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Silica deposition in superheated geothermal systems

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ABSTRACT

Superheated geothermal systems represent two phase system consisting of precipitated silica in dispersed phase with the superheated steam. The work presents computational approach to predict silica transport and deposition in superheated geothermal systems. Advection diffusion model was implemented using OpenFoam. The model includes effect of Brownian diffusion, turbulent diffusion, turbophoresis, Saffman lift force, drag force and thermophoresis on silica particle motion. The OpenFoam solver developed was validated for gas particle flows showing good agreement. Deposition characteristics of silica particles in superheated steam flow were studied.

1. INTRODUCTION

High enthalpy superheated steam extracted from deep geothermal systems offers greater potential for power generation than conventional geothermal systems. In an attempt to achieve superheated steam the Icelandic Deep Drilling Project was established in year 2000 (Palsson et al, 2014). The well IDDP-1 was drilled which produced fluid with an enthalpy of > 3170 kJ/kg and the well head pressure up to 150 bar. The fluid however consists of silica in gaseous phase which precipitated as the pressure was lowered down (Markusson and Hauksson, 2015). Presence of high quantity of silica in superheated steam can be explained because of increase in silica solubility in vapour phase with increase in pressure. Figure 1 shows the solubility of amorphous and quartz silica obtained from simulation on MATLAB using thermodynamic model given in literature (Karsek et al, 2013). Simulation results show the effect of pressure on silica solubility which increases fast in higher pressure range similar to IDDP-1. The precipitated silica observed in IDDP-1 is found to be in dusty phase which can cause scaling due to deposition on the surface of power plant equipments such as heat recovery system. Predicting deposition of silica particles flowing in superheated steam can help in better designing of equipments.

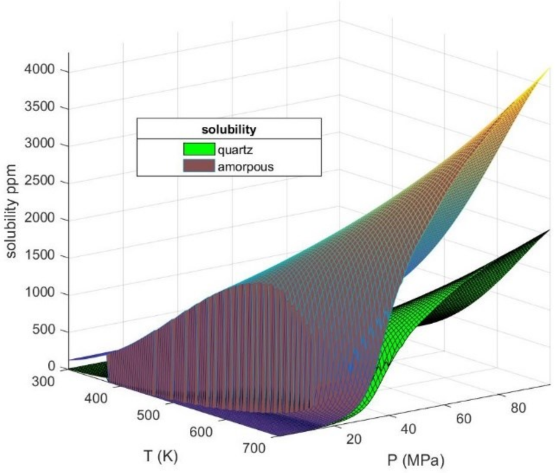


Figure 1: Amorphous and Quartz solubility at different temperature and pressure

Silica in superheated steam flow is analogous to gas flow with particles in dispersed phase. Modeling such two phase flow involves two major approaches: Lagrangian particle tracking approach where individual particles are tracked along the flow and the Eulerian approach where both phases are treated as continuous. Application of Lagrangian tracking approach for modeling particle dispersed in fluid can be found in literature (Guha, 2008). Particle deposition in turbulent flow was calculated by Kallio and Reeks (1989). The model however ignored deposition due to Brownian diffusion. Other work using similar approach with fluid flow characteristics determined using direct numerical simulation and large eddy simulation can be found in literature (Ounis et al, 1993). Most commercial CFD codes for dispersed particle laden flow are based on approach well known as mixed Eulerian-Lagrangian approach such that the fluid flow field assumed continuous and particles tracked using Lagrangian method. Problem with Lagrangian approach arrives as the number of particles increases which increase the computational time proportionally. To overcome this, small number of particles are tracked to get an overall picture of flow. However when the particle concentration needs to be considered the problem becomes serious. The intensiveness of Lagrangian models helps make good to understand physics of flows but also expensive for application in practical engineering problems.

Eulerian approach on the other hand overcomes major disadvantages present in Lagrangian approach but still suffers from difficulties involving models for turbulence closure and proper boundary conditions. A simple Advection-diffusion model for predicting particle deposition was applied by Johansen (1991) and later improved shown in independent work done by Guha (1997) and by Young and Leeming (1997). The model takes into account Brownian and turbulent diffusion, turbophoresis, Saffman lift and electrostatic force contributing to deposition. Though the model offers simplicity in solving equations, difficulty arises in solving problems with particle discontinuities and correct treatment of boundary conditions as discussed in the work by Slater and Young (2001). The current work shows implementation of advection-diffusion model for modeling two phase flow involving silica dispersed in superheated steam flow using OpenFOAM (OpenFOAM, 2014) an open source CFD package. The existing turbulence models and solvers in the software were used directly to obtain fluid flow variables required to solve the particle flow equations. The particle continuum equations were written in OpenFOAM notation such that boundary conditions can be applied directly on the variables. The solver developed was then used to study deposition characteristics of silica particles in superheated steam flow.

