Journal of Petroleum Science and Engineering 141 (2016) 133–143

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Application of magnetic nanoparticles mixed with propping agents in enhancing near-wellbore fracture detection

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ARTICLE INFO

Article history:
Received 24 April 2015
Received in revised form
11 December 2015
Accepted 18 January 2016
Available online 19 January 2016

Keywords:
Fracture detection
Nanoparticles
Proppant
Magnetic susceptibility

ABSTRACT

Reliable evaluation of proppant placement in hydraulic fractures is challenging because there are environmental and regulatory concerns about existing techniques which use radioactive tracers. Recent research investigations have shown the potential for the application of nanoparticles as contrast agents for reservoir characterization and advanced reservoir surveillance. This paper demonstrates a new technique for using nanoparticles as contrast agents mixed with proppants that can enhance borehole geophysical measurements, such as magnetic susceptibility, thereby improving the near-wellbore detection of proppants in hydraulic fractures. The methods used in this paper include both laboratory experiments and numerical simulations. The experimental approach consists of (a) synthesizing paramagnetic nanoparticles and (b) carrying out a series of magnetic susceptibility core logging measurements, in the presence of the superparamagnetic nanoparticles (i.e., with a core/shell structure with size of 60–70 nm) mixed with proppants. Numerical simulations are performed simultaneously to confirm that the nanoparticles remain concentrated in hydraulic fractures as is demonstrated in the experimental work. We developed a two-phase flow model to investigate the spatial distribution of nanoparticles when they are injected into a hydraulically fractured porous media, in which the hydraulic fractures are filled with propping agents. Furthermore, we used numerical simulations to investigate the effects of heterogeneity as well as rock and fracture properties on spatial distribution of nanoparticles in the porous media.

The results of laboratory experiments showed that the relative enhancement of the volume susceptibility of the fractured zones depend on factors such as the type of proppants (e.g., magnetic versus non-magnetic proppants), the concentration of nanoparticles in the injected solution, and the volume of nanoparticle solution and proppants. The use of magnetic nanoparticles lead to a significant enhancement in the detection of fractures, even with widths as small as 0.3 cm. The numerical simulations on synthetic examples show that the nanoparticle concentration in hydraulic fractures is significantly higher than that in the surrounding porous rock in the case of tight formations. We have then illustrated from the experimental and numerical methods that the superparamagnetic nanoparticles, which are mainly concentrated in the fractures can be used as contrast agents mixed with the proppants to highlight the fractures and detect the location of proppants. This detection technique can be applied in the field by using the borehole magnetic susceptibility tools for pre-fracturing and post-fracturing measurements in open-hole wells.

1. Introduction

In hydraulic fracturing, proppants are used to create conductive pathways for reservoir fluids by keeping the created fractures propped open. The success of a hydraulic fracturing stimulation process will largely depend on creating fractures that have geometries that are as close as possible to the model design geometry in the target zone. It is therefore necessary to have a good understanding of the location and geometry of the fractures generated by the treatment. This valuable information can be used to calibrate fracture models, design better fracture treatments, plan future workovers and infill drilling, and improve the reservoir characterization used in calculating fracture performance and recovery from the fractured wells.

Radioactive tracers have been used to evaluate the effectiveness of a fracture treatment. In this method, the fracturing fluid and proppants are tagged to give an indication of the propped height. The gamma rays emitted by these radioactive isotopes are detected and measured by gamma ray spectroscopy when the well

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http://dx.doi.org/10.1016/j.petrol.2016.01.027
0920-4105/

Nomenclature

C	concentration of nanoparticles, ppm
d	core diameter, L, cm
D_l	loop sensor diameter, L, cm
$\mathbf{D}$	combined diffusion–dispersion tensor of nanoparticles, L^2/t, m^2/s
$\mathbf{F}$	flux of fluid, m/t, kg/s
k	permeability of matrix, L^2, mD
k_{dep}	deposition rate coefficient of nanoparticles, 1/s, s^{-1}
$\mathbf{M}$	mass accumulation, m, kg
q	source/sink of fluid, m/t, kg/s
r	density of material, m/L^3, kg/m^3
S_w	water saturation, fraction
$\mathbf{v}_w$	fluid velocity, m/t, kg/s
μ_0	permeability of free space, dimensionless
μ_r	relative permeability of the specimen, dimensionless
κ	volume specific magnetic susceptibilities, dimensionless
κ_{rel}	relative response, dimensionless
κ_{uncor}	uncorrected volume specific magnetic susceptibilities, dimensionless
χ	mass normalized susceptibility, dimensionless
ϕ	porosity, fraction

