An experimental and modeling study of barite deposition in one-dimensional tubes

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ABSTRACT

Barium sulfate deposition on the inner surface of a tube is one of the most serious oil field problems affecting oil field water injection systems. The effects of tube length, liquid volume, deposition time, the profile of the Ba^{2+} concentration in the outlet and the pressure drop in the tubing were evaluated using a graphite furnace atomic absorption spectrometer (GFAAS) and pressure transducer methods. The deposition model of $BaSO_4$ in the tube is presented using coupled mass balance and fluid flow equations. The deposition model contains two governing parameters, the kinetic coefficient and the deposition coefficient, which can be estimated from experimental data. The predictions from the simplified model for barium sulfate scale were in good agreement with experimental data and laboratory observations. In addition, it was proved that many factors are important for deposition kinetics, including the accumulated barium ion amount, the initial flow rate, the initial barium concentration and the deposition time. Scanning electron microscopy (SEM) images of the inlet and outlet of the tube reveal the deposition thickness and morphology.

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1. Introduction

Despite the increasing use of renewable energy, including hydro-electricity, wind and wave power, solar and geothermal energy and combustible renewables, the world consumption of fossil fuel increases continually. In the meantime, conventional fossil fuels are rapidly being depleted (Fan et al., 2010). This had led to increased research into techniques to improve the secondary recovery of oil and gas. The injection of seawater into oilfield reservoirs has proven to be one of the most economical methods for helping maintain reservoir pressure, thereby enhancing oil recovery.

A common problem with this procedure is that the formation water in the reservoir often contains high concentrations of alkaline-earth metal ions (such as Ba^{2+}, Ca^{2+}, and Sr^{2+}). When injected seawater, which contains sulfate ions (SO_4^{2-}), comes into contact with the formation water in the region of the well bore, the resulting highly insoluble mineral scale blocks producing well tubing and may also affect the porosity of the reservoir. Scale deposition is therefore one of the most serious oil field problems that affect oil field water injection systems. This deposition sometimes results in a reduction of oil and gas production by plugging the oil producing formation matrix or causing fractures or perforations. It can also plug production lines and equipment and hinder fluid flow. Scale can be deposited in down-hole pumps, tubing, casing flow-lines, heater treaters, tanks and other production equipment and facilities, which can cause production equipment failure, emergency shutdown, increased maintenance costs, and an overall decrease in production efficiency (Binmerdhah et al., 2010, Carageorgos et al., 2008; Morizot and Neville, 1999). Barite is an extremely insoluble mineral (2.5 mg/L, 25 °C) that is important to the petroleum industry as a unique scaling agent (Blount, 1977; Rosseinsky, 1958).

Scaling tendency is generally determined by considering the solubility of scale-forming minerals for a set of given conditions. Most commercially available scale predictions adopt a thermodynamic approach to calculating the saturation index and the amount of scale that has to precipitate to achieve the equilibrium state for a given brine system (Aoun et al., 1999; Gardner and Nancollas, 1983). However, the thermodynamic approach is based on the precipitation of barium sulfate in bulk solution systems, which is substantially different from the deposition of scale onto solid surfaces. A reliable model capable of predicting such scaling problems may be helpful in planning a water flood scheme. It may also aid in selection of an effective scale prevention technique through the prediction of scaling tendency, type and potential severity.

2. Related work

In the process of precipitation from a dilute solution, two stages are observed (Johnson and O'Rourke, 1954), the induction period

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Notation

a	specific surface area of tube ($1\ m^{-1}$)
C_i	concentration of species i (mmol/L)
C_{Ba}	concentration of Ba^{2+} (mmol/L)
ΔC	excess concentration of Ba^{2+} (mmol/L)
d	inner diameter where the deposition takes place (m)
d_0	inner diameter of tube (mm)
D_i	diffusion coefficient of species i
f	friction factor
J_i	total flux of species i ($mol/m^2\ s$)
k	reaction rate coefficient
n	reaction order
P	pressure (kPa)
ΔP	differential pressure (kPa)
ΔP_0	initial differential pressure when fluid goes through the tube (kPa)
Re	Reynolds number
r_D	deposition rate of barium sulfate (mmol/L s)
r_i	rate of production of species i (mmol/L s)

u	flow velocity (m/s)
$\overline{u}$	mean flow velocity (m/s)
v	volumetric flow rate of solution (mL/min)
v_0	volumetric flow rate of solution (mL/min)
t	time of deposition (min)
T_{Ba}	accumulated barium ion amount (mmol)
Δx	length of tube (m)
μ	viscosity (Pa s)
β	deposition coefficient

