleum Engineers (November, 2015).