

Quantitative simulation of silica scale deposition from physical kinematics perspectives

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Silica scaling restricts the heat extraction and deteriorates the power generation efficiency in geothermal systems. We conducted a deeply stepped analysis on the scaling phenomena with physical kinematics. We simulated the mechanical action on fine particles considered to be spherical in geothermal fluid. In addition, we evaluated the probability of particle re-entrainment from the wall surface and compared the scale deposition rate obtained from different ways of direct calculations. We succeeded not only in matching the order of deposition rate with experimental data, but also explaining the tendency of increase in partial scale deposition amount. Furthermore, our simulation using particles with various diameters indicates the prevention effect of scale buildup by controlling the colloidal aggregation.

1. INTRODUCTION

Scale deposition can damage the pipe systems in geothermal power plants. Although the formation of scale on the pipe wall due to produced mineral salts could be mitigated with chemical treatments or surface modifications, these countermeasures are still at an insufficient level. Siliceous scale deposition most often occurs when the geothermal brine initially at or near saturation in reservoirs is cooled and supersaturated in the course of energy extraction. Accurate predictions of this phenomenon can give way to preventive maintenance for sustainable energy resources. Hence, the reliable and quantitative simulation of the scale accumulation is critical for production availability.

As a novel initiative which is completely different from the chemical prediction method of scale growth widely used so far, Mizushima *et al.* (2016) proposed a scale precipitation prediction method that took physical factors acting on silica particles into account, and reproduced the increase of local scale deposition depending on fluid flow velocity^{1,2}. Simplified and omitted elements in this approach have been complemented by another study which is also based on physical kinematics³.

In this research, we further investigate the theories of hydrokinetics to deal with scale accumulation process and carry out a more detailed calculation with respect to the effect of fluid shear rate and stochastic elements on particle motion. Besides the computation of uniform particles moving from silica suspension to the wall surface, we put forward the quantitative and qualitative simulation of fine

particles on the wall where some particles come unstuck with the aim of elucidating the field observation⁴ and scaling diversity correlated with polymerization of the silica monomer.

2. SIMULATION MODEL

(1) Particle behavior in colloidal suspension

We regard the silica involved in scale deposition as spherical colloidal particles with the diameter of 100nm and evaluate the mechanical balance in the process where the silica particles flowing in the medium fluid adhere to the wall surface.

a) Fluid condition

We set a two-dimensional parallel plate channel (Figure 1) in order to reproduce the geothermal fluid flow. The current of hot water inside the piping system is regarded as the Hagen-Poiseuille flow and the properties of geothermal fluid including flow rate, temperature, wall material and pipe diameter are the same as those of laboratory experiment⁵ conducted by Hosoi and Imai (1982) for the validation of our calculation. Concerning the fluid behavior near the wall surface, we use two types of boundary condition with and without slip flow⁶.

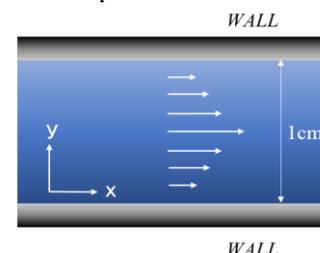


Figure 1 2D parallel plate channel

b) Motion equation

We directly calculated discretized equation of particle motion which is described as

$$m\dot{\mathbf{u}}_p = \mathbf{F}_D + \mathbf{F}_{BG} + \mathbf{F}_{VdW} + \mathbf{F}_{ELE} + \mathbf{F}_B \quad (1)$$

where m is particle mass, \mathbf{u}_p is particle acceleration vector, \mathbf{F}_D is drag force by fluid, \mathbf{F}_{BG} is the total of gravity and buoyancy force, \mathbf{F}_{VdW} is the Van der Waals attractive force, \mathbf{F}_{ELE} is electrostatic repulsive force, and \mathbf{F}_B is force by the Brownian motion. With this direct numerical analysis, it is possible to track the particle behavior stably without any restriction due to the grid intervals.

c) Particle adhesion to the wall

In the process of particle adhesion to the wall surface, we use the simulation method³⁾ based on diffusion behavior due to the fact that the dominant factor for the particle motion with the particle size below 500 nm is the Brownian motion⁷⁾. Figure 2 describes one of the particle trajectories.