Subscripts

0	initial state
In	at the inlet
out	at the outlet
Ba	Ba^{2+} ion
SO_4	SO_4^{2-} ion
$BaSO_4$	$BaSO_4$ crystal

and the growth period, in which the reaction is limited by nucleation and the slow growth of the newly formed crystals, respectively. The precipitation is interpreted as being initially controlled by the nucleation reaction and finally controlled by the growth reaction, so that the rate of precipitation in the bulk solution or on the tube is dependent on the growing crystal surface and the concentration of the solution. The theoretical equations for the induction period and the growth period have been derived and are well-supported by experimental data (Johnson and O'Rourke, 1954).

Reddy and Nancollas (1971a, 1971b) examined the kinetics of crystallization of calcium carbonate (calcite) at 25 °C by following the changes in calcium and hydrogen ion concentration when stable supersaturated solutions are inoculated with calcite seed crystals. The calcite growth follows a rate equation that is second-order with respect to concentration, suggesting a surface-controlled process.

Packter (1976) showed that nucleation occurred during the induction period and regular crystal growth took place onto the crystallites formed during the induction period. The crystal growth was rate-controlled in this range by the rate of deposition of metal salt ions onto the growing crystal surfaces, which depends on both the overall surface area and on the residual excess solute concentration in solution (Karpinski, 1980). For the overall reaction and for the surface growth step, the reaction order varied across the entire interval from 1.0 to 2.0 (Karpinski, 1980), and even exceeding 2.0 (Tavare and Chivate, 1978).

Boak et al. (2005, 2006) presented a kinetic analysis of barite deposition that can predict the declining trends of the barium and sulfate concentrations. Barite seed materials of higher surface area induce faster depletion of scaling ions. A more accurate analytical kinetic model based on the equilibrium solubility of barite over long times was also considered.

Hasson et al. (1978, 1986) developed a model for predicting the deposition of calcium carbonate in pipes. The wall crystallization may be described by combining the convective diffusional resistance and the surface reaction resistance. Segev et al. (2012) provided a rigorous kinetic analysis based on Hasson's model, which enabled them to assess the wall deposition of a crystallizing $CaCO_3$ scale layer from a supersaturated solution in isothermal turbulent flow through a tube.

To reliably predict well behavior during oilfield scaling, the effect of porous media flow on the $BaSO_4$ scaling kinetics is studied systematically. Merdhah and Yassin (2009) estimated the rate of $BaSO_4$ scale formation by monitoring the core effluent's barium ion concentration at various temperatures (50–80 °C) and differential pressures (100–200 psig). The results indicated that the reaction rate constant coefficient increased with increasing differential pressure.

He et al. (1996) developed a semiempirical mathematical model to predict inhibitor efficiency for barium sulfate scale control in industrial processes. This model can be used for selecting effective inhibitors and determining the minimal effective concentration needed for a given system.

Collins (2005) described a novel semi-quantitative kinetic approach coupling the nucleation induction time and mass transfer to predict the location of barium sulfate formation and deposition. Sorbie presented a generalized kinetic coupled adsorption/precipitation model (Sorbie, 2010, 2012) that is fully dynamic and consistent. This model was validated by experimental work (Ibrahim et al., 2012).

Woods and Harker (2003) described a mathematical model for one-dimensional flow of injected and formation water in porous media, including mass balance equations for barium cations, sulfate anions and barium sulfate salt molecules. The dispersion of both barium cations and sulfate anions is assumed to occur as diffusive type mixing with an effective diffusion coefficient D that may be considered constant for a given flow system.

In addition to the above modeling, Bedrikovetsky et al. (2004, 2006) developed a modified Darcy's law that contains a formation damage coefficient describing permeability loss due to salt deposition, which can predict the velocity. This assumes that the diffusion coefficient and the reaction rate coefficient linearly rely on the fluid velocity, but in practice, the reaction rate is also proportional to the specific surface area, which was not addressed in previous studies (Carageorgos et al., 2008; Bedrikovetsky et al., 2006). To describe the deposition rate in tubing, the effects of solution velocity, residence time, and the specific surface area should also be considered.

3. Experimental methods

3.1. Experimental apparatus

The deposition kinetic apparatus is shown in Fig. 1. The primary experimental deposition apparatus consists of two XINGDA SZB-1