is logged across the interval of the fracturing job (Gadekea et al., 1991; Gadeken and Smith, 1986). Some of the limitations of this method are the relatively short half-life of the tracers, the depth of investigation of the gamma ray tools, and, most importantly, environmental and regulatory concerns on the use of radioactive materials. McDaniel et al. (2009) introduced another nuclear technique to address the environmental and safety concerns associated with the use of radioactive tracers. In this technique, resin-coated proppant is incorporated with a taggant that becomes radioactive when irradiated by a neutron source downhole, for a period sufficient for detection by spectrum and natural gamma ray detectors. Some limitations of this technique include its dependence on having uniform and known concentration of taggant, logging speed, tool design (location of source and detectors), and shorter depth of investigation (McDaniel et al., 2009). Saldungaray et al. (2012) proposed another nuclear method and applied it in the field to determine fracture height. The method uses a high thermal neutron capture compound (HTNCC) taggant incorporated in the proppant. The compensated neutron tool (CNT) or pulsed neutron capture (PNC) tool are used to detect the presence of HTNCC by comparison of pre-fracturing and post-fracturing logging runs. In some cases, only the post-fracturing CNT log can be run, and the near to far detector ratios, as well as the detector count rates can be used to determine the presence of the proppants. Some limitations of these techniques could be the effect of borehole environments and borehole conditions, since these methods require uniform conditions of measurement.

In this work, superparamagnetic nanoparticles are used as contrast agents to tag the proppants. The presence of the proppants can therefore be detected by logging tools sensitive to the magnetic properties of the nanoparticle agents. The injection of nanoparticles with proppants or proppants containing magnetic nanoparticles has been previously introduced to detect location of hydraulic fractures (Barron et al., 2012; Crews et al., 2010; Huh et al., 2014; Potter et al., 2011a, 2011b; Schmidt and Tour, 2012). However, the sensitivity of borehole geophysical measurements to the presence of these contrast agents in the fractures has not been quantified yet. Magnetic nanoparticles have been used successfully in biomedical engineering for targeted drug delivery and as contrast agents in magnetic resonance imaging (MRI). Research studies in the petroleum industry have been investigating the development of nanoparticles as contrast agents for reservoir characterization and advanced reservoir surveillance. Some of the ongoing research studies are investigating the use of nanoparticles as contrast-enhancing agents to enhance traditional data acquisition methods such as nuclear magnetic resonance (NMR), controlled source electromagnetic (CSEM) surveys. Rahmani et al. (2013) carried out numerical simulations of magnetic permeability measurements and showed the value of using superparamagnetic nanoparticles as magnetic contrast agents in crosswell electromagnetic tomography. Barron et al. (2010) described research efforts by the Advanced Energy Consortium (AEC) to investigate a downhole magnetic susceptibility tool that can detect proppants tagged with superparamagnetic nanoparticles.

Magnetic susceptibility can be explained simply as the measure of the ability of materials to be magnetized when exposed to a magnetic field. It is expressed as the ratio of the magnetization induced in a sample to the induced magnetization. The magnetic susceptibility measurements depend on the mineralogy and geochemical components of the rock, and are enhanced by the presence of magnetic components in the rock. Magnetic susceptibility can be expressed either as volume susceptibility (κ) or as a mass normalized susceptibility (χ). The volume susceptibility is a dimensionless quantity in the SI system of units. The mass susceptibility is equal to the volume susceptibility divided by density and has units of cubic meters per kilogram in the SI system of units (Dearing, 1994). Previous studies showed the potential of magnetic susceptibility measurements for rock characterization and identification of oil-bearing intervals (Ali et al., 2013; Potter, 2007; Potter et al., 2011a, 2011b).

The superparamagnetic nanoparticles have a relatively higher magnetic susceptibility than the natural environment of the formation, hence, when pumped with proppants during hydraulic fracture stimulation treatments, they can act as contrast agents that highlight the fracture and detect the location of the proppants. In field applications, magnetic susceptibility measurements can be made using a borehole magnetic susceptibility tool (Robinson et al., 2008). Morrow et al. (2014) conducted laboratory experiments and compared the relative magnetic susceptibility of mixtures of magnetic nanoparticles and proppants against the magnetic susceptibility of shale core samples. They estimated the amount of magnetic nanoparticles required per well to achieve detection above the shale samples. However, the effect of fracture width and volume of investigation of the magnetic susceptibility sensors, which is important in the detection of propping agents was not taken into account in Morrow et al.'s publication. In this paper, we investigate the possibility of using mixtures of nanoparticles and proppants to characterize fractured rock samples using magnetic susceptibility measurements.

In addition to the sensitivity analysis on the effect of magnetic nanoparticles on magnetic susceptibility measurements, we must investigate the transport of these nanoparticles in the reservoir for their functionality condition *in situ*. A few publications have documented numerical simulation work investigating the transport of nanoparticles in porous media. The focus of these publications is mainly on the application of nanoparticles for improved oil recovery and CO_2 storage. Ju et al. (2006) developed a mathematical model for the predicting the transport performances of polysilicon nanoparticles, which are used for enhancing water injection and improving oil recovery. El-Amin et al. (2012, 2013)