ARTICLE IN PRESS

Journal of Petroleum Science and Engineering xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Barite scale formation and inhibition in laminar and turbulent flow: A rotating cylinder approach

Fei Yan[a,*], Zhaoyi Dai[a], Gedeng Ruan[a], Hamad Alsaiari[a], Narayan Bhandari[a], Fangfu Zhang[a], Ya Liu[a], Zhang Zhang[a], Amy Kan[a], Mason Tomson[a,b]

[a] Department of Civil and Environmental Engineering, Rice University, Houston, TX 77005, United States
[b] Nanosystems Engineering Research Center for Nanotechnology-Enabled Water Treatment (NEWT), Rice University, Houston, TX 77005, United States

ARTICLE INFO

Keywords:
Mineral scale
Scale inhibitor
Barite
Turbulence
Laminar
Rotating cylinder

ABSTRACT

Turbulent flow in oilfield pipes is very common, especially around chokes, tubing joints, and safety values. However the flow is generally laminar in laboratory tests for mineral scale formation and evaluation of scale inhibitors. The objective of this study is to investigate mineral scale formation and inhibition under laminar and turbulent conditions. A novel testing method of rotating cylinder apparatus has been developed to generate flow that spans from laminar to turbulent regimes (Reynolds number from 176 to 11,249) under field temperature of 70 °C. Barite scale formation and inhibition by several typical inhibitors were investigated under different hydrodynamic conditions. Barite precipitation kinetics experiments showed no significant difference in precipitation kinetics between laminar and turbulent flow without scale inhibitors. However in the presence of scale inhibitors, precipitation kinetics was slower under turbulent condition. Barite precipitate was collected at the end of the experiment and examined by scanning electron microscope (SEM). SEM images display major difference in barite size and morphology between different flow regimes - highly crystalline barite with an average size of 10 µm in laminar flow and amorphous barite of much smaller size in turbulent flow. Adsorption kinetics experiments of scale inhibitors on barite shows faster kinetics in turbulent flow than that in laminar flow possibly due to enhanced mass transfer in turbulence. It is proposed that the slower barite precipitation kinetics with inhibitors in turbulent flow is due to enhanced adsorption of scale inhibitor on barite crystals, and the mechanisms of enhanced adsorption include larger specific surface area and faster mass transfer rate. These results indicate that scale inhibitors may be more effective under some turbulent conditions, as opposed to previous observations. The insights presented in this work will help to understand scale control in oilfield pipes especially under turbulent conditions, and develop optimal doses of scale inhibitors with regard to flow regimes.

1. Introduction

Mineral scale formation is a major problem in oil and gas production systems, and scale control is critical to ensure successful production of oil and gas from reservoirs that produce brine (Kan and Tomson, 2012). To manage mineral scale in the production system, scale inhibitors are generally applied via continuous injection or squeeze treatment (Kelland, 2014; Yan et al., 2014). Several laboratory testing methods have been developed to evaluate the tendency of mineral scale formation and the efficiency of scale inhibitors. Static jar test and dynamic loop are two traditional testing methods used in the laboratory for the study of scale formation (Kelland, 2014). In a static jar test, the solution is generally mixed or stirred by a stir bar at a moderate stirring rate, and the fluid in the static jar test is in the laminar flow regime. The dynamic loop (or tube blocking) test is another widely used testing method and represents more realistic downhole temperature, pressure and flow conditions. However, the flow regime of dynamic loop is also laminar. So the evaluation of mineral scale formation in the laboratory is conducted in the flow regime of laminar flow in most cases.

