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Computational Modelling and Experimental Investigation of Silica Particle Transport and Deposition Occurring in Superheated Geothermal Steam

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ABSTRACT

The work presents the application of an advection-diffusion model for predicting precipitated silica transport and deposition occurring in superheated geothermal steam. The computational model takes into account the effect of Brownian and turbulent diffusion, turbophoresis, lift and drag force on particle motion. The simulation results were verified with experimental measurements for particles ranging from 1- 20 μm in diameter. The model simulation shows agreement with the measured data. An increase in deposition velocity in diffusion-impaction regime is observed, signifying silica particle agglomeration as an important factor controlling deposition.

1. INTRODUCTION

Superheated steam extracted from deep geothermal systems offers the potential to extract greater power output than from conventional geothermal systems. Utilizing steam in the superheated state makes it possible to attain high turbine efficiency as guided by Baumann rule (DiPippo, 2008), thus adding to work output. Utilization of the superheated steam, however, faces a challenge due to the high concentration of silica dissolved in the superheated steam. Presence of high silica concentration in superheated steam was reported in the IDDP-1 well which was drilled as a part of Icelandic Deep Drilling Project (Palsson et al, 2014). An amount of 66 ppm of precipitated silica was measured in IDDP-1 (Markusson and Hauksson, 2015). The maximum concentration of silica in the superheated steam can be approximated by its solubility in the geothermal fluid at a maximum pressure corresponding to the reservoir conditions. Figure 1 (a) shows the solubility of amorphous and quartz silica as a function of temperature and pressure obtained from simulation done in MATLAB using a thermodynamic model proposed by Karsek et al. (2013). As shown by figure 1(b), the silica solubility increases with an increase in pressure near to supercritical region.

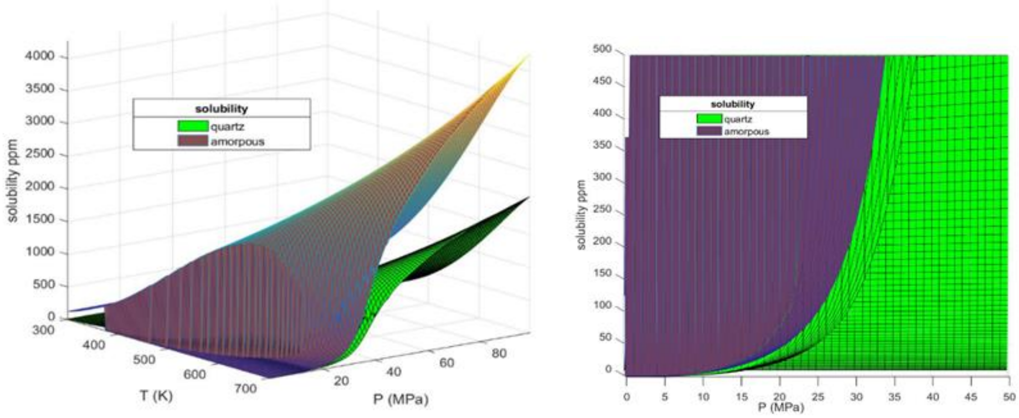

Figure 1: Amorphous and Quartz solubility at different temperature and pressure: (a) Isometric view; (b) right hand view

Research and development on utilizing geothermal fluid with steam in the superheated state is quite recent. The theory of silica precipitation occurring in superheated steam as observed in IDDP-1 is yet to be developed. It is supposed that silica occurs in dissolved gaseous phase in superheated steam due to high pressure and gets precipitated when lowering down the pressure. For the flow involving silica in superheated steam, modeling the silica particle transport in superheated steam can help in understanding the process of silica deposition occurring in the later stages after precipitation and the factors controlling it. A study of scaling under controlled hydrodynamic conditions was done by Brown and Dunstall (2000) to understand the effect of different hydrodynamic parameters on particle transport. The study shows that the effect of scaling increases with an increase in particle diameter. The study, however, does not provide a definite theory or model to predict the silica scaling rate.