2. NUMERICAL MODEL

2.1 Fluid phase conservation equation

In order to solve conservation equations for particle phase flow, relations for velocity profile, eddy viscosity and velocity fluctuations for fluid flow are required. For simple geometries, empirical relations of Kallio and Reeks (1989) are followed. For more complicated geometries, it is suggested to use more general method of solving conservation equations for fluid flow phase. The expressions for Reynolds averaged mass and momentum conservation equation in Cartesian coordinates for fluid flow are given as:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho_f}\frac{\partial p}{\partial x_i} + \nu_f \frac{\partial^2 \bar{u}_i}{\partial x_i \partial x_j} + \frac{\partial \overline{u_i' u_j'}}{\partial x_i} \tag{2}$$

where $\bar{u}_i$ is the Reynolds averaged velocity in i^th^ direction, p is the pressure, ρ_f and ν_f are the fluid density and kinematic viscosity respectively and the last term in Eq. 2 represent gradient of velocity fluctuations. The current work uses k-ω model for modeling turbulence required to obtain velocity fluctuations and the scalar property eddy viscosity.

2.2 Particle phase equations

Conservation equations required for particle concentration and momentum balance are expressed in Cartesian form as:

$$\frac{\partial c_p}{\partial t} + \frac{\partial (c_p v_i)}{\partial x_i} = 0 \tag{3}$$

$$\frac{\partial c_p v_i}{\partial t} + \frac{\partial (c_p v_i v_j)}{\partial x_j} = c_p\left(F_{drag,i} + F_{lift,i} + F_{thermophoretic,i}\right) \tag{4}$$

Where v_i the particle velocity, c_p is the particle concentration in mass per unit volume and terms on the right hand side represent the different forces per unit mass acting on particle. The expression for different forces are given in literature (Slater and Young (2003).

The above equation requires averaging after inserting the expressions for different force terms on the right hand side of equation 4. Both density and non density weighted averaging can be applied obtaining the same final result. Details of the derivation can be found in the literature (Guha, 1997; Slater and Leeming, 2003). The final expressions of the equations as derived by Slater and Young (2003) are given as:

$$\frac{\partial \bar{c}_p}{\partial t} + \frac{\partial (c_p \bar{v}_i^c)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[(D_B + D_T)\frac{\partial \bar{c}_p}{\partial x_i}\right] \tag{5}$$

$$\frac{\partial \bar{v}_i^c}{\partial t} + v_j^c \frac{\partial (\bar{v}_i^c)}{\partial x_j} = -\frac{\partial \left(\overline{\chi u_i' u_j'}\right)}{\partial x_j} + \left(\frac{\bar{u}_i - \bar{v}_i^c}{\tau_p}\right) + 0.725 \sum_{\substack{j=1 \\ j \neq i}}^{3} \left[\left(\frac{\rho_f}{\rho_p}\tau_p \left|\frac{\partial \bar{u}_j}{\partial x_i}\right|\right)^{\frac{1}{2}} \left(\frac{\bar{u}_j - \bar{v}_j^c}{\tau_p}\right)\right] - \frac{K_T}{m T_f}\frac{\partial T_f}{\partial x_i} \tag{6}$$

Where, D_B and D_T are the coefficient of Brownian and turbulent diffusion, $\bar{v}_i^c$ is the density averaged particle convective velocity, χ is the ratio of particle mean square velocity to the fluid mean square velocity, K_T is the thermophoretic force coefficient, m is the particle mass, ρ_f and ρ_p are the fluid and particle density and τ_p is the relaxation time expressed as:

$$\tau_p = \frac{2\rho_p r_p^2}{9\mu_f} \tag{7}$$

Where r_p is the particle radius.

2.3 Temperature equation

Thermophoresis is observed whenever there is temperature gradient in the fluid flow. The temperature gradient can occur due to heat source present or due to temperature difference between inlet fluid and boundaries. For cases such as in heat exchanger with no heat source and temperature gradient occurring only due to different boundary temperature, transport equation for the scalar field temperature is expressed as:

$$\frac{\partial T_f}{\partial t} + \frac{\partial(\bar{u}_i T_f)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\alpha_T \frac{\partial T_f}{\partial x_i}\right] \tag{8}$$

Where T_f is the fluid temperature and α_T is the thermal diffusivity.

2.4 Flow mesh and boundary conditions

Figure 2 shows the mesh description of the test case. Block mesh structure is used such that the number of mesh per unit length increases towards the wall. This is done in order to capture concentration gradient which increases sharply near wall. The smallest size of mesh is kept equal to the radius of the particles in the flow. The boundary conditions applied near wall is perfect absorbing which assumes that the particles stick to the wall once they hit. To obtain this zero gradient of particle concentration and velocity are applied.