Turbulent flow is very common in oilfield pipes especially around chokes, tubing joints, gas lift valves and safety valves. At these locations, flow direction or rate changes abruptly and turbulence is generated. It was reported that scale formation was induced by turbulence through the use of gas to lift a well at a field in the Middle East (Johnston et al., 2014). Recently scale formation and inhibition under turbulent conditions have been investigated. A new dynamic loop apparatus was developed by installing a small bore valve in the coil to simulate the turbulent flow around chokes and downhole safety valves (Benvie et al., 2012). Static jar test and gas sparged bottle

* Corresponding author.
E-mail address: feiyan@utexas.edu (F. Yan).

http://dx.doi.org/10.1016/j.petrol.2016.10.030
Received 18 April 2016; Received in revised form 27 September 2016; Accepted 17 October 2016
Available online xxxx

test were implemented to investigate the effect of turbulence (Sutherland et al., 2013). A dynamic rotating cylinder was designed and used to examine the effect of turbulence on the mass deposition for several scale inhibitors (Chen et al., 2014). The experimental results from these studies revealed that the effect of turbulence was not consistent across different groups of scale inhibitors. Literature on industrial crystallization also shows contradictory results of flow or shear on nucleation and crystallization (Chen et al., 2005; Forsyth et al., 2014; Liang et al., 2004; Penkova et al., 2006). The impact of turbulence on scale formation and control has been a fundamental question in oilfield scale control. Although several studies have been conducted on this topic, there are no clear and consistent conclusions on the effect of turbulence, and the mechanism of shear or flow on scale formation and control remains unknown.

In this study, we developed a rotating cylinder apparatus to generate flow that spans from laminar to turbulent regimes (Reynolds number from 176 to 11,249). Barite precipitation kinetics was carefully examined to compare the kinetics between laminar flow and turbulent flow conditions. Several scale inhibitors including DTPMP, PPCA and PVS were tested to examine the influence of hydrodynamic conditions on different scale inhibitors with various functional groups.

2. Theory and experiment

2.1. Flow system in a rotating cylinder apparatus

A rotating cylinder system was set up as shown in Fig. 1. The inner cylinder was rotating while the outer cylinder was kept stationary. The inner rotating cylinder was manufactured by a stainless steel rod with a Teflon sleeve. The diameter of the stainless steel rod and Teflon sleeve was 1/4 in. (0.635 cm) and 3/8 in. (0.953 cm) respectively, and the length of the Teflon sleeve was 3 in. (7.62 cm). A glass vial with an inner diameter of 2.20 cm served as the outer stationary cylinder. The inner cylinder was rotated by a motor of the agitator (Arrow Engineering), and the rotational speed was adjusted via monitoring the speed by a digital tachometer.

In fluid dynamics, the flow confined in the gap between two rotating cylinders is called Taylor–Couette flow (Taylor, 1923). Similar to pipe flow, the flow regime of Taylor-Couetter flow can be predicted by

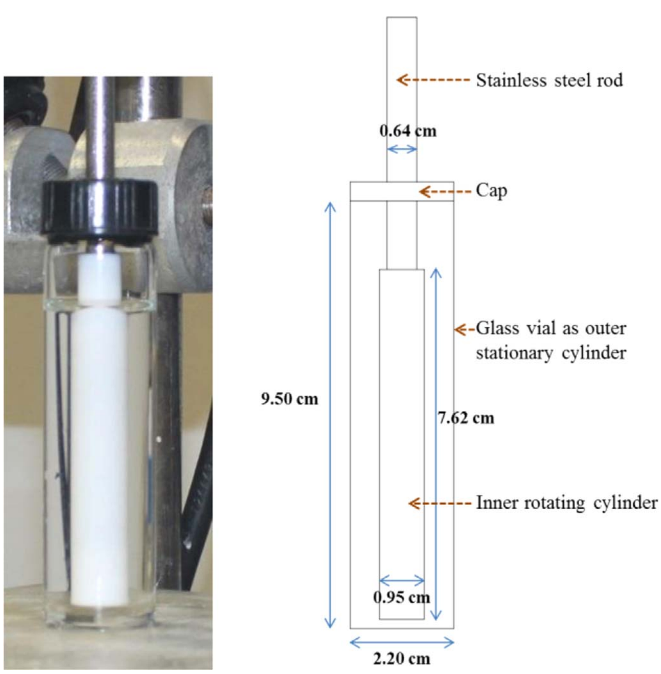

Fig. 1. Rotating cylinder apparatus.

