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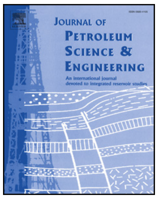

Towards a better understanding of wormhole propagation in carbonate rocks: Linear vs. radial acid injection

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ABSTRACT

Understanding acid reactive flow and the formation of wormholes in carbonate rocks is important for designing successful acidizing operations. Linear coreflooding experiments have been widely carried out to gain insights about the dissolution process for varying rock types and acid systems. However, carbonate reservoir stimulation is dictated by radial flow configuration. As such, it is critical to bridge the gap between linear acid injection and radial acid injection. In this work, a series of radial acid injection and linear acid flow experiments are conducted at various injection rates while maintaining the same operating conditions. The objective is to develop a better understanding of the acidizing process under radial flow conditions at larger scale while applying high confining stresses as only a limited number of radial flow experimental studies have been reported in the literature. This is expected to provide guidance for the optimization and control of the matrix acidizing process for the field operations. The radial acidizing tests are performed on rectangular block samples with dimensions of $20 \times 16 \times 16$ in. We use a quantitative acidizing model to select few representative acid injection rates due to the complexity of the experiments and limited availability of large block samples. This model shows good predictive capability when compared to the experimental results. Pore volume to breakthrough (PVBT) and optimum injection rate are determined for both radial and linear acidizing experiments. Lower PVBT values are obtained for the radial acidizing case. This is mostly associated with the larger rock pore volume exposed to acid for the radial block in comparison to the linear cylindrical core. High-resolution CT scan images of the acidized radial carbonate blocks and cylindrical cores are generated and analyzed. The CT scan images show different wormhole morphology when varying the acid injection rates. Similar branching features are obtained for the optimal wormholes in linear and radial tests. Injecting the acid at the optimal rate leads to fewer transverse branches but thicker when compared to the experiment at higher injection rate that requires more acid volume to breakthrough. The low injection rate results in the largest diameter wormholes with high tortuosity. The high-resolution nondestructive imaging and analysis has enabled to gain insight on the interaction between the acid and the rock sample under radial flow conditions. This analysis has revealed that the wormhole propagation direction is not only governed by the effective stress differential but also can be aligned with the fabric layers due to the sedimentation conditions of the rock.

1. Introduction

Matrix acidizing is a common technique in well stimulation operations to enhance the connectivity between the wellbore and the formation, bypass damaged zones that are usually affected by drilling and/or completions operations, and enable the oil flow to the wellbore. The acidizing operation is performed by injecting reactive fluids (commonly hydrochloric acid due to its relatively low cost and strong dissolution reactions with calcite and dolomite) below the fracturing pressure of the formation to dissolve and disperse the rock solid giving rise to highly conductive channels usually referred to as wormholes. The acid treatment is usually controlled in a region within a few feet around the wellbore depending on the penetration depth of the wormholes (Garrouch and Jennings, 2017). To discern the mechanisms associated

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with the dissolution process of the acid, numerous coreflooding experiments combined with sophisticated visualization techniques have been carried out (Fredd and Fogler, 1998; Tardy et al., 2007; Liu et al., 2017a,b; Izgec et al., 2010) and numerical models of reactive flows in porous media have been developed and analyzed (Ghommem et al., 2015; Panga et al., 2005; Gong and El-Rabaa, 1999; Liu et al., 2017a,b; Xue et al., 2017a,b; Babaei and Sedighi, 2018; Akanni, Naser-El-Din and Gusain, 2017; Wei et al., 2017; Maheshwari et al., 2013; Kalia and Balakotaiah, 2007; Kalia and Balakotaiah, 2009; Ghommem and Brady, 2016; Xue et al., 2017a,b). These studies have examined the sensitivity of the acidizing process to the operating reservoir conditions (temperature and pressure), rock properties (mineralogy, permeability, heterogeneity), and acid system characteristics (viscosity, reaction rate, diffusion coefficient). Five typical dissolution patterns have been identified experimentally (Fredd and Fogler, 1998) and captured numerically (Ghommem et al., 2015; Panga et al., 2005; Xue et al., 2017a,b; Maheshwari et al., 2013; Kalia and Balakotaiah, 2007), namely, face dissolution, conical wormhole, dominant wormhole, ramified dissolution, and uniform dissolution. Dominant wormhole constitutes the desirable acidizing regime because it leads to the deepest wormhole penetration within the formation with the least amount of injected acid. Other recent research studies have focused on the effect of the formation parameters on the wormhole propagation and permeability enhancement [Wang et al., 2017; Gomaa et al., 2018]. For instance, Wang et al., 2017 analyzed the pore network characteristics of core samples taken from an oilfield at different stages of waterflooding. They showed that the improvement of pore network connectivity and the increase in the porosity and permeability are mostly associated with the dissolution, detachment, and migration of fine particles and clay minerals. They developed then a pore network model that accounts for the experimentally observed mechanisms including the detachment and entrapment of fine particles. The simulation results are in qualitative agreement with their experimental counterparts.