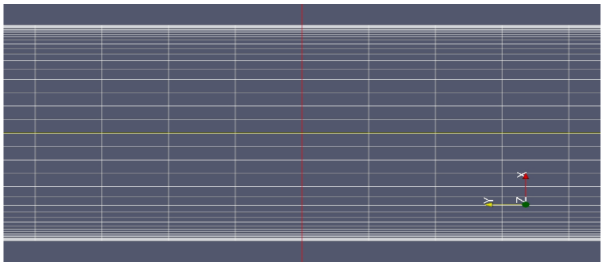


Figure 2: Mesh description for the test case

3. RESULTS AND DISCUSSION

Simulation were done for the validation of implemented model to obtain variation of deposition velocity with particle relaxation time. The particle relaxation time and deposition velocity in non-dimensional form are expressed as:

$$\tau_+ = \frac{\tau_p u_*^2}{\nu_f} \tag{9}$$

$$V_{dep+} = \frac{J_{wall}}{u_* \bar{c}_p} \tag{10}$$

Where J_{wall} is the particle flux per unit area towards the wall.

Figure 3 shows the variation of dimensionless deposition velocity with dimensionless particle relaxation time for a fully developed pipe flow on a logarithmic scale. The graph shows the comparison of simulation results obtained using OpenFOAM implemented model with the experimental results from Liu and Agarwal (1974) for two different Reynolds numbers for droplets in gas and that of Wells and Chamberlain (1967) for particle in gas flow. Comparison shows good agreement with the experimental results. Results shows clear distinction of the three different regimes of deposition. First is the diffusion regime where deposition occurs mainly due to Brownian and turbulent diffusion for small particles size. Decreasing deposition velocity in this region occurs due to decrease in Brownian diffusion as the particle size increases. The second regime called diffusion impaction regime where steep increase in deposition occur mainly due to increase in lift and turbophoretic force effects. Unlike lift force, turbophoretic force decreases as particle relaxation time increases but the turbophoretic component of convective velocity increase proportionally with particle relaxation time. The third regime consists of particle inertia where deposition velocity slows down as the particle size increases further. Detailed explanation about effect of each parameter on deposition characteristics for each regime is well explained in literature (Guha, 1997, Young and Leeming 1997).

The solver developed was used for studying silica particle flow in superheated steam flow. The superheated steam was assumed at 165℃ and 1.2 bar of pressure. This corresponds to 60℃ superheat. The temperature and pressure chosen for simulation were lower than superheated geothermal systems though keeping the superheat of same degree. The low range is chosen to show the effect of thermophoretic forces on deposition occurring in lower fluid density ranges. The Reynolds Number for the pipe flow was 4000. These thermodynamic conditions also corresponds to the ongoing experimental studies on deposition characteristics of silica steam flow. It is to be noted that the change in thermophysical properties and characteristics of fluid will change the particle size corresponding to given dimensionless relaxation time as shown by Eq. 9 but the overall feature of the deposition velocity as a function of relaxation time remains the same.

Figure 4 shows variation of concentration of silica particle for different relaxation times obtained using different particle size for the same flow conditions. Particle of very small size subject to Brownian motion causes concentration distribution to evolve uniformly if the external force is absent. However the presence of turbulence causes formation of dense clusters of particles such that non uniform particle distribution is developed because due to turbulence near wall. Degree of preferential concentration depend upon ratio of particle to fluid inertia. Very small size particles follow all motions of turbulence and disperse with fluid elements as shown in fig. (a). As the size increases, the particles does not follow curved streamlines causing concentration (fig. (b)). However as the inertia increases with further increase in particle size, the particles become too sluggish to have a longer response during eddy´s lifetime and hence preferential concentration decreases (fig. (c), fig. (d)).

