Journal of Natural Gas Science and Engineering 27 (2015) 842–851

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

The pressurization effect of jet fracturing using supercritical carbon dioxide

Zhenguo He, Shouceng Tian*, Gensheng Li, Haizhu Wang, Zhonghou Shen, Zhengming Xu

State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing, Beijing, 102249, China

ARTICLE INFO

Article history:
Received 7 August 2015
Received in revised form
16 September 2015
Accepted 17 September 2015
Available online 28 September 2015

Keywords:
Supercritical carbon dioxide
Hydro-jet fracturing
Pressurization effect
Parametric study

ABSTRACT

Hydro-jet fracturing is a unique hydraulic fracturing method, and has been recognized worldwide as an effective well-stimulation method for oil and gas production. However, because of controversy about the method's impact on water consumption and environmentally quality, hydraulic fracturing faces increasing restrictions. The demand for decreased water usage has promoted research on the use of non-aqueous fracturing fluids. In particular, the idea of using supercritical carbon dioxide (SC-CO_2) fluid has attracted a lot of interest. Using SC-CO_2 as a fracturing fluid is more effective and has significant advantages compared with water-based fluids. The unique properties of the SC-CO_2 fluid facilitate fracture propagation, formation of complex fracture networks, and elimination of flow blockage in the rock matrix and pores. Therefore, the SC-CO_2 jet fracturing technique may effectively enhance oil and gas recovery. Similar to hydro-jet fracturing, the pressurization effect in the perforation tunnel is a key precondition for successful jet fracturing with SC-CO_2. This study investigated these effects using numerical simulations and experimental studies. Our results show that the pressurization effect during SC-CO_2 jet fracturing improves with an increase in pressure difference, ambient pressure, nozzle diameter, and fluid temperature. However, pressurization becomes weaker with increasing casing hole diameter and annulus spacing. Comparing SC-CO_2 and water jet fracturing pressurization effects suggests that using SC-CO_2 jetting has advantages over water jet fracturing under in situ reservoir conditions. As the working depth increases, SC-CO_2 jet fracturing achieves better pressurization than the water jet. The novel approach in our preliminary study begins to prove the feasibility of applying SC-CO_2 jet fracturing to leverage unconventional resources.

1. Introduction

Hydraulic fracturing has been an indispensable method for the commercial extraction of hydrocarbons in shale and tight reservoirs, where the permeability is ultra-low (i.e., in the nanodarcy range). In particular, hydro-jet fracturing is regarded as a unique, cost-effective and efficient well-stimulation treatment, due to its capability to accomplish a multi-stage pin-point fracturing during only one trip and without the use of mechanical packers. Further, unlike perforation bullets, hydro-jet perforation does not create a compacted zone (Surjaatmadja et al., 2–6 November 1998; Li et al., 2010).

Fig. 1 shows the hydro-jet fracturing process. A perforation tunnel is formed by an abrasive water jet. Main fractures open under the high static pressure. Fracturing is accomplished due to a jet pressurization effect. The pressurization effect mechanism is illustrated in Fig. 2 (Tian et al., 2009) and is summarized as follows: (a) the high velocity of the jet and its stagnation in the tunnel create a pressure difference (i.e., pressurization value, P_v) between the pressures in the tunnel (P_a) and the annulus (P_c); (b) the entrainment of the jet in the annulus creates a 'hydraulic isolating ring'; and (c) the pressurization effect leads to the sum of the pressurization value and the annulus pressure to exceed the fracture initiation pressure (i.e., $P_v + P_a > P_f$), which leads to fracture initiation and propagation. The high dynamic energy of the jet in the annulus makes the pressure lower than the formation pressure, explained with the Bernoulli Equation. Therefore, the annulus fluid is prevented from flowing toward existing fractures without the use of mechanical packers. The existing fractures and cracks are thereby effectively "protected" and do not re-open. The pressurization effect is one of the key preconditions for successful hydro-jet fracturing. For this reason, it has been applied worldwide, including

---

* Corresponding author.
E-mail address: tscsydx@163.com (S. Tian).

http://dx.doi.org/10.1016/j.jngse.2015.09.045

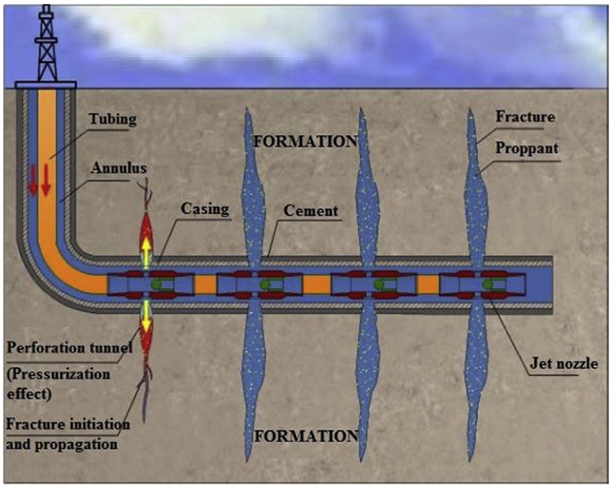

Fig. 1. Schematic representation of hydro-jet fracturing.