A better insight into the mechanism of silica particle transport and deposition can be obtained using Computational Fluid Dynamics (CFD). Due to applications involving gas-particle flows in many engineering and scientific works, considerable progress has been made by the researchers in modeling of two-phase flows. The first model called free flight model for predicting deposition of particles suspended in gas flow was introduced by Freidlander (1957). The model assumes particle motion by diffusion up to certain distance called stop distance and then free flight towards the wall. The model predicts a monotonic increase in particle deposition with an increase in particle relaxation time, a characteristic of a particle in fluid flow, proportional to the its size and flow velocity. This contradicts the results from the experimental measurement for higher relaxation time (Liu & Aggarwal, 1974). A simplified Eulerian model called the diffusion-inertia model was developed for isothermal flows (Zaichik et al., 1997a) and for flows involving heat transfer (Zaichik et al., 1997b) with low inertia particles. Later improvements were made in the model by two way-coupling to include back effects of particles on the fluid (Zaichik et al., 2010). The model suffers, however, from the disadvantage of application to low inertia particles only. A two-fluid model using the advection-diffusion equation was applied by Johansen (1991) for modeling particle deposition on a vertical wall. The equations for the advection-diffusion model were later simplified by uncoupling the advection-diffusion equation from the equation for mean particle velocity, shown in the independent work done by both Guha (1997) and Young and Leeming (1997). The advection-diffusion model takes into account the major mechanisms contributing to deposition such as Brownian and turbulent diffusion, turbophoresis, Saffman lift, and electrostatic forces. The present work applies the advection-diffusion model for studying silica particle deposition in superheated steam flow. The work uses OpenFoam (OpenFOAM, 2014), an open-source package as a platform for implementing the model. Continuum equations for particle flow were written in OpenFoam notation and existing turbulence models and solvers in the software were used to solve for the required fluid flow variables.

It is important to validate experimentally the applied two-phase flow computational model, for its application in to silica particles in superheated steam flow. Experiments were therefore performed for validating the results from the computation model. Extensive experimental studies on particle deposition in vertical tubes with airflow available in the literature (Lee and Gieseke, 1994), were used to inform the design of experiments within this study. The current experimental setup was designed and constructed to determine silica deposition in superheated steam flow for different relaxation times. The experimental measurements were compared to data from the literature regarding particles in airflow with similar relaxation time range as well as the computational model simulation.

2. COMPUTATIONAL MODEL

The implemented advection-diffusion model uses available solver in OpenFoam for simulating gas phase (steam) flow. The details of the gas phase flow equations are available in the literature (OpenFoam, 2014). For modeling turbulence in a gas flow, commonly used two-equation k-ε model available in OpenFoam was selected. For modeling particle (silica) phase, density-weighted averaged equations derived in the work of Slater and Young (2003) were used. The final equations are written as:

$$\frac{\partial \bar{c}_p}{\partial t} + \frac{\partial (c_p \bar{v}_i^c)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[(D_B + D_T)\frac{\partial \bar{c}_p}{\partial x_i}\right] \tag{1}$$

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

where $\bar{u_j}$ is the Reynolds averaged fluid velocity along direction j, c_p is the particle concentration in mass per unit volume, ρ_f is the density of the fluid, $\bar{v}_i^c$ is the density-averaged particle convective velocity, D_B is the coefficient of Brownian diffusion, D_T is the coefficient of turbulent diffusion and χ is the ratio of particle mean square velocity to the fluid mean square velocity. The detailed expressions for the coefficients are available in the literature (Slater and Young, 2003). The particle relaxation time τ_p for the Stokes regime is expressed as:

$$\tau_p = \frac{2\rho_p r_p^2}{9\mu_f} \tag{3}$$

where ρ_p and r_p are the density and radius of a particle, respectively, and μ_f is the dynamic viscosity of the fluid.

3. EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup, shown in figure 2, consists of an 18kW boiler for steam generation, a cyclone separator (S_1) for removing moisture, a 500W superheater (SH), an ejector and screw feeder assembly for particle injection, a cyclone separator (S_2) for removing bigger size particles. Also, it has a test section assembly consisting of 1.5 long concentric pipe section for measuring silica particle flux towards the pipe surface. An additional assembly consisting of a probe having a length of 10 cm and diameter of 3.65 mm, sharpened at the front and other end connected to a cone-shaped flask was used for collecting particles from the flow. The flow rate through the sampling flask is measured by condensing the steam flow using condenser C_1. The particles were collected on a membrane filter placed in the cone flask. The measured concentration of the collected particles on the filter paper was used to calculate the mean flow concentration in the flow. The superheated steam coming out of the test section was condensed by passing it through a condenser heat exchanger (C_2) and then collected for measuring the flow rate. The system was well insulated and heated using heating tape to avoid heat loss from the flow.