Carbonate acidizing and wormhole propagation are commonly investigated by conducting linear coreflooding experiments where hydrochloric acid (HCl) solution is injected into small cylindrical core plugs, such as 1.5 × 6 in. (diameter × length). Results from these conventional linear experiments have provided extensive knowledge on acidizing and wormholing mechanisms but under conditions of essentially 1D flow along the axis of the plug (Fredd and Fogler, 1998; Liu et al., 2017a,b; Izgec et al., 2010). Although these experimental studies give useful insights on the dissolution process, field acidizing operations dictate radial (divergent) acid flow conditions around the openhole wellbore that influence wormholing aspects such as initiation, branching, and death, in a way that cannot be simulated in linear coreflooding. To understand those essentially 3D wormholing mechanisms, experimentation in larger-scale testing systems able to replicate flow conditions around the wellbore must be considered. In contrast to coreflooding systems, which are quite common, the chances of finding the larger-scale testing equipment required for radial acidizing tests vanish quickly as the sample size increases. This, as well as increasing complexity of experimental procedures and limited availability of large-enough rock samples, is the reason only few large-scale radial acidizing experiments have been published to date (McDuff et al., 2010). This paper presents the results of three radial acidizing experiments conducted in large rectangular block samples of rock with dimensions (height × length × width) 20 × 16 × 16 in. using the polyaxial stress frame in Schlumberger Dhahran Carbonate Research Center (SDCR).

On the other hand, the accessibility of linear acidizing testing allows for the characterization of the wormholing process in particular rock types, including those obtained from the actual reservoir cores. Currently, acidizing treatment design tools upscale the data obtained in linear tests to design optimal well treatment schedules including the selection of pumped volumes, rates, and fluids that deliver deepest wormhole penetration at minimal acid volume injected. Considering the above-mentioned differences between linear and radial flows, the actual wormholes and resultant conductivity of the acidized wellbore may differ significantly from the ones predicted by linear studies. Because it is practically impossible to conduct a large-scale radial acidizing test for each job design, it is critical to bridge the gap between linear acid injection and radial acid injection. In this work, a series of linear acidizing coreflooding experiments are conducted at various injection rates while maintaining the same operating conditions (temperature and pressure) as radial acidizing tests to point out the main differences in the wormholing features.

The paper is organized as follows. First, we describe the experimental setup and procedures for radial and linear acidizing tests. Then, for each series, we describe the obtained results, which include the transient pressure variations during acid injection, pore volume to breakthrough (PVBT), the identified optimum injection rate, and visualization of the created wormholes with high resolution X-ray computed tomography (CT). We conclude the paper with the discussion of the observed similarities and differences between linear and radial acid injection results.

2. Experimental methodology

2.1. Fluid and rock properties

In all radial and linear acidizing experiments reported here, identical stimulation fluid was used, which formulation and properties are given in Table 1.

Rock samples—linear cores and blocks—were sourced from the Indiana limestone outcrops and can be viewed to a high degree of accuracy as composed of a pure calcite (calcium carbonate, $CaCO_3$). Geometrical dimensions, dry mass density, initial pore volume, porosity and water-based permeability were directly measured for each linear core sample as part of the linear acidizing experimental protocol (see Section II.3) and reported in the Table 2 below.

As for the radial acidizing block samples, direct measuring of density, porosity and permeability of the whole block becomes a challenge due to significant size and weight of the sample. Instead, those parameters were measured on 1.5 × 2.5 in. (diameter × length) plugs cored from the blocks after the acidizing experiment. To ensure that the sampled rock material represents the initial unstimulated rock, the plugs were cored from the corners of the blocks. The CT imaging of the blocks confirmed later that the created wormholes were always located far away from the corners from where the plugs were taken. The water-based permeability of the blocks defined in this way was found in the rangebetween 6 and 10 mD. For each block, Table 3 reports the dry density and porosity values along with standard deviations obtained from measurements conducted on 3 plugs cored from the corner of the block. The initial pore volume is defined here as the product of the average porosity of the tested plugs and the block total volume.

From Tables 2 and 3 one can see that porosity and permeability of the blocks appeared a bit higher than the permeability of the linear cores. However, within linear core samples and radial blocks rock properties variation of properties is small.

All acidizing experiments in this work were conducted on fully-saturated rock samples. Large block samples for the radial acidizing tests were saturated with tap water, and deionized (DI) water was used to saturate the cylindrical cores for the linear tests. For the comparison

Table 1
Formulation and properties of the stimulation fluid used in radial and linear acidizing tests.

Formulation		15% wt. HCl and 0.2% wt. corrosion inhibitor
Density, g/ml		1.075
Dynamic viscosity, cP	25 °C	1.15
	37 °C	0.95