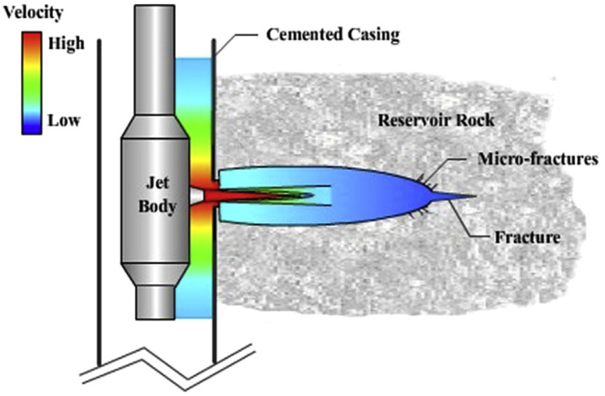

Fig. 2. Schematic representation of the pressurization mechanism/effect in the perforation tunnel during hydro-jet fracturing.

thousands of successful applications demonstrating good stimulation performance in China (Jiang et al., 2014).

Despite these successes, fracturing operations, including hydro-jet fracturing, have recently faced controversy, due to the use of large amounts of water, and associated droughts, water contamination, and low-level earthquakes (Scanlon et al., 2014; Ellsworth, 2013). Some countries prohibit hydraulic fracturing. Therefore, research on non-aqueous fracturing fluids has been advancing, in an effort to reduce water usage (US Energy Information Administration (EIA), 2014; Howarth et al., 2011; Rogala et al., 2013). The novel idea of using supercritical carbon dioxide (SC-CO_2) fluid as a fracturing fluid has attracted particular attention and interest, and is believed to have great potential (Kollé and 6–8 November, 2000; Gupta et al., 2005; ALAdwani, 2007; Middleton et al., 2015).

SC-CO_2 fluid is created when the temperature and pressure of it components are above critical values (T_c = 31.1 °C and $P_c = 7.38$ MPa). These critical values are easier to reach than with other substances, such as SC-H_2O and SC-CH_4. The SC-CO_2 fluid has unique properties, including a low viscosity close to that of gas, a large density close to that of liquid, very low surface tension, and higher miscibility with hydrocarbons (like CH_4) than other commonly used fluids. Its competitive adsorption effect helps CO_2 to replace CH_4 in the formation, reducing the blockage of oil and gas flow and enhancing production (Lillies et al., 1982; Tudor et al., 1994). Scientists have already explored the opportunities and challenges of using SC-CO_2 as a non-aqueous fracturing fluid, and have determined that it is a novel and promising non-aqueous fracturing approach, with significant advantages (Middleton et al., 2015; Dong et al., 2013; Wang et al., 2012). Based on the advantages of the SC-CO_2 fluid and hydro-jet pin-point fracturing without mechanical packers, this paper proposes a new SC-CO_2 jet fracturing technique. There are some challenges with this approach, because the density and viscosity of SC-CO_2 is much lower than water. So far, few reports have examined the effect of using a water jet compared to using a SC-CO_2 jet. For example, there are concerns about whether the same pressurization effect can be achieved in the perforation tunnel of a SC-CO_2 jet as in a water jet (Middleton et al., 2015; Cheng et al., 2013; Wang et al., 2015; Wang, 2013, 2006). Compared to the previous research, which illustrated the pressurization performance using a 2-D numerical model, this paper addresses the concern using 3-D numerical simulations and a lab experiments, and explores the pressurization effect under higher temperature and pressure conditions at the bottom of the hole in deep wells. We anticipate that this research will significantly impact future research and application of SC-CO_2 jet fracturing.

2. Numerical simulation

2.1. Meshing

As Fig. 3 shows, the geometric model used in the numerical simulation is based on an existing experimental framework, and includes a jet nozzle, an annulus and a perforation tunnel. The cone-shaped jet nozzle consists of two orifices and one contraction section. The length-to-nozzle diameter ratio is 2 and the contraction angle is 30.5°. The perforation tunnel consists of a spindle-shaped and a cylindrical section. The total length of the simulated tunnel is 600 mm, and the maximum inner diameter is 60 mm. The nozzle and inlet diameters of the perforation tunnel and the annulus size change depending on the different parameters used in the simulation.

The blue round surface in Fig. 3 (in the web version) marks the nozzle inlet; this parameter determines the inlet of the computational domain and is set as a pressure inlet condition. The two small round surfaces at the simulated annulus and the end of the simulated perforation tunnel (marked in red in Fig. 3 (in the web version)) represent the outlets of the computational domain. They are set as the pressure outlet condition. Because gradients of flow velocity and pressure vary sharply, as do the flows in the opposite direction at the inlet of the tunnel and the annulus, a local mesh refinement is used for these regions to improve the calculation accuracy. Therefore, hexahedral structured grids are used around

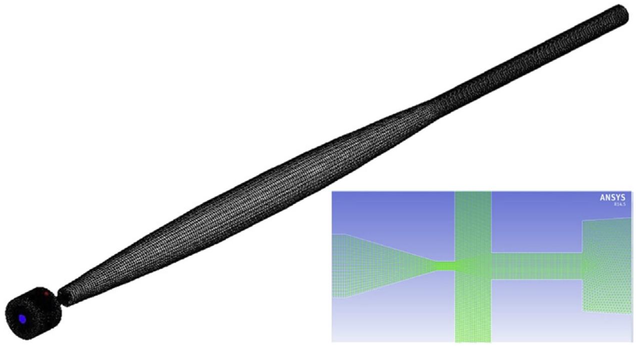

Fig. 3. Physical model of the flow field and meshing (local refinement included).