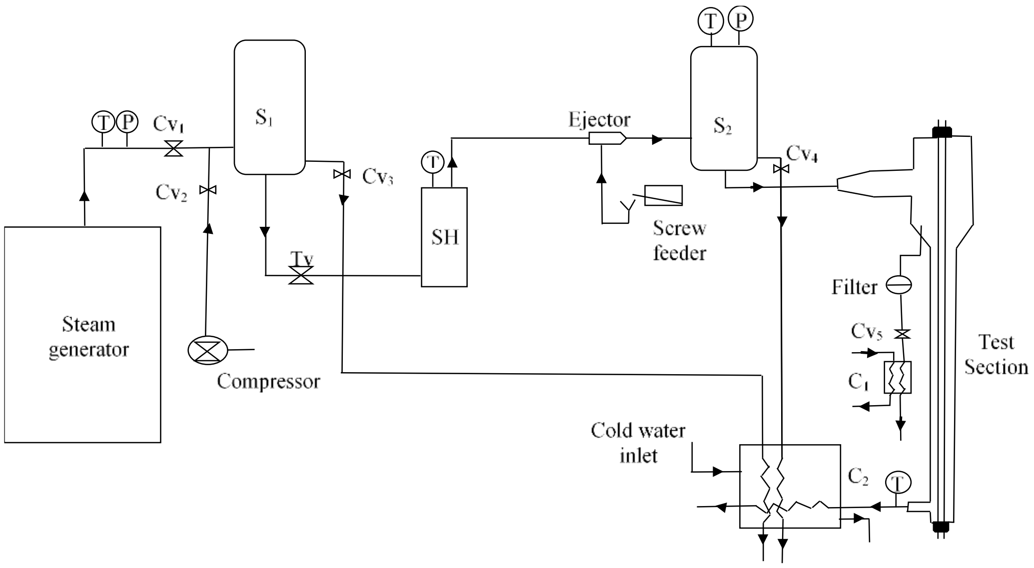

Figure 2: Schematic diagram of the experimental setup

The measurements were done with steam running at a constant mass flow rate of 150 g min^{-1}. The superheated steam at the inlet of the test section was at 160℃ and 1.4 bar abs. The two-phase mixture therefore had a considerable degree of superheat at the inlet of the test section. The flow had a Reynolds number of 3800. The particles used in the experiment were silica fume of density 2200 kgm^{-3} and with 97% purity. The experiment was run using steam and particles for an average duration of an hour after a steady state is achieved. The steam flow and particle injection were then shut down and air was run for a few seconds to remove all steam from the test section to avoid condensation upon cooling. The deposited particles were collected on the polished surface of the inner pipe of the test section, coated with a polytetrafluoroethylene (PTFE) lubricant. The lubricant is thermally stable and insoluble in water. The coating caused a decrease in the coefficient of restitution and an increase in the energy loss of particles striking the surface, hence reducing the effect of rebound or re-entrainment.

For measuring particle concentration on the surface of the pipe, a particle sampling and counting technique using a digital microscope and image processing, as described by Kvasnak et al. (1993), was used. The particle flux J_w on the pipe wall is calculated using the following equation:

$$J_w = \frac{N_w}{t\, A_{image}} \tag{4}$$

where N_w is the number of particles of a specific size on the surface image, A_{image} is the area of image and t is the time duration of the sampling.

The mean flow concentration of the particles is obtained using the following equation:

$$\bar{c}_p = \frac{N_{filter}A_{filter}}{A_{image}A_{probe}} \frac{1}{t\, V_{probe}} \tag{5}$$

where N_{filter} is the number of particles of a specific size on the filter paper image, A_{filter} is the filter area, A_{probe} is the inlet cross section area of the probe and V_{probe} is the flow velocity through the probe measured by condensing the superheated steam passing through the probe.

The non-dimensional deposition velocity is then given by:

$$V_+ = \frac{J_w}{u^* \bar{c}_p} \tag{6}$$

where $\bar{c}_p$ is the mean particle concentration and u^* is the friction velocity, defined as:

$$u^* = V_{av}\sqrt{\frac{f}{2}} \tag{7}$$

where V_{av} is the average fluid velocity and f is the Fanning friction factor calculated using Blasius law for turbulent flows and smooth walls.

The non-dimensional particle relaxation time is given by:

$$\tau_+ = \frac{\tau_p u^{*2}}{\nu_f} \tag{8}$$

where τ_p is the particle relaxation time and ν_f is the kinematic viscosity of the fluid.