Reynolds number of the system. The Reynolds number is defined as the ratio of momentum forces to viscous forces as follows:

$$Re = \frac{\text{Inertial forces}}{\text{Viscous forces}} = \frac{\rho \upsilon L}{\mu} = \frac{\upsilon L}{\nu} \quad (1)$$

where υ is the mean velocity of the fluid [L/T], L is the characteristic length of the system [L], ρ is the density of the fluid [M/L^3], μ is the dynamic viscosity of the fluid [M/(L*T)], and ν is the kinematic viscosity of the fluid ($\nu = \mu/\rho$) [L^2/T].

In a Taylor-Couette flow system with a stationary outer cylinder, the characteristic length is the gap between two rotating cylinder and the velocity used to calculate Re is the velocity of the inner rotating cylinder, so Re for Taylor-Couette flow is defined as follows (Swinney and Gollub, 1981):

$$Re = \frac{\omega R_1 (R_2 - R_1)}{\nu} \quad (2)$$

where R_1 and R_2 are the radii of the inner rotating cylinder and outer stationary cylinder respectively [L], and ω is the angular velocity of inner rotating cylinder [1/T].

The theory of fluid mechanics shows that there exist several critical values of the Reynolds number in a Taylor-Couette flow system, e.g. Re_1 and Re_2. For $Re < Re_1$, the flow is steady, purely azimuthal, and laminar, which is known as circular Couette flow; for $Re_1 < Re < Re_2$, Couette flow becomes unstable and Taylor vortex flow or wavy vortex flow emerges; beyond a certain Reynolds number Re_2, there is the onset of turbulence. These critical values Re_1 and Re_2 were determined by fluid dynamics experiments and they depend on the radius ratio R_1/R_2, and the height to gap ratio $h/(R_2\text{-}R_1)$, where h is the height of the cylinders. Fluid dynamic experiments with similar radius ratio and height to gap ratio to this study predicted that Re_1 is between 100 and 200 and Re_2 is about 10 to 20 times greater than Re_1 for our rotating cylinder apparatus (Swinney and Gollub, 1981).

In this study revolutions per minute (RPM) of rotating cylinder was set to either 25 (low flow experiment) or 1600 (high flow experiment), and Table 1 shows the corresponding Reynolds number and flow regimes. The solution was kept in a water bath at 70 °C. The viscosity and density of brine at 70 °C was calculated by ScaleSoftPitzer (Kan et al., 2015). Dyes were added to flows in both low flow experiment and high flow experiment to visually check the flow pattern. Laminar flow at RPM of 25 and turbulent flow at RPM of 1600 were confirmed by the flow visualization images of dye patterns.

2.2. Barite precipitation kinetics

Barite oversaturated solution was prepared by mixing cation (Ba^{2+}) solution and anion ($SO_4{}^{2-}$) solution. The cation, anion and final solutions have the following background salt composition: 1 M NaCl, 25 mM $CaCl_2$, 5 mM KCl, and 10 mM 1,4-Piperazinediethanesulfonic acid, i.e. PIPES (pH =6.7). The cation and anion solutions were preheated in 70 °C water bath, mixed and kept at 70 °C water bath during the course of the experiment. The molar concentrations of barium and sulfate in the final solutions were equal and they were adjusted to give different saturation index (SI) values in each experiment. SI is defined as the ten based logarithm of ion activity product over solubility product, i.e. SI=$\log_{10}\{c(Ba^{2+})\,\gamma(Ba^{2+})c(SO_4{}^{2-})\,\gamma(SO_4{}^{2-})/K_{sp}\}$, where c represents ion concentration, γ represents ion activity coefficient, and K_{sp} is solubility product. The activity coefficients of

Table 1
RPM, Reynolds number and flow regime for rotating cylinder experiments.

	RPM	Reynolds number	Flow regime
Low flow experiment	25	176	Laminar
High flow experiment	1600	11,249	Turbulent