Reproduction of complicated scale form in pipe systems from hydrodynamic perspectives

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Scale precipitation could seriously damage all flow path equipment in oil, gas and geothermal power plants. The formation process of scale is very complex and some phenomena which cannot be explained by simple chemical kinetics need to be considered. One of them is the local scale deposition at the joint of piping structure, and we attempted its prediction and visualization by the lattice Boltzmann method (LBM) for a more advanced analysis on silica particle motion in a flow of geothermal fluid based on fluid dynamics. We improved the stability of flow calculation coupled with the microscopic analysis. In this process, we extracted shear and normal flow with respect to the virtual wall surface, which is calculated by evening out the solid-fluid boundary in the LBM-simulation. We succeeded in reproducing the complicated scale development protruding into the flow due to the influence from flow properties in the field. Furthermore, we indicated that the scale shape changes depending on the pressure difference in inlet and outlet boundaries. This means the flow condition can provide an account of structural difference and our analysis has wide versatility for scale related problems in earth resource engineering.

1. INTRODUCTION

Various mineral compounds including silica, calcium and magnesium are dissolved in geothermal brine and adhere to all the flow path equipment of the power plant as scale. Since it is difficult to remove them, the flow path of the fluid is clogged. The efficiency of energy production is drastically deteriorated by this blockage, and then, frequent maintenance, which involves a significant cost, is required. In order to take appropriate countermeasures against the phenomena of scaling, numerical analyses for predicting the scale growth are indispensable. Besides the pipe conduit in geothermal power plant, the deposition of chemical compounds in permeable rocks known as cementation are of importance to seal underground disposal of radioactive wastes and carbon capture and storage (CCS) in a closed space in the subsurface to avoid any detrimental substances leaking out. Since the process of scale deposition is similar to that of the cementation, our method would be applicable to the other cases, too.

Estimation of scale growth based only on chemical reactions is insufficient to describe complex and local scale shapes. For example, the scale protrusion and extension at the piping seam consists of some processes related to various physical and chemical factors. Mizushima *et al.* (2016) [1)] described the preferential scale deposition with the focus on silica particle movement affected by shear flow velocity. Although their study successfully reproduced the specific shape of scale growth, some important factors (e.g. Brownian motion) for predicting silica particle behavior were ignored. In order to compensate for incomplete elements of their research, a numerical analysis of the Brownian movement and the re-discrete behavior from the wall of fine particles was also conducted [2)].

In this research, we refine the hybrid model of microscopic analysis and macroscopic scale description with physical kinematics[3)] and formulate the flow rate dependence of scale precipitation. We also visualize the local deposition of siliceous scale with the lattice Boltzmann method (LBM), where the rate gradient of crystal growth is determined by the particle re-entrainment rate from inner wall. Through this process, we aim to reproduce the scaling phenomena as observed in real fields and reveal the structural change of silica scale due to flow rate difference.

2. SIMULATION METHODS

(1) Deposition process of fine particles

A motion equation for direct calculation of silica particle diffusion in fluid is expressed as

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

where m is particle mass, $\dot{\boldsymbol{u}}_p$ is particle acceleration vector, $\boldsymbol{F}_D$ is drag force by fluid, $\boldsymbol{F}_{BG}$ is the total of gravity and buoyancy force, $\boldsymbol{F}_{VdW}$ is the Van der Waals attractive force, $\boldsymbol{F}_{ELE}$ is electrostatic repulsive force, and $\boldsymbol{F}_B$ is force by the Brownian motion. We focused on the diffusion effect by Brownian motion and tracked the particle behavior near the pipe wall (Figure 1).

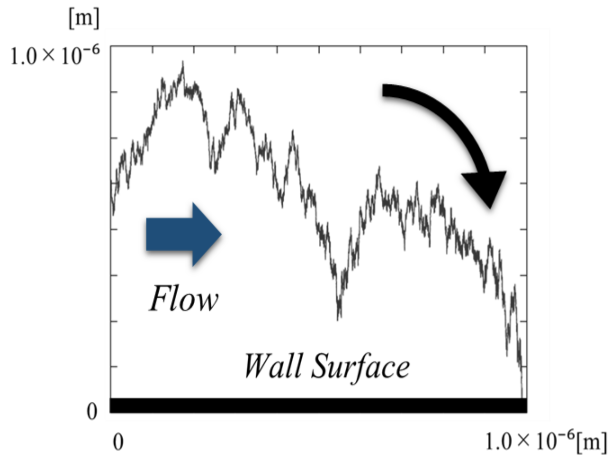

Figure 1 Particle adhesion from geothermal fluid to pipe wall

(2) Detachment process of fine particles

Some of the silica particles peel off from wall surface due to flow influence before forming chemical bonds and becoming the scale completely. We quantitatively evaluated the total amount of fine particles which are detached from inner wall by shear flow under specific conditions of geothermal brine (Figure 2).