4. RESULTS AND DISCUSSION

Figure 3 shows the result from the simulation and experimental measurements for the variation of deposition velocity with particle relaxation time. Results from the experiment for silica particle deposition in superheated steam was compared with the data from the literature for aerosol deposition in airflow by normalizing the relaxation time. The simulation result shown by the curved line in the figure distinguishes three different regimes of deposition. First, the turbulent diffusion regime (the left on the graph) where mainly Brownian and turbulent diffusion causes deposition. The regime shows slight decrease in deposition velocity with increase in relaxation time due to decreased effect of Brownian motion with increase in particle size. Second, the diffusion-impaction regime (middle on the graph) where deposition occurring mainly due to impaction caused by lift and turbophoresis. The deposition in this regime increases exponentially with an increase in relaxation time. The deposition in this regime occurs due to the particles trapped in the flow eddies which are carried towards the wall because of the turbulence gradient. Third (the right on the graph), the inertia regime where deposition is mainly governed by particle inertia. The particles size in this regime are too large and become sluggish to respond to the turbulent gradient, causing reduced deposition. The data from the experimental measurements correspond to the diffusion-impaction regime. An exponential increase in deposition velocity in this regime shows the influence of particle relaxation time on the deposition. The results from the experiment shows lower value of deposition velocity for a given relaxation time as compared to that from the simulation. This can be explained based on the projected area diameter measured, assuming shape of the particle to be spherical. In reality, the larger size particles formed by agglomeration are supposed to form different shapes such as disk etc., having lower value of relaxation time than obtained in the calculation. For silica precipitated in superheated geothermal steam, increase in particle size or relaxation time due to agglomeration can, therefore, increase scaling significantly.

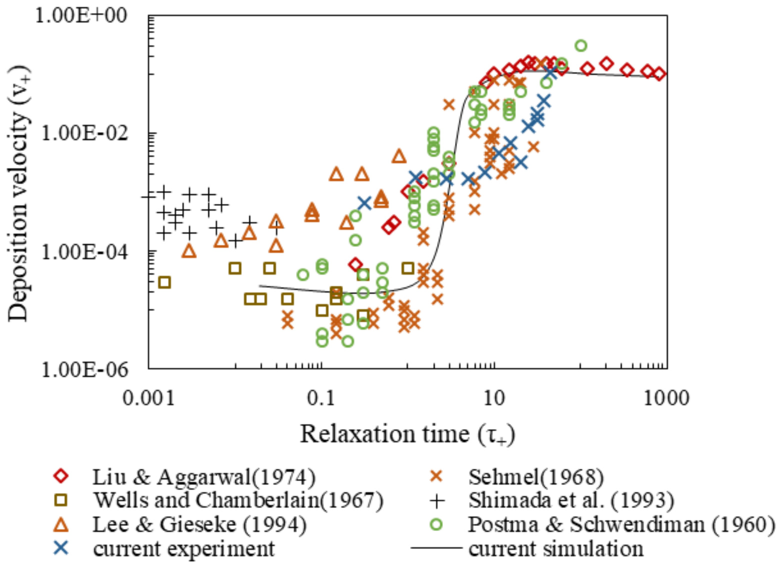

Figure 3: Variation of non-dimensional deposition velocity with non-dimensional particle relaxation time

Figure 4 shows the simulation results for the variation of non-dimensional silica particle concentration, wall normal velocity and forces per unit mass along the wall normal distance for different dimensionless particle relaxation times. As seen from the figure, the silica particle concentration near the wall first increases (fig. (4a), fig. (4b)) and then decreases (fig. (4c), fig. (4d)) with an increase in particle relaxation time. Very small particles are well distributed due to Brownian motion. The presences of turbulence increases particle concentration near the wall which can be observed as Brownian effect decreases due to an increase in particle size. With further increase in particle size, the concentration next to the wall decreases as particles become too sluggish to have a longer response during an eddy's lifetime.

The wall normal particle velocity increases continuously with an increase in particle relaxation time. For low relaxation times, flux towards the wall is mainly due to diffusion, as shown by concentration gradient near the wall (fig. (4a), fig. (4b)). The turbophoretic force provides acceleration to particles against the direction of viscous drag. For higher relaxation times, lift forces increase causing the convective velocity of silica particles towards the wall to increase. In this range, the particle motion is mainly governed by impaction (fig. (4c), fig. (4d)). The negative value of velocity and forces in the graph represents the direction towards the wall. The net particle acceleration can be obtained by subtracting the drag force from the sum of all forces acting towards the wall.

