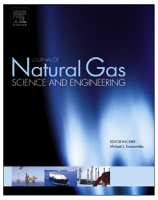
Journal of Natural Gas Science and Engineering 30 (2016) 213–220

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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



Enhancing the physical plugging behavior of colloidal silica nanoparticles using binomial size distribution

Saeed Ghanbari, Abbas Naderifar*

Chemical Engineering Department, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran

ARTICLE INFO

Article history:
Received 28 November 2015
Received in revised form
14 February 2016
Accepted 15 February 2016
Available online 18 February 2016

Keywords:
Nanomaterials
Polymer-coated nanoparticles
Size distribution
Physical plugging
Colloidal silica

ABSTRACT

Silica nanoparticles were amply used as one of the common drilling fluid nano-sized additives. Polyethylene glycol-coated colloidal silica nanoparticles with binomial size distribution were prepared and dispersed in water-based drilling fluid. Dynamic light scattering (DLS) analysis shows that the size distribution of nanoparticles has two peaks at 20.5 nm and 115 nm. Intact plugs from a well-preserved clay-rich carbonate formation were obtained and were characterized using X-ray Powder Diffraction (XRD) analysis and Field Emission Scanning Electron Microscope (FE-SEM) observations. Pore Pressure Transmission (PPT) technique was used to investigate the effect of nanoparticles on pressure penetration through the rock sample. Effect of size distribution of nanoparticles on the plugging process was studied and the performance of silica nanoparticles in water-based drilling fluid was optimized. The colloidal silica nanoparticles with binomial size distribution proved superior plugging performance to monodisperse nanoparticles. In addition, due to improved plugging, satisfactory results were obtained using lower concentration of nanoparticles in the drilling fluid. Drilling fluid with 7 wt% silica nanoparticles with binomial size distribution showed the same satisfactory results as the drilling fluid with 10 wt% monodisperse silica nanoparticles. Moreover, polyethylene glycol, as a steric stabilizer, showed excellent performance in reducing the agglomeration among the nanoparticles in aqueous suspensions.

1. Introduction

Nowadays, the groundwork of the incoming industrial revolution belongs to nanotechnology. Nanotechnology is defined as the study and engineering of matter at dimensions and tolerances of less than 100 nm. Engineered nanoscale materials have been designed and developed by many researchers, and were successfully used in various fields such as pharmaceutical, biomedical, electronics, energy, environmental, materials and petroleum industry (Drexler, 1986; Kickelbick, 2003; Sorensen and Klabunde, 2001; Zeng et al., 2002).

Today's tremendous demand for energy calls for new sources of energy, and shale reservoirs have been become a major opportunity in oil and gas production globally, especially with the advent of novel techniques such as multi-fractured horizontal wells (MFHWs). Considering their nanoscale pores and unique properties, which flows through shale reservoirs cannot be precisely explained by Darcy formula, economic production from shale reservoirs has been quite a challenge for petroleum and drilling engineers in the last decades, and certainly demands significant capital cost and high-tech instruments and facilities (Mohaghegh, 2013).

The wellbore instability during the drilling process of shale reservoirs has been investigated experimentally and mathematically by many researchers. Numerous models were presented in the literature aiming to simulate the flow through the reservoir, and to elaborate on the concomitant effects on rock properties. To accurately elaborate on the wellbore instability problems, Shen et al. reported on a multi-physics coupling model incorporating geomechanics, hydrodynamics, and erosion through Young modulus, flow velocity, and plastic yield. They successfully simulated the process providing an insight for wellbore design and oil production (Shen et al., 2015). Chen et al. focused their research on developing a novel pressure transient response model reflecting multiple migration mechanisms in shale gas reservoir simultaneously (Chen et al., 2015). To further analyze the wellbore instability, Ma et al. proposed a mathematical model for shale gas reservoirs based on a quantitative solution for stress induced by mechanical, hydraulic and chemical effects, and the effective stress tensor around the

---

* Corresponding author.
E-mail address: naderifar@aut.ac.ir (A. Naderifar).

http://dx.doi.org/10.1016/j.jngse.2016.02.028

borehole in a cylindrical coordinate system (Ma and Chen, 2015). In their efforts to add more credibility and accuracy to the mathematical models, Liang et al. considered the coupling of multi-weakness planes and porous flow in their wellbore stability model. Scrutiny of their results revealed that the number of weakness planes, difference in weakness plane occurrence, and diverse water saturation levels considerably influence wellbore stability during drilling (Liang et al., 2014). Sheng et al. developed a model considering the effects of Knudsen diffusion, surface diffusion, gas adsorption and desorption and slippage in multi-scaled pore media in the seepage process (Sheng et al., 2015). Recently, a new strength criterion for wellbore stability analysis was introduced by Shi et al. describing rock strength with higher accuracy than Mohr-Coulomb criterion (Shi et al., 2015).

To further investigate the wellbore stability, Dokhani et al. shed more light on the role of moisture adsorption in wellbore stability of shale formations. They offered a new workflow for wellbore stability analysis based on sorption potential of shale formations (Dokhani et al., 2015). A comprehensive discussion on various complex aspects of thermal effect on rock failure in gas-drilling shale-gas wells by Li et al. (Li et al., 2014). Jain et al. synthesized polyacrylamide-g-polyethylene glycol/silica nanocomposite, and used it as a drilling fluid additive for shale formation. In their research, effect of this nanocomposite on rheological properties as well as on shale inhibition property was examined (Jain et al., 2015).