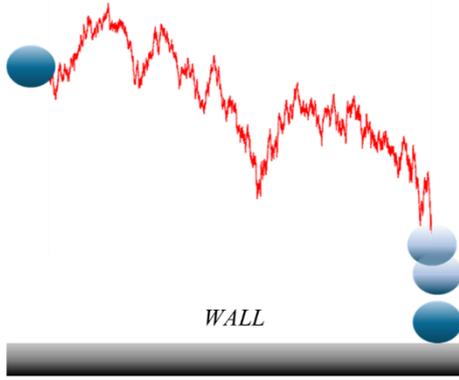


Figure 2 Diffusion orbit of a colloidal particle

(2) Particle re-entrainment from the wall surface

There is a field observation that clarifies relatively large amount of scale deposition in the stagnant part of the flow⁴⁾ (Figure 3). As a process incorporating the influence of shear flow, we adopt the rotary-detachment model^{3,8-12)}. Figure 4 shows a schematic figure of the rotational moment balance around the contact part P , where d is particle diameter, a is contact radius obtained from the Hertz's elastic contact theory¹³⁾. The particle detachment condition by taking moment balance into consideration is expressed as

$$\mathbf{F}_S \cdot \sqrt{\left(\frac{d}{2}\right)^2 - a^2} > \mathbf{F}_A \cdot a \quad (2)$$

where \mathbf{F}_S is separation force mainly composed of

hydrodynamic action and \mathbf{F}_A is adhesion force.

a) Stochastic process by random force

Assuming that the Brownian random force acts on the uniform particles on the wall surface as well as in the fluid, we add \mathbf{F}_B to \mathbf{F}_S and \mathbf{F}_A . Of the 100,000 particles, the number of particles satisfying the condition (2) is counted and incorporated into scale deposition rate.

b) Stochastic process by particle size distribution

It has been reported that the Brownian motion of particles may have anisotropy near the interface^{14,15)}. In consideration of this possibility, we introduce a stochastic process with another approach that gives variation in particle size. As the first step for this simulation, we analyzed the critical diameter of silica particle for the shear flow (Figure 4). The threshold at which the separation moment exceeds the adsorption moment and the particles peel off seems to vary significantly depending on the properties of the fluid flow. Regarding the distribution function of particle diameter, it has been reported that particles in a colloidal solution form a bimodal distribution since colloidal particles suspended in water in the range from several nm to μm agglomerate with or repel each other according to the surrounding conditions^{16,17)} (Figure 5). We also apply this functional model to the calculation of particle detachment rate and conduct a more multifaceted analysis of the effect of shear flow on scale growth. The probability density function of particle number N is described in the form of a lognormal distribution as

$$\frac{dN}{d \ln r} = \frac{N_f}{\sqrt{2\pi} \ln \sigma_f} \exp \left[-\frac{(\ln r - \ln r_f)^2}{2(\ln \sigma_f)^2} \right] + \frac{N_c}{\sqrt{2\pi} \ln \sigma_c} \exp \left[-\frac{(\ln r - \ln r_c)^2}{2(\ln \sigma_c)^2} \right] \quad (3)$$

where N_f , σ_f , r_f , N_c , σ_c and r_c are modal particle number, standard deviation and modal radius of fine and coarse particles, respectively. As a parameter that determines the shape of each mode, the volume ratio of fine modal particles f is represented by

$$f = \frac{V_f}{V_f + V_c} \quad (4)$$

where V_f and V_c are the volume of fine and coarse particles. By integrating the probability density function, we obtain the total weight of particles that don't move from the wall under specific conditions

and incorporate it into the particle detachment rate. Here, we set the mean diameter of colloidal particle to 100nm and the volume ratio f to 0.20, 0.25, 0.50, 0.75, and 0.80.

