Journal of Petroleum Science and Engineering 159 (2017) 952–969

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Determination of the optimum wormholing conditions in carbonate acidizing using NMR

Mohamed Mahmoud

King Fahd University of Petroleum & Minerals, Saudi Arabia

ARTICLE INFO

Keywords:
NMR
Carbonate cores
Coreflooding
CT scan
Pressure drop
Acidizing

ABSTRACT

The current optimum wormhole injection rate during acid stimulation treatment in a carbonate formation is defined as the injection rate that creates a dominant wormhole with the minimum acid volume. Wormholes are created to connect the reservoir to the wellbore by bypassing the drilling fluid damage and to enhance the wellbore productivity by increasing the effective wellbore radius in carbonate formations. Currently, the pressure drop and computed tomography scan (CT scan) are used to define the acid optimum injection rate and wormhole shape in the stimulated carbonate rock cores. However, these two techniques assess the interconnectivity of the created wormhole to the rest of the pore system in the reservoir in a coarse way.

In this paper and for the first time new definitions and new approach to the optimum injection rate and wormhole evaluation during carbonate stimulation are introduced. Coreflooding experiments were performed using 3-inch Indiana limestone cores at 100 °C at different injection rates. A suite of stimulation fluids such as emulsified acid, hydrochloric (HCl) acid, gelled HCl acid systems based on polymers and viscoelastic surfactant (VES), and chelating agents were used in this study. Nuclear Magnetic Resonance (NMR) was used to evaluate the efficiency of different stimulation fluids in creating wormholes and their interconnectivity with the surrounding pore distributions in the rock. A new dimensionless number, pore interconnectivity number, is introduced to describe the interconnectivity between the created wormhole and the rest of the pore size distributions in the rock. Optimum wormhole shape is determined at the highest interconnectivity number. The optimum injection rate for a specific fluid can also be determined at the highest interconnectivity number.

Detailed NMR scanning of the core was found to be a good assessing tool for the type of the stimulation fluid and locating the optimum wormholing generating conditions. For example, using a 3-inch length Indiana limestone core, conventional coreflooding experiments showed that 2 cm^3/min injection rate generates the minimum acid volume HCl/VES acid system, however, NMR scan showed an injection rate of 3 cm^3/min generates the highest pore interconnectivity for the wormhole. Gelled acidizing fluids such as HCl based on polymers created wormholes that were clearly identified by CT scan and pressure drop but the NMR scan showed that these wormholes are completely isolated from the rest of the surrounding pore system due to polymer residue plugging the pores. This isolation will reduce the production rate due to minimal radial fluid entry at the wormhole surface. Radial flooding experiments through the wormhole and production from the side of the core confirmed the findings of NMR scan regarding the interconnection between the wormholes and other pores in the rock. Strong relationship was found between the interconnectivity number and core radial permeability around the wormhole.

1. Introduction

Carbonate acidizing is a common practice in oil and gas producing wells and water injection wells to remove the damage due to drilling and to enhance the productivity/injectivity of the reservoir. Acids are used to create conductive channels (wormholes) that connect the undamaged regions in the reservoir to the wellbore. The generated wormholes facilitate the flow of oil and gas from the reservoir to the wellbore by increasing the effective wellbore radius. In addition, they enhance the injectivity of water in water injection wells.

The productivity enhancement due to the acid treatment is a strong function of the acidized radial distance from the wellbore. Total recovery of the well productivity after acid stimulation requires acid penetration radius of 3 m from the wellbore in the case of a well that is not affected by damage in the near-wellbore area (Muskat, 1947). To achieve this high penetration radius, the acid should be injected at the maximum possible

E-mail address: mmahmoud@kfupm.edu.sa.

https://doi.org/10.1016/j.petrol.2017.10.004
Received 17 May 2017; Received in revised form 8 September 2017; Accepted 2 October 2017
Available online 6 October 2017

injection rate to achieve the optimum wormhole formation. The acid injection rate is related to the acid consumption rate which can be described by Damkholer number.

1.1. Different methods to determine the optimum wormholing conditions

1.1.1. Damkholer number (N_{Da})

Damkholer number (N_{Da}) is the ratio between the acid reaction rate to the acid injection rate and can be described as follows (Fredd and Fogler, 1998a, 1998b; Lund et al., 1975):

$$N_{Da} = \frac{\tau D_e^{2/3} L}{Q} \tag{1}$$

Where; N_{Da}, is the acid Damkholer number, dimensionless, τ, is the rock tortuosity factor, D_e, is the effective diffusion coefficient, L is the core length, and Q is the acid injection rate. The latter equation is used to describe the Damkholer number when the reaction is controlled by the mass transfer rate. If the reaction is controlled by surface reaction (in which the acid diffusion rate is very rapid compared to the acid reaction at the surface), the following equation can be used to describe the Damkholer number:

$$N_{Da} = \frac{\tau d L \kappa}{Q} \tag{2}$$

Where; τ, is the rock tortuosity factor, d, is the rock sample diameter, L is the rock sample length, κ is the overall dissolution rate constant, and Q is the acid injection rate. Fredd and Fogler (1997) developed a modified Damkholer number that considers the effects of product transport, reactant transport, and reversible surface reaction as follows:

$$N'_{Da} = \frac{\pi D L \kappa}{Q} \tag{3}$$

Where; D is the diameter of the wormhole and L is the length of the wormhole. Fredd and Fogler (1997) concluded that the optimum dominant wormholes were created at modified Damkholer numbers of 0.17 for different acidizing fluids they have tested. The tested fluids were 0.25 M DTPA (Diethylene tri amine penta acetic acid) at pH 4.3, 0.25 M EDTA (Ethylene diamine tetra acetic acid) at pH 13, 0.25 M CDTA (Cyclohexylenedinitrilotetraacetic acid) at pH 4.4, 0.25 M EDTA at pH 4, and 0.5 M HCl. They defined the optimum condition of the wormhole generation by the Damkholer number at which the wormhole is generated with the minimum volume of acid injected (minimum pore volume to acid breakthrough). Different fluids were tested at different concentration and different pH values and all of them revealed the optimum wormhole formation at 0.17 modified Damkholer number which means this number does not depend on the fluid type. Also they reported an optimum modified Damkholer number value of 0.3 at which dominant wormholes with less branches were formed with different fluids. One can conclude that, the optimum conditions of wormhole formation can be obtained by controlling the modified Damkholer number of the acidizing fluid between 0.17 and 0.3.

Huang et al. (2000a, 2000b) introduced the following form of the optimum Damkholer number:

$$(N_{Da})_{opt} = \frac{\left(\frac{\pi}{20}\right)^{\frac{3}{2}} r_{\max}^3}{k\bar{L}} \tag{4}$$

Where; r_{max} is the maximum pore radius, k is the rock matrix permeability, and L is the average pore length. This formula will give a specific Damkholer number for a fixed rock lithology.

1.1.2. Peclet number (N_{Pe})

The Peclet number is the acid convection rate divided by the acid diffusion rate and can be written as follows (Mahmoud et al., 2011):

$$N_{pe} = \frac{vL}{D_l} \tag{5}$$

Where; v is the Darcy velocity, L is the rock sample length, and D_l is the longitudinal dispersion coefficient. The Darcy velocity can be determined as follows:

$$v = \frac{Q}{A\varphi} \tag{6}$$

Where; Q is the aid injection rate, A is the rock cross-sectional area and ϕ is the rock porosity. Based on their findings they showed that the optimum wormhole shape can be generated at higher Peclet number compared to that at low values of Peclet number. The Peclet number can be increased by injecting the acid at a higher rate and by reducing the acid dispersion to the wormhole walls. Longer wormhole length and low fluid loss to the wall can be obtained by increasing the Peclet number.

1.1.3. Optimum injection rate (Q_{opt}) and optimum acid flux (u_{opt})

The optimum injection rate in carbonate acidizing is defined as the injection rate at which the wormholes are generated with the minimum volume of the injected acid (Wang et al., 1993; Economides et al., 2014; Fredd and Fogler, 1999; Glasbergen et al., 2009; Mostofizadeh and Economides, 1994).

Wang et al. (1993) found that the optimum injection rate during carbonate acidizing is a strong function of acid concentration and temperature. They found out that the acid mass consumed to generate wormholes at the optimum injection rate was lower for low acid concentrations compared to higher acid concentrations. When 15 wt % HCl acid was used the total mass consumed to generate wormhole at the optimum injection rate was 1.2 g and when 3.4 wt % HCl was use the total mass consumed was 0.59 g. Also they found that increasing the temperature increased the value of the optimum injection rate. The shift in the location of the optimum injection rate with temperature can be attributed to the change in the reaction regime.

Huang et al. (2003) tested different acidizing fluids on carbonate rocks and they located different optimum injection rates. They tested the same concentration, 10 wt %, for Long Chain Carboxylic Acids (LCA), acetic acid, EDTA chelating agents and found different optimum injection rate because the different reactivity of each fluid with the rock.

The optimum acid flux (u_{opt}) for HCl acid and acetic acid respectively can be related the optimum Damkholer number as follows (Huang et al., 2000a, 2000b):

$$u_{opt,HCl} = \frac{E_{f0} C_{HCl}^{m-1} \exp\left(-\frac{\Delta E}{RT}\right)}{N_{Da,opt}} \tag{7}$$

$$u_{opt,HAC} = \frac{E_{f0} k_d^{m/2} C_{HAC}^{m/2-1} \exp\left(-\frac{\Delta E}{RT}\right)}{N_{Da,opt}} \tag{8}$$

Where; u_{opt} is the optimum acid flux, C is the acid concentration, E_{f0} is the reaction rate constant, ΔE is the activation energy, m is the reaction order, R is the gas constant, k_d is the acetic acid dissociation constant, T is the reaction temperature, HAC is the acetic acid, HCl is the hydrochloric acid.

Li et al. (2017) showed that the optimum acid flux at which the wormhole will be created is highly affected by the acid temperature. The did numerical simulation study and showed that the acid temperature effect on the wormhole creation was significant compared to the effect of the initial reservoir temperature. The volume required to generate the wormhole as well as the optimum injection rate of the acid increased with increasing the injected acid temperature.

Gong and El-Rabaa (1999) showed the optimum injection rate at which the wormhole is created with the minimum injected acid volume is located on the transition from the mass transfer controlled regime to the surface reaction controlled regime. They showed that at low injection