The role of physical and chemical processes of silica scale growth in geothermal wells

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Silica scaling remains to be a major restriction for geothermal heat extraction. Our goal is to construct the model reproducing the real silica scaling. To meet this goal, we develop the multi-scale modeling of silica scale growth and compare the simulation result of the amount and the distribution of silica deposition and the data from a laboratory or a field experiment to verify our model. In meso-scale model, the adhesion of the colloidal silica is analyzed using Lagrangian method, while, in the macro-scale model, LB simulation is performed using the scale growth rate obtained at the meso-scale model. From our simulation result, the real phenomenon is reproduced quantitatively and qualitatively, which has not been reproduced in the reaction kinetics. It is, therefore, necessary to emphasize the adhesion of the colloidal silica should be taken into account for reproducing silica scaling.

1. INTRODUCTION

Silica scaling in pipe systems, including heat exchangers, is one of the most significant problems in the geothermal power plants. The deposited material accumulates on the inside of pipes and reduces the effectiveness of utilization of the geothermal resources by clogging pipes. A similar problem is faced in the oil & gas industry with calcium carbonate scaling¹⁾.

Geothermal fluid at high temperature and pressure is in chemical equilibrium with the surrounding rock. The temperature and pressure of this fluid decreases as it is extracted from the reservoir and cycled through the pipe systems. Silica concentration then exceeds the amorphous silica solubility leading to precipitation. These colloidal silica particles are transported to pipe surfaces and gradually accumulate.

There have been a number of experimental studies on the kinetics of silica scale formation²⁻⁵⁾. Although they determined the kinetic parameter using both experimental data and derived the kinetics of silica dissolution-precipitation from theoretical considerations, it has been reported that the magnitude of deposition rate is extremely lower than that in the fields^{6,7)}.

A high rate growth of scale is often observed where the flow stagnates⁸⁾. The inhomogeneous flow could influence the scale growth, which is an alternative process by which the colloidal

silica is transported to a surface and adhere the surface. However the mechanism has not been well understood.

We construct the multi-scale model of the silica scaling considering the particle deposition of colloidal silica on the pipe wall in order to evaluate the hydrodynamical effect quantitatively. Our findings are compared with two observation in the literature^{9,10)} to verify our model.

2. NUMERICAL METHODS

The multi-scale modeling of silica scale growth is developed. The scale growth rate in the macro-scale model is determined from the analysis based on the meso-scale model.

(1) Particle motion

In the meso-scale model, the trajectory of a particle near the wall surface is calculated by solution of the linear momentum equations¹¹⁻¹³⁾

$$m\mathbf{u}_p = \mathbf{F}_D + \mathbf{F}_{BG} + \mathbf{F}_{ELE} + \mathbf{F}_{VDW}, \quad (1)$$

where m is the particle mass, $\mathbf{u}_p$ is the particle velocity and $\mathbf{F}_D$ is the drag force, $\mathbf{F}_{BG}$ the buoyancy force and gravity, $\mathbf{F}_{ELE}$ the electrostatic force and $\mathbf{F}_{VDW}$ the van der Waals force.

(2) Lattice Boltzmann method (LBM)

We use the lattice Boltzmann method to simulate fluid flow. In the lattice Boltzmann model, the two-dimensional nine-directional (D2Q9)¹⁴⁾ lattice

Bhatnager-Gross-Krook model (LBGK)¹⁵⁾ is set. In this model, the directions of the discrete velocity are given as

$$c_i = \begin{cases} c \{\cos(i\pi/4), \sin(i\pi/4)\} & \text{for } i = 0, 2, 4, 6 \\ \sqrt{2}c \{\cos(i\pi/4), \sin(i\pi/4)\} & \text{for } i = 1, 3, 5, 7 \\ (0, 0) & \text{for } i = 8 \end{cases} \quad (2)$$

where $c = \Delta x / \Delta t$ is the particle speed. The evolution equation of the particle velocity distribution function $f_i(\mathbf{x}, t)$ reads

$$f_i(\mathbf{x} + \Delta \mathbf{x}, t + \Delta t) - f_i(\mathbf{x}, t) = -\frac{1}{\tau} [f_i(\mathbf{x}, t) - f_i^{eq}(\mathbf{x}, t)], \quad (3)$$

where $\Delta \mathbf{x}$ and Δt are the lattice spacing and the time step respectively. The relaxation time τ is a parameter which characterizes the constitutive behavior of the fluid considered at a macroscopic level. It is related to the macroscopic kinetic viscosity ν of the simulated fluid as