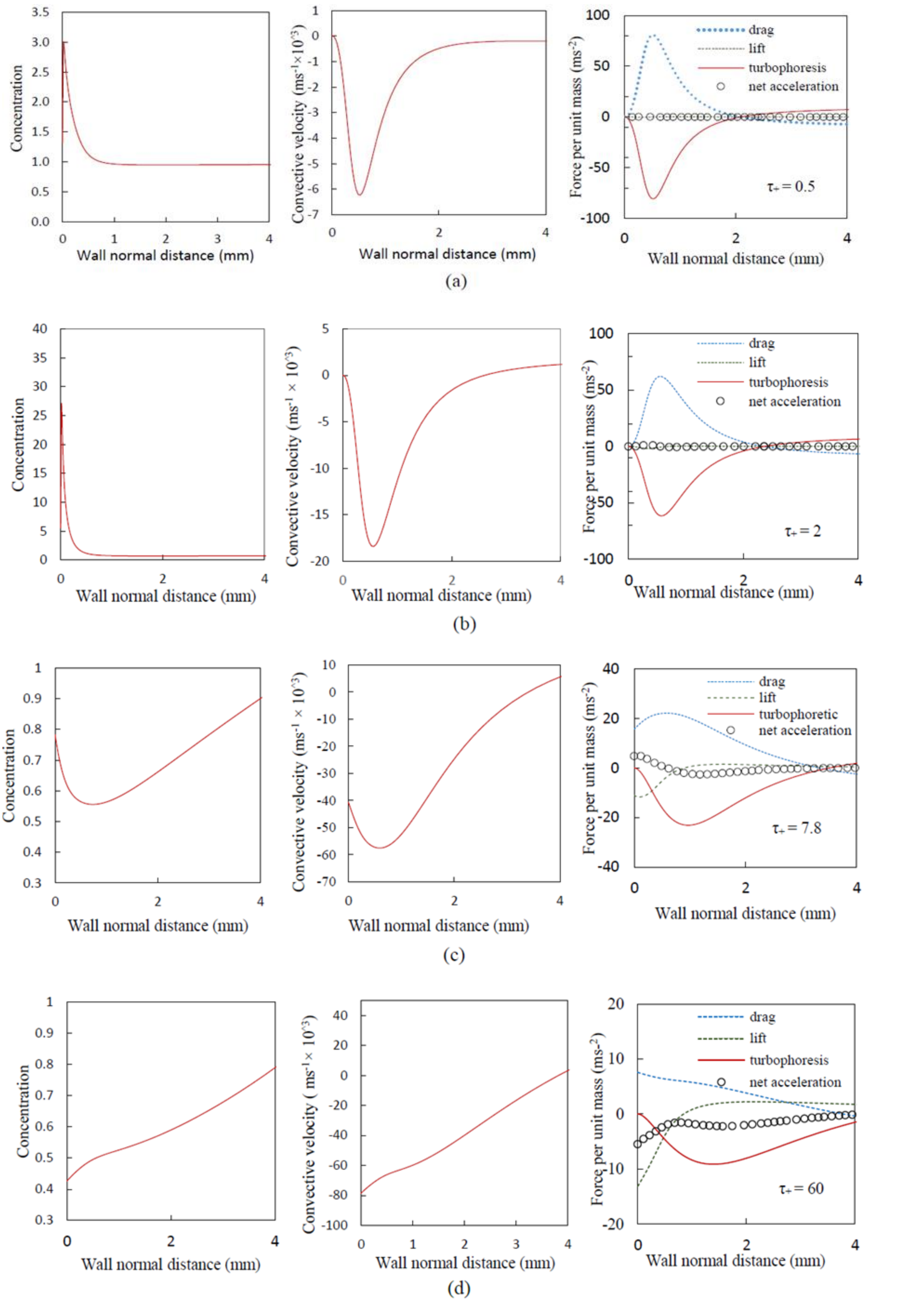

Figure 4: Particle concentration non-dimensionalized by bulk mean concentration ($\bar{c}_p$), Wall normal velocity and Forces per unit mass for different dimensionless particle relaxation times (a) 0.5 (b) 2.0 (c) 7.8 (d) 60

5. CONCLUSION

Silica particle transport and deposition in superheated steam flow was studied using computer simulation and experiments. Results shows effect of different forces contributing to silica particle flux towards the wall. The deposition velocity is found to be increasing exponentially with increase in the particle relaxation time in the diffusion-impaction regime thus showing the effect of silica particle agglomeration on deposition. This shows possibility to control deposition by controlling the particle agglomeration. The work shows the applicability of the advection-diffusion model for the design and analysis of geothermal systems consisting of silica in superheated steam.

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