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Feasibility of reservoir fracturing stimulation with liquid nitrogen jet

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ABSTRACT

In this paper, a new idea of fracturing with liquid nitrogen jet was proposed because the conventional liquid nitrogen fracturing treatment has difficulty in controlling the fracture initiation location and creating multi-separated fractures along the wellbore. To analyze the feasibility of this treatment, the flow field of liquid nitrogen jet was simulated using computational fluid dynamics method, and the cracking effect of liquid nitrogen on rock was tested by laboratory experiments. The results indicated that under the same nozzle pressure drop, the liquid nitrogen jet presented better performance in abrasive particles acceleration and pressure boosting in perforation cavity than water jet. In addition, the impact effect induced by liquid nitrogen jet was equivalent to that generated by water jet. Liquid nitrogen could bring about additional cracking effect on rock because of cryogenic cooling, water freeze and nitrogen vaporization, which were also beneficial for the improvement of stimulation reservoir volume and the formation of fracture network. What's more, the liquid nitrogen jet induced the pressure boosting effect in cavity and the hydrodynamic sealing effect in annulus, which could realize the control of fracture location and the isolation of wellbore respectively without any machinery packers or bridge plugs. In conclusion, the liquid nitrogen jet fracturing presented apparent superiorities not only in avoiding the problems in hydraulic fracturing but also in overcoming the technical shortcomings of conventional liquid nitrogen fracturing. This technique will play a significant role in oil and gas development with a promising future.

1. Introduction

Liquid nitrogen is an important work fluid for oil and gas development, which has been widely used in petroleum engineering (Shouldice, 1964). At the end of 20th century, it was successfully used as a fracturing fluid to create artificial fractures in formation (Mcdaniel et al., 1997; Grundmann et al., 1998). During liquid nitrogen fracturing, liquid nitrogen is pumped into wells at the typical fracturing flow rate and cryogenic temperature (−195.6 to −146.9 °C). As the relative inertness, liquid nitrogen has an excellent compatibility with other fluids in formations and does not take part in any emulsification as well. Thus, liquid nitrogen does not induce the expansion of clay minerals and the change of formation water saturation during fracturing. On the contrary, it can reduce the water block damage happened in drilling and completion treatments, thereby improving the rock permeability and seepage channel (Enayatpour et al., 2013). So, liquid nitrogen (nitrogen gas) presents an excellent compatibility with reservoir fluids and the issues of water sensitivity and blocking can be avoided effectively. Moreover, water consumption and pollution can be solved fundamentally because of its waterless characteristic (Rassenfoss, 2013). For those reasons, liquid nitrogen is expected to be one of substitutes for water-based fracturing fluid.

After fracturing, the liquid nitrogen in the reservoirs can completely gasifies because its critical temperature is extremely low (about −146.9 °C). The gasification of liquid nitrogen could reduce the pressure in the well and increase the pressure difference between the reservoir and wellbore. As a result, the fracturing liquid can flow back without the additional swabbing or gas lift treatment. During liquid nitrogen fracturing, thermal stress will be generated when liquid nitrogen flows in the main fractures, resulting in tensile or shear damage on the main fracture surface then forming secondary fractures orthogonal to main fracture plane. Additionally, the decrease in temperature could cause the shrinkage of mineral grains in the rocks, which may lead to the open of the closed natural fractures (Cai et al., 2014). All these could promote rock cracking and fracture network formation during fracturing process. Liquid nitrogen is harmless to groundwater and drinking water because it contains no such chemical component, like friction reduction agent, bactericidal agent, etc., as

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added into conventional fracturing fluid. It is mainly nitrogen gas that flows back to the ground after fracturing. Therefore, this treatment is expected to be a preferred stimulation method in arid and fragile ecological areas.

With the rapid development of horizontal well technology, multistage fracturing has been the key technology for reservoir stimulation (Taylor et al., 2010; King, 2012). As the rubber packer and bridge plug easily fail to work under the extremely cryogenic conditions, multistage fracturing with liquid nitrogen seems to be impossible. So, the conventional liquid nitrogen fracturing had great difficulty in controlling the fracture initiation location and creating multi-separated fractures along the wellbore. For conventional liquid nitrogen fracturing, the isolation method, which is called “frozen water” diverter, is injecting 0.5–0.8 m^3 of water to seal the fracture zone (Mcdaniel et al., 1997; Grundmann et al., 1998). However, the new fractures will only initiate above the frozen zone, being a technical bottleneck when applying this method.

Hydrajet fracturing is a stimulation method which integrates the operations of jetting perforation, fracturing and isolation (Surjaatmadja et al., 1998; Li et al., 2010). Hydrajet fracturing can control the fracture initiation location accurately and isolate wellbore effectively utilizing the pressure boosting effect in perforation cavity and the hydrodynamic sealing effect in annulus (Qu et al., 2010; Sheng et al., 2013). After the fracture is created, the high speed jet will continually blast into the cavity and fracture. In this case, the nozzle, annulus, cavity and fracture form a jetting system, which plays a role like jet pump (Surjaatmadja et al., 2002). According to Bernoulli principle, a low pressure area around the high speed jet is formed. Because of the pressure difference between jet and surrounding fluid, this “jet pump” can draw the annulus fluid into the fractures other than the fractured zone (Qu et al., 2014). Consequently, hydrajet fracturing can perform pin-point fracturing precisely and create several multi- separated fractures without machinery packer in one trip.