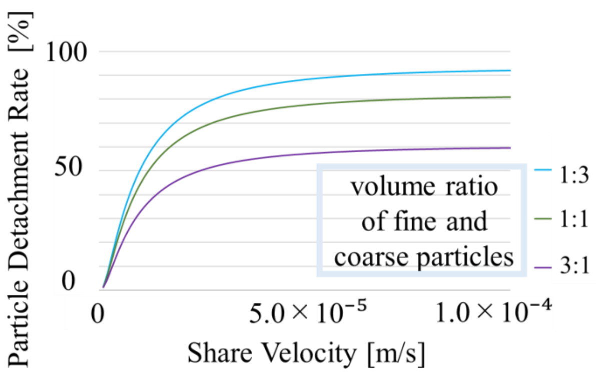

Figure 2 Detachment rate of fine particles with bimodal size distribution
(We set 3 types of volume ratio of fine and coarse particles, which depends on the medium fluid.)

(3) Visualization of complicated scale structure

a) Lattice Boltzmann method (LBM)

We attempted to visualize a time sequence of the scale shape in a pipe with the macroscopic analysis using LBM coupled with the microscopic calculation. The fundamental idea is that gases/fluids can be imagined as consisting of a large number of small particles moving with random motions[4]. The exchange of momentum and energy is achieved through particle streaming and billiard-like particle collision. For a two-dimensional model, a particle is restricted to stream in a possible of 9 directions, including the one staying at rest (Figure 3).

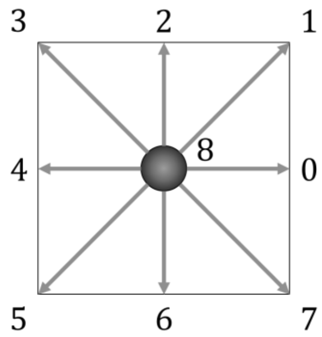

Figure 3 The two-demensional nine-directional (D2Q9) lattice for LB-simulation

b) Build-up scheme of silica scale

We apply volumetric calculation[5,6] to each solid-fluid interface. Solid cells with at least one adjacent fluid cell are set as calculation targets based on the following equation,

$$V_r(t + \Delta t) = V_r(t) + \frac{1}{\Delta x^2} \cdot \frac{R}{\rho_p} \Delta t \qquad (2)$$

where V_r is volume ratio of the scale, Δx is grid space for LB-simulation, R is scale deposition rate obtained from microscopic analysis on silica precipitation process and ρ_p is the density of fine silica particles. V_r is updated every time step by R, which is a function of flow velocity, and if its value exceeds 1, one of the neighboring fluid cells is randomly selected and turns into a solid cell. At this time, in order to increase the stability of the crystal growth, we introduced a calculation that automatically complements the cavity grids due to random scale generation. When the total number of generated scale grids becomes 20, the flow calculation and scale count are reset (Figure 4).

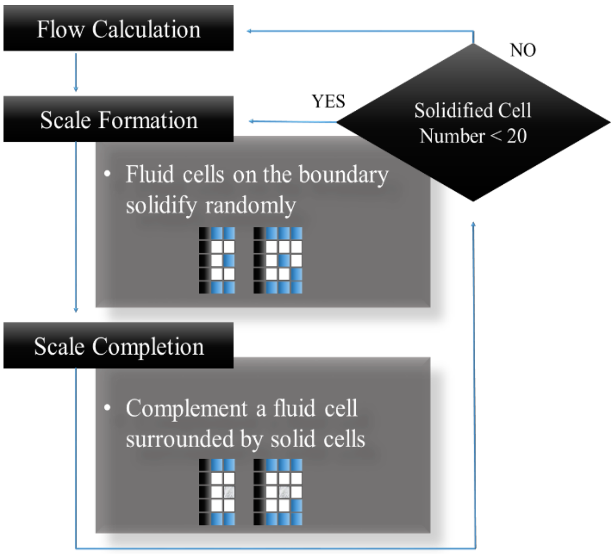

Figure 4 Schematic workflow of scale description with LB-simulation

(4) Simulation model

a) Joint section in pipe system

We set two-dimensional channel of hot water flow with sudden expansion (Figure 5) to reproduce the local deposition of silica scale due to the difference of fluid behavior. Parameter values used for fluid calculation in LBM are described in the Table 1.