Polyethylene glycol (PEG)-coated silica nanoparticles proved excellent aqueous stability, which put them as the best choice for surface modification in recent studies focused on the application of engineered nanoparticles in oil and gas industry including enhancing oil recovery, nanosensors in hydrocarbon reservoirs, and wellbore stability (Amanullah and Ramasamy, 2014; Krishnamoorti, 2006; Sensoy et al., 2009; Wittmar et al., 2012). The repulsive force and solvation layer of PEG, covalently bound to the nanoparticle at one end, yet extends far into the surrounding medium, prevent the aggregation among nanoparticles, in which event the unique properties of nanoparticles would be maintained in aqueous suspensions. Actually, the usage of polymers (steric stabilizers) grafted onto the particle surfaces, which impart steric hindrance to particles dispersed in aqueous suspensions, has been one concrete solution to the encountered problems regarding the aggregation between nanoparticles, especially under conditions similar to those of oil reservoir and drilling fluids (Zhang et al., 2007).

A variety of nanoparticles was utilized in the drilling fluids to improve the overall performance of drilling process in shale gas formations (Li et al., 2015; Sensoy et al., 2009; Ward et al., 1999; Zhang, 1999; Zhang et al., 1999). A large portion of researches was focused on problems associated with the drilling process of shaly, clay-rich formations to find an answer for this fundamental question: “What actions can be done to stabilize the wellbore, and to enhance the drilling process using water-based drilling fluid?” According to Van Oort (Van Oort, 1994), Darcy flow of water into the compact matrix of clay-rich carbonate formations has a significant effect on pore pressure. Due to low permeability of these rocks, the pore pressure cannot be transferred to the far field; therefore, water influx will result the elevation of pore pressure in near-wellbore zone in time. This phenomenon is usually encountered during the drilling of clay-rich carbonate formation using water-based fluid. The more the pore pressure elevates, the more the rock would be prone to yield at the weakest spots. Silica nanoparticles were firstly implemented in the water-based drilling fluid to decrease pressure and water invasion into the clay-rich carbonate formation (Sensoy et al., 2009). It is therefore vital to investigate and optimize the performance of silica nanoparticles in the drilling fluid.

In accordance to previous studies, clay-stabilization approach was used to maintain wellbore stability in clay-rich carbonate formations (Beihoffer et al., 1990; Lawless and Bourne, 1992). Due to time-lag in the transport of inhibitors, which is one of the main shortcomings of clay inhibitors, this approach was a failure, even though a variety of additives entitled ‘Inhibitor’, aimed to avoid pore pressure elevation, was utilized in water-based drilling fluids. A complete discussion on clay-inhibitors and their limitations was made by Van Oort (Van Oort, 2003).

As asserted in a number of previous studies (Abrams, 1977; Van Oort, 2003; Van Oort et al., 1996), prevention of water/filtrate influx into the formation is the key to wellbore stabilization. Therefore, Permeability reduction has turned out to be the best approach in preventing the pressure penetration into compact, clay-rich carbonate formations, and in maintaining wellbore stability as well.

In this research, PEG-coated colloidal silica nanoparticles with binomial distribution were used to minimize the pressure penetration into the formation as well as to optimize their performance in the drilling fluid. By adjusting the size distribution, the authors not only enhanced the plugging behavior of colloidal silica nanoparticles, but also achieved the same results using lower concentration of nanoparticles in the drilling fluid in comparison to previous works, which would be economically very desirable (Sensoy et al., 2009).

2. Materials and methods

2.1. Materials

Two types of silica nanopowder were supplied from Aldrich with a primary domain size of 25 nm and 115 nm according to DLS measurements. PEG (99%, 100,000 MW) was also purchased from Aldrich and used without further purifications. Distilled water was used throughout the experiments.

2.2. Particle dispersion and surface modification

High colloidal stability determines the efficiency of the plugging behavior of silica nanoparticles. Intending to prepare a highly stable colloidal silica sample, the surface of silica nanoparticles were coated by PEG, imparting steric stability mechanism to the colloid. For surface modification, certain amount of SiO_2 nanopowder was dispersed in 350 ml distilled water using ultrasonication. Afterwards, PEG was added to the SiO_2 dispersion under vigorous mixing at 70 °C. Electrical heater and magnetic stirrer were utilized during the experiment. The mixture stirred for 3 h to ensure the reaction between PEG and the surface of silica nanoparticles. The final sample is an opaque white colloidal silica solution (Fig. 1). In order to prepare a binomial colloidal silica sample, the same procedure was applied using 175 ml water for each of 25 nm and 115 nm SiO_2 nanopowders; and the two solutions were mixed subsequently to get a colloidal sample with binomial size distribution. The Final volume of sample added up to 350 ml. Several samples with different mass ratios of 25 nm and 115 nm silica nanoparticles (NP) were prepared in order to analyze the effect of size distribution on the physical behavior of them. The size distribution of the sample is shown in Fig. 2, in which two peaks at 20.5 nm and 115 nm can be noticed. Owing to the brilliant performance of PEG grafted on the surface of nanoparticles, as steric stabilizer, the samples were highly stable, and no particle precipitation was observed after 10 months.