Journal of Natural Gas Science and Engineering 30 (2016) 539–547

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Numerical simulation and X-ray imaging validation of wormhole propagation during acid core-flood experiments in a carbonate gas reservoir

Alireza Safari [a, b, *], Mojtaba Moradi Dowlatabad [c], Ali Hassani [d], Fariborz Rashidi [e]

[a] Mehran Engineering and Well Services Co, Tehran, Iran
[b] Department of Petroleum Engineering, Amirkabir University of Technology, Tehran, Iran
[c] Institute of Petroleum Engineering, Heriot-Watt University, Edinburgh, UK
[d] Research Institute of Petroleum Engineering (RIPI), Tehran, Iran
[e] Chemical Engineering Department, Amirkabir University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 31 March 2015
Received in revised form
16 February 2016
Accepted 22 February 2016
Available online 27 February 2016

Keywords:
Numerical model
Acid core-flood
Carbonate reservoir
X-ray imaging
Wormhole

ABSTRACT

Acidizing is a sophisticated stimulation treatment that significantly improves production rate particularly in the carbonate reservoirs. However, performance evaluation of the treatment requires extensive laboratory experiments. This includes investigation of various parameters such as temperature, pressure, mineralogy of the rock and the effect of chemical diverters in the zones with high contrast permeability (Safari et al. (2014). A tuned mathematical model, capable of describing the acidizing in core-scale, can play a vital alternative role due to high expenses of the required experiments. In this paper, we used a simulation model, tuned by experimental data, to be used as an alternative tool for modeling acidization. Since wormhole propagation is strongly geometry dependent, the model was solved in a 3D domain rather than its original dimension, i.e. 2D in Panga (2005) model, to simulate the propagation more accurate.

Mass transfer, continuity, and energy equations were combined to develop a model, which simulates the acid flow in porous media accurately. The model, a cross-link between two different scales: pore-scale and Darcy-scale considers the effect of convection, diffusion, and particularly chemical reactions.

In this study, a complete package including acid core-flood experiment, X-ray imaging and numerical simulation of the wormhole propagation was performed to study acid flow in the porous media. The acid core-flood experiment was performed on a core sample from a gas reservoir in south of Iran. In addition to X-ray imaging technique employed to visualize the result of acid core-flooding, a simulation model was developed in finite element analysis software. The model has the dimensions of the core sample. The required chemical reaction equations were implemented in the simulation model to simulate the wormhole propagation process. A very good agreement was achieved when the simulation results were compared with experimental results and X-ray imaging outputs.

The model, as an invaluable tool could be used to study the different aspects of acidizing treatment such as acid efficiency curve, simulation of parallel flooding, etc. This then helps to determine key parameters and optimized conditions for achieving a successful acidizing treatment.

1. Introduction

Generally, all applied sciences are based on conducting experiments and interpreting their results. These experiments are to investigate the impact of various parameters affecting performance of the system. One of the most common methods is to employ an appropriate mathematical model to evaluate effect of individual system variables and their mutual effects. In this study, we used a model that was developed by Panga (2005) to simulate wormhole propagation in the acid-flood experiments in a carbonate gas reservoir.

Many experimental studies such as Fredd and Fogler (1998),

* Corresponding author. Mehran Engineering and Well Services Co, Tehran, Iran. Tel.: +98 919 444 8393.
E-mail addresses: a.safari@mehranservices.com, a.safari@aut.ac.ir (A. Safari), Mojtaba.moradi@pet.hw.ac.uk (M.M. Dowlatabad), hassania@ripi.ir (A. Hassani), rashidi@aut.ac.ir (F. Rashidi).

http://dx.doi.org/10.1016/j.jngse.2016.02.036
1875-5100/

Bazin (2001), Safari et al. (2014) investigated the wormholing process and acid efficiency curve. The majority of the studies focused on limestone formation, however, for instance, Fredd and Fogler (1998) showed a significant difference in pore volume to breakthrough curve for the dolomite core used. This kind of difference occurs especially at low temperatures, in which reaction rate in dolomite is much slower than in limestone. The pore scale heterogeneity, which exists because of the different structure of the microbial carbonate, is also reported important by Ziauddin and Bize (2007). Many other experimental studies investigated various parameters that can affect reaction between acid and rock matrix during any acid-based treatment (Mumallah, (1991, 1996, 1998); Sjoeberg and Rickard, (1984); Taylor et al., (2006); Taylor and Nasr-El-Din, (2009)).

Since majority of studied core's mineral composition was consisted of calcite (73%) and dolomite (25%) plus very little amount of siderite (>1%), following reactions were the main mechanism of change while acid injection:

$$\text{I)}\ CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + H_2O \quad (1)$$

$$\text{II)}\ CaMg(CO_3)_2 + 4HCl \rightarrow CaCl_2 + MgCl_2 + 2CO_2 + 2H_2O \quad (2)$$

$$\text{III)}\ FeCO_3 + 2HCl \rightarrow FeCl_2 + CO_2 + H_2O \quad (3)$$

Besides the laboratory activities, many other studies were performed to develop models simulating the flow of the acid in porous media.