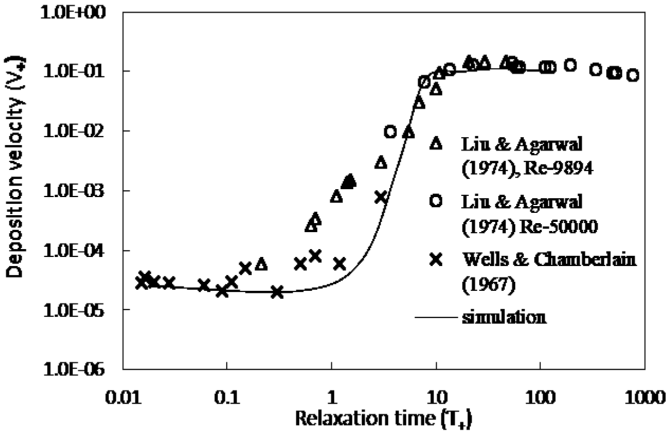
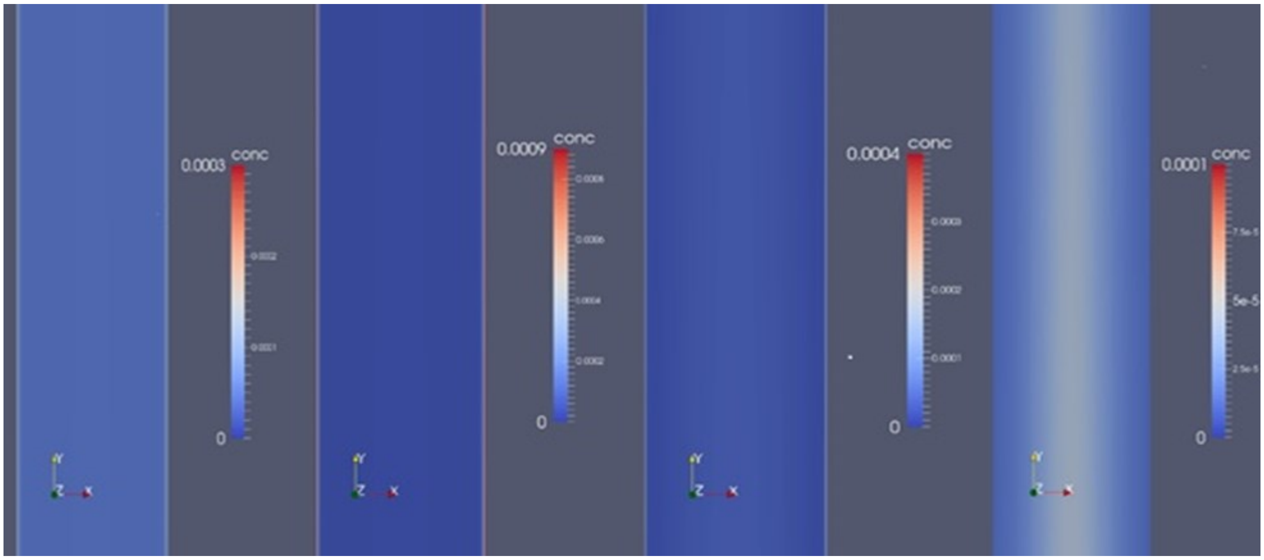


Figure 3: Variation of non-dimensional deposition velocity with non-dimensional particle relaxation time



(a) (b) (c) (d)

Figure 4: Variation of particle concentration for different dimensionless particle relaxation times (a) 0.5 (1.25µm), (b) 2.0 (2.5µm), (c) 17.8 (7.5µm), (d) 60 (13.8µm)

Figure 5 shows the effect of temperature gradient in a superheated steam flow on silica deposition velocity. Thermophoresis plays important role in deposition for particles with smaller relaxation time. Simulation results shows increase in deposition velocity with increase in temperature difference between mean gas temperature and wall temperature. As seen from the graph, deposition rate increases faster at lower temperature gradients.

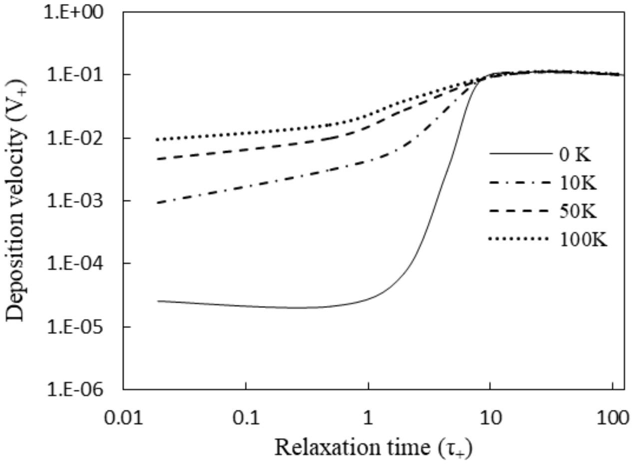


Figure 5: Effect of temperature gradient in a flow on deposition velocity

4. CONCLUSION

The present study shows implementation of advection diffusion model using OpenFoam, an open source CFD package for study of silica particle deposition in superheated steam flow. Solver was developed utilizing functions and utilities available in the used CFD package. The solver validation was done for the case of deposition problem in a particle gas flow through a vertical pipe with experimental results available from literature. Considering the analogy of superheated steam with silica in dispersed phase to the gas particle flow, the solver offers its application in study of geothermal systems with precipitated silica in superheated steam. Simulations were done for the case of silica in superheated steam. Variation of concentration distribution along the flow for different relaxation time range were shown. Effect of thermophoretic force occurring due to temperature gradient in a flow on the silica deposition was studied showing higher deposition at smaller relaxation time range. The model offers advantage of computational time saving and scope for utilization in geothermal applications involving superheated steam with silica in dispersed phase.

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