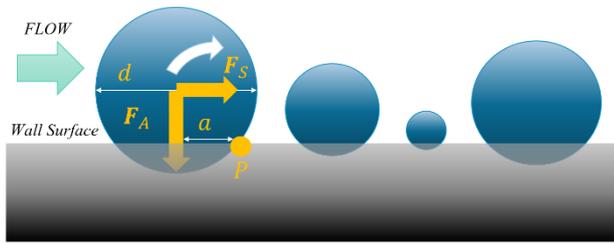


Figure 3 Rotary-detachment model

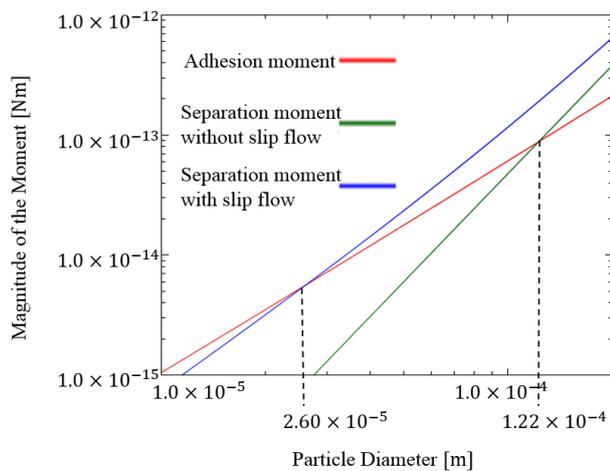


Figure 4 Comparison of magnitude of each moment in Rotary-detachment model without Brownian motion

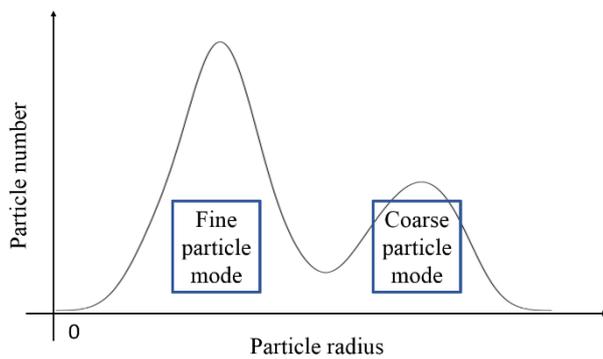


Figure 5 Bimodal distribution function

3. RESULTS

(1) Particle detachment rate

Figure 6 shows the change of each detachment rate of particles where the shear velocity of medium fluid is in the realistic range. In the case where

particles have variations in diameter, the particle detachment rate is more sensitive than previous simulation with Brownian motion and it is expected that the rate ultimately converges as the shear velocity increases. Each result could give a consistent explanation to the field observation⁴⁾.

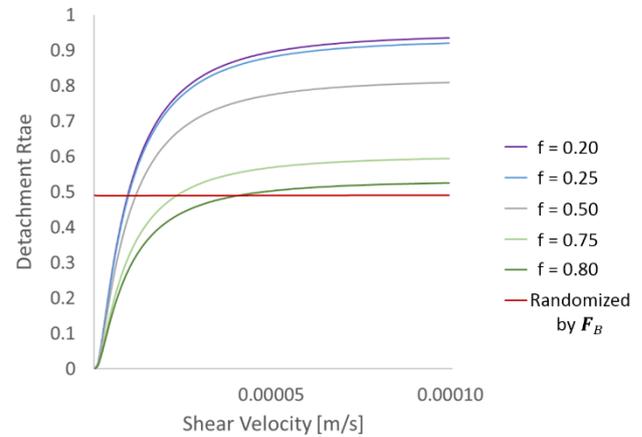


Figure 6 The relationship between fluid shear velocity and particle detachment rate

(2) Quantitative validation of scale deposition

Table 1 shows the amount of scale accumulation on the pipe wall per unit surface area. Our calculation results show good agreement with the experimental data⁵⁾ and suggest that the scale deposition can be suppressed by accelerated polymerization of the colloidal particles.

Table 1 Scale deposition amount per 24h

	Scale precipitation [g/m ²]		
	f	No-slip Flow	Slip Flow
Simulation results	0.20	1.1	0.69
	0.25	1.1	0.70
	0.50	1.1	0.74
	0.75	1.1	0.84
	0.80	1.1	0.87
	Randomized by F_B	0.56	0.55
Experimental data ⁵⁾		0.42 ~ 1.7	

4. CONCLUSION

We developed the hydrodynamic approach of scale deposition and constructed a quantitative method covering a broad range of actual phenomena with random elements. Numerical result of silica deposition rate is in good consistency with that of the measured data in laboratory and geothermal field. It is a remarkable achievement in this research that we

elucidate the necessity to incorporate the physical process into the prediction of scale deposition and the possibility of scale inhibition with particle polymerization.

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