Steefel and Lasaga (1994) described a numerical model for computing coupled multi-component chemical reactions, multi-species chemical transport, hydrodynamic flow, and heat transfer. Their model employs a new algorithm which solves simultaneously for multi-component reactions and solute transport in one and two dimensions and which uses kinetic formulations for mineral dissolution and precipitation reactions, making the a priori assumption of equilibrium between water and minerals unnecessary.

Liu et al. (2013) used a model which couples a two-scale continuum model simulating wormholing in the invaded zone and a reservoirflow model for the compressed zone was used to study the wormhole propagation behavior under reservoir conditions. Their results showed that the normally distributed porosities simulate wormholing better.

Generally, these models can be categorized into four main groups: namely fractal, capillary tube, pore network, and continuum (average) models.

Relating important dimensionless group to experimental observation is a solution that is followed in fractal models (Fredd and Fogler (1998), Fredd (2000), Daccord and Lenormand (1987), Frick et al. (1994), Pichler et al. (1992)).

Capillary tube models are capable of evaluating effect of mass transfer, mutual relation of the wormholes, fluid loss, and reaction on wormhole growth. Interaction and competition between wormholes are key outputs of capillary tube models. Although these models are quite simple, they do not consider the effect of chemical reaction in pore scale as well as transport mechanism. This simplifications may affect the optimum conditions for acidizing (Hung et al. (1989), Huang et al. (1999, 2000), Buijse (2000)).

Pore network model represents porous media in form of many paths that are connected in nodes. Studies performed by Fredd and Fogler (1998) and Hoefner and Fogler (1989) are well-known examples of such modeling. Hagen–Poiseuille relationship describes acid flow in these paths for laminar regime. The acid reaction is considered in form of increase in diameters of these paths. However, scaling up of the result to the field conditions is an issue for these models. Applying such models require large computational power while including heterogeneities effect in pore scale is not usually straightforward.

Due to the deficiencies of first three categories of models, it is generally believed that continuum models are more precise in systematic study of acidizing process. There are three continuum models available: Liu et al. (1997), Golfier et al. (2002), and Panga (2005). While acid is entering the pores, if the reaction rate is very slow compared to the mass-transfer rate, the concentration gradients are negligible. In this case, the reaction is considered to be in the kinetically controlled regime, and a single concentration variable is sufficient to describe this situation. However, if the reaction is very fast compared to the mass transfer, steep gradients develop inside the pores. This regime of reaction is known as the mass-transfer controlled regime. The Liu et al. (1997)'s model does not take account for mass transfer in reaction and considers chemical reaction at local equilibrium. This model has some

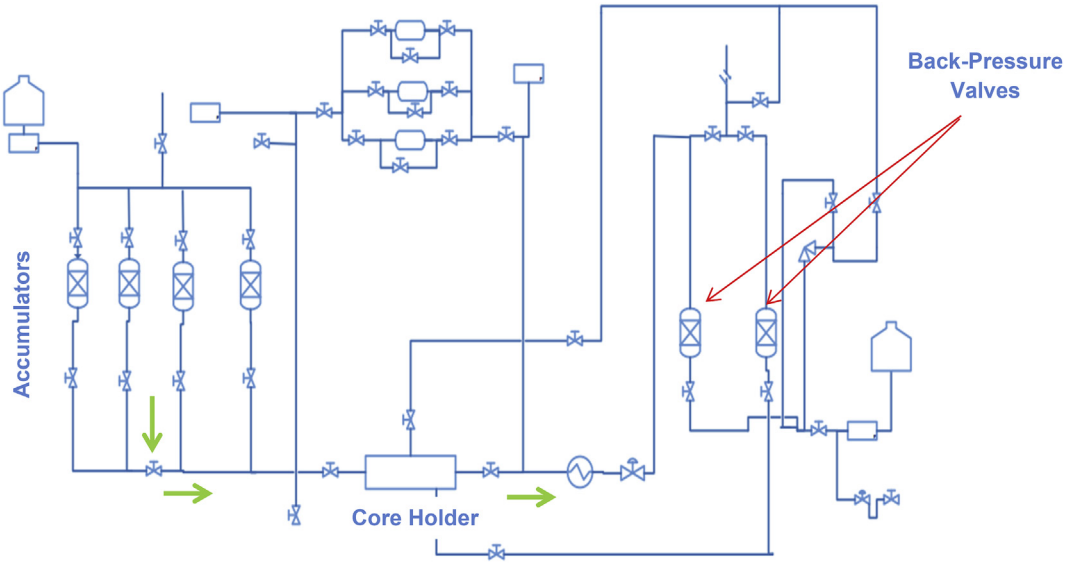

Fig. 1. Schematic of experimental setup used during experiments. The green arrows show the direction of flow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)