b) Boundary conditions for LB-simulation

We use Bounce-back rule to express non-slip boundary of solid and fluid cells in flow calculation with LBM. For verification of the change in the scale shape depending on the flow velocity, the pressure difference at the inflow/outflow boundary was set in two patterns.

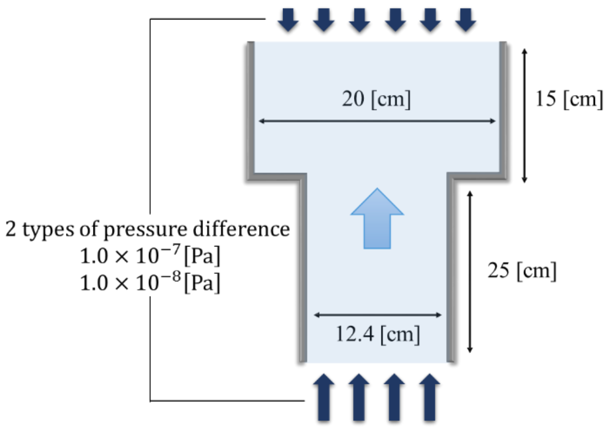

Figure 5 Simulation model

Table 1 Parameters for LB-simulation

Time Interval	1.0×10^{-2}[s]
Grid Space	1.0×10^{-3}[m]
Kinematic Viscosity of Water	1.0×10^{-6}[m²/s]
Silica Density	2.0 [g/cm³]
Pressure Difference	1.0×10^{-7}[Pa] or 1.0×10^{-8}[Pa]

3. RESULTS

It is confirmed that the silica scale preferentially precipitates at the pipe joint where the flow velocity in the parallel direction of the wall is slow. Furthermore, the shape of the scale growth is affected by the flow rate given by pressure difference in inlet and outlet boundaries. The results shown in Figures 6 and 7 excellently reproduce the cross section observed in various geothermal wells (Figures 8 and 9). Normal flow to the pipe wall develops and scale protrusion is found around the casing seam with a swift stream. On the other hand, the silica scale extends along the wall with a slower current.

Figure 6 Scale form
(pressure difference : 1.0×10^{-7}[Pa])

Figure 7 Scale form
(pressure difference : 1.0×10^{-8}[Pa])

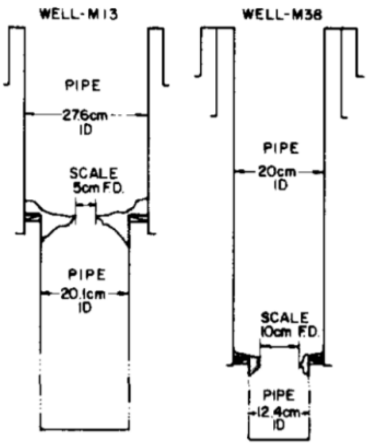

Figure 8 Scale protrusion in the pipe system[7)]

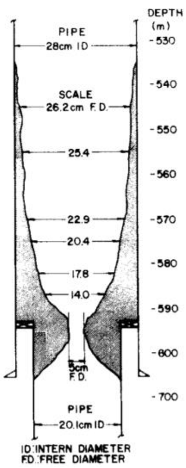

Figure 9 Scale extension in the pipe system[7)]

4. CONCLUSION

We aimed to create the two-dimensional model with hydrodynamic analyses to enhance the reproducibility of local development of silica scale. We succeeded in finding the main factor of various form in scale deposition by focusing on physical kinematics. To clarify the correlation between fluid behavior and scale shape could be effective for setting optimum conditions in pipelines and monitoring of crack occlusion. For further improvement of our simulation model, chemical parameters such as pH and temperature should be taken into consideration.

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