Referring to hydrajet fracturing principles, the idea of fracturing with liquid nitrogen jet (liquid nitrogen jet fracturing) was proposed in this paper. Compared with the hydrajet fracturing, liquid nitrogen jet fracturing could enhance the isolating effect by combing “water frozen” diverter. Thus, the liquid nitrogen jet will be an effective tool to realize the multistage liquid nitrogen fracturing. To analyze the feasibility of this treatment, several relevant fundamental researches were conducted, such as: The flow field of liquid nitrogen jet was simulated by computational fluid mechanics (CFD) method; the rock cracking effect due to liquid nitrogen cryogenic cooling, water freeze and nitrogen vaporization was analyzed with laboratory experimental tests.

2. Characteristics of liquid nitrogen jet

2.1. Flow field and impact characteristics

High speed jet is the core factor for hydrajet fracturing because it can ensure the fractures to initiate at the desired position and create along the well bore subsequently (Li et al., 2014). To verify the feasibility of fracturing with liquid nitrogen jet, the flow field of liquid nitrogen jet was simulated using CFD method. Fig. 1 shows the geometry model of the jet flow field. The model consisted of two domains: the internal space of the nozzle and the jet region (the space between nozzle and the right wall). Because the jet field was generated by an axial symmetry nozzle whose axis was in line with X coordinate (i.e. axial distance), the model was set to be symmetrical along the axial direction. Correspondingly, the X coordinate was set as the symmetry axis. During jetting process, the liquid nitrogen flowed through nozzle inlet, impacted the right wall, and then flowed out the flow domain. Given this situation, the boundaries were set as shown in Fig. 1.

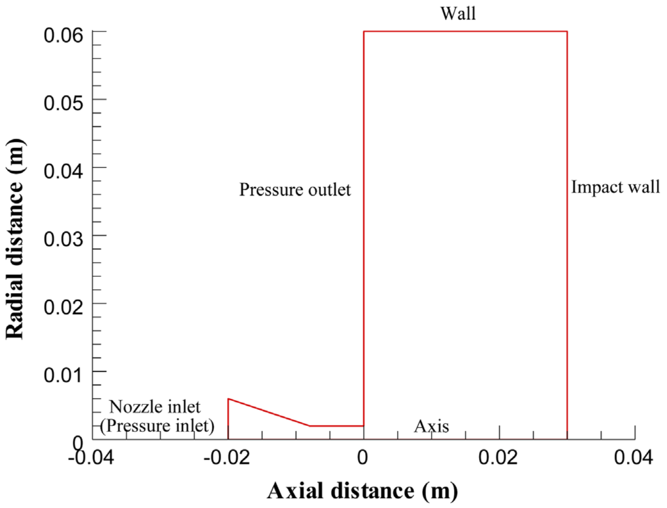

Fig. 1. The geometry model and boundaries.

Fig. 2 shows the velocity and pressure distributions of liquid nitrogen jet. The simulation parameters were set as in Table 1. The results showed that the high pressure liquid nitrogen transformed into high speed jet because of the nozzle chocking effect (Fig. 2(a)). At the right end of the flow field, the jet velocity decreased quickly and the stagnation pressure increased correspondingly, as shown in Fig. 2(b).

With the same nozzle pressure drop, confining pressure and nozzle structure, the flow field of water jet was also simulated. As water is solid at 100 K, its jet flow field cannot be simulated. In most cases, the thermodynamic parameters of water are slightly affected by pressure and temperature. Therefore, it is reasonable to assume water jet as isothermal flow. The thermodynamic parameters of water were set as follows: the density of 998.2 kg/m^3, the viscosity of 10.03×10^{-4} Pa s, the thermal conductivity of 0.6 W/(m K), and the isobaric heat capacity of 4.182 kJ/ (kg K). The numerical results indicated that the liquid nitrogen jet displayed a higher velocity than water jet, as shown in Fig. 3. Take the nozzle pressure drop of 20 MPa for example, the maximum velocity of liquid nitrogen jet was about 11.09% than water jet. However, the impact pressure of liquid nitrogen jet, which is equal to the difference between stagnation pressure and confining pressure, was very close to that of water jet. Consequently, the liquid nitrogen jet presented a higher velocity and an equivalent impact effect compared with water jet.

2.2. Acceleration characteristics of liquid nitrogen jet on abrasive particles

Although liquid nitrogen jet could obtain well impact effect, extremely high jetting pressure is required to cut and slot materials. Take the water jet for example, it requires up to 700–1000 MPa jetting pressure to cut steel. In well completion engineering, abrasive jet, normally generated by adding abrasive particles (e.g. quartz sand) into fluid, is usually used to penetrate the casing, cement and formation rock. Previous studies have shown that abrasive water jet can effectively create a perforation cavity with a 25–30 MPa jetting pressure (Huang et al., 2008). The maximum diameter and length of perforation cavity can be up to 50 mm and 800 mm, respectively (Huang et al., 2015). The key of perforation with abrasive jet is that whether the high speed jet can accelerate abrasive particles to high enough velocity to impact the steel casing, cement and formation rock.