$$\nu = \frac{c^2 \Delta x}{3} \left(\tau - \frac{1}{2} \right). \quad (4)$$

$f_i^{eq}(\mathbf{x}, t)$ is the local equilibrium distribution function. In order to recover the correct Navier-Stokes equations, the local equilibrium distribution function is defined as

$$f_i^{eq} = \omega_i \rho \left[1 + 3 \frac{(\mathbf{c}_i \cdot \mathbf{u})}{c^2} + \frac{9}{2} \frac{(\mathbf{c}_i \cdot \mathbf{u})^2}{c^4} - \frac{3}{2} \frac{u^2}{c^2} \right], \quad (5)$$

where ω_i represents the weight factors, ρ is the flow density and $\mathbf{u}$ is the flow velocity vector given as follow:

$$\rho = \sum_{i=0}^8 f_i(\mathbf{x}, t), \quad \mathbf{u} = \sum_{i=0}^8 f_i(\mathbf{x}, t) \cdot \mathbf{c}_i. \quad (6)$$

We describe the transport of colloidal silica macroscopically with the convection-diffusion equation (CDE) written as

$$\frac{\partial C}{\partial t} + (\mathbf{u} \cdot \nabla) C = D \nabla^2 C, \quad (7)$$

where C is the concentration and D is the diffusion coefficient. In this paper, the mass transfer for LB model adopts D2Q5 model¹⁶⁾, which is different from D2Q9 models but any real loss of accuracy. The D2Q5 model can be successfull used to simulate the cause with very small D by adjusting λ without any loss of simulation stability¹⁷⁾.

We apply the algorithm of the deposition used in the LB simulation of crystal growth^{18,19)} or soot deposition^{20,21)}. Each node at the interface represents a control volume with a size of $\Delta x \times \Delta x$ (in lattice units) and is located at the center of this control volume. We update the volume ratio of silica scale based on the growth rate. When it exceeds 1, a nearest neighboring fluid solid becomes a solid node.

3. RESULTS

(1) Derivation of scale growth rate

The growth rate at macro-scale is derived from meso-scale model of particle adhesion on the wall surface. We consider the case of a spherical colloidal silica particle moving parallel to a vertical or horizontal wall in a wall-bounded linear shear flow. Our simulation is performed on any H to obtain constitutive expressions of threshold separation from the particle center to the wall H and the time up to adhesion T , using the shear rate S and the length of the interest area X . (Fig. 1) The growth rate of silica scale R^{cc} at the control cell ($\Delta x \times \Delta x$) is given as

$$R^{cc} = \frac{\rho(H\Delta x)C}{T} \quad (8)$$

(2) Quantitative verification of macro-scale model

Hosoi and Imai (1982) carried out an experiment of the artificial silica formation in the laboratory. We predict the amount of silica deposition on the glass wall surface to compare directly with the experiment⁹⁾ using the deposition rate determined by the analysis based on the meso-scale model. As a result, the predicted amount of surface deposition is consistent in amount as compared with that observed by the experiment⁹⁾ (Table. 1). The mass of surface deposition estimated by the general reaction kinetics has the magnitude extremely lower than the amount of laboratory experiment⁹⁾.

(3) Scale profile in geothermal well

In the production well, a higher rate of silica scale growth is observed where the flow stagnates (Fig. 2)¹⁰⁾. To reproduce that feature and investigate the accuracy of our model, the prediction of silica scale growth in model B (Fig. 3) is performed. Our scale profile had good agreement with an observation in the geothermal well¹⁰⁾ as shown Fig. 4.

4. Conclusion

We develop the multi-scale physicochemical model considering the colloidal silica deposition for correctly predicting silica scale formation. The transient simulation of silica scale growth is performed using the lattice Boltzmann method. We quantitatively and qualitatively produce the silica scale formation in our simulations, which has not been reproduced in the reaction kinetics. We would like to emphasize that the colloidal silica deposition should be taken into account for reproducing the silica scale growth. We also conclude that shear rate is a significant factor determined the scale growth

Figure 1 threshold separation as a function of shear rate and length of interest area and time up to adhesion as that of threshold separation.

Table 1 Mass of surface silica deposition 24 h after initiation of calculation.

Mass of surface silica deposition [g/m ²]	
Our result	1.20
Hosoi and Imai (1982)	0.42–1.7
Chemical kinetics	5.18×10^{-5}

Figure 2 Scale profile in geothermal well¹⁰⁾

rate.

Figure 3 model B (initial condition)

Figure 4 Time change of build-up of silica scale

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