Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Aqueous Potassium Carbonate Droplets Injection in Superheated Steam Flow: Computational Modelling and Experimental Investigation

Gudrun Saevarsdottir, Vijay Chauhan, Maria Gudjonsdottir

School of Science and Engineering, Reykjavik University, Menntavegur 1, 101 Reykjavík, Iceland

gudrunsa@ru.is

Keywords: CFD; flashing; geothermal; two-phase flow

ABSTRACT

Particulate and acid gas scrubbing from geothermal steam can be achieved without considerable loss in the fluid superheat by using aqueous potassium carbonate solution with high boiling point elevation as a scrubbing medium. This work presents a discrete phase model using Euler-Lagrangian approach for simulating the behavior of aqueous potassium carbonate droplets in superheated steam flow. The model takes into account the effect of salt concentration on boiling point elevation and density of the solution. The simulation results from the model were validated using results from experiments. Results from the simulation were in accordance with experimental results, where an increase in boiling point elevation with an increase in injected salt solution concentration was observed.

1. INTRODUCTION

Utilization of superheated geothermal steam offers an opportunity to extract high power output with greater turbine efficiency (DiPippo, 2008). The superheated geothermal steam extracted from high enthalpy unconventional geothermal systems, however, contains acid gas and solid particulate impurities (Armannsson et al., 2014). The superheated steam, therefore, requires scrubbing before utilization. Several methods have been proposed by researchers for mitigating impurities from the superheated steam (Hjartarson et al., 2014). The methods, however, have a drawback in terms of their ability to mitigate both acid gas and solid impurities simultaneously while retaining the steam superheat. An effective way of treating superheated geothermal steam using aqueous potassium carbonate as a scrubbing medium was proposed by Chauhan et al. (2018). The method offers the advantage of scrubbing steam without significant loss in its superheat. The actual degree of superheat attained by the droplets without precipitation, however, depends upon factors such as droplet concentration, droplet-steam volumetric ratio, temperature and residence time in the superheated steam flow. A detailed analysis of the process is therefore required to know the actual performance of the system.

A better understanding of a two-phase flow system with liquid droplets in steam can be obtained using computational fluid dynamics (CFD). For modeling of two-phase flow, two distinct approaches can be followed: Euler-Euler approach in which both phases are assumed as continuous and Eulerian-Langrangian approach in which one phase is assumed continuous and the other as dispersed. A two-fluid model based on Eulerian-Eulerian approach was used by Srikantiah and Wang (1989) to study the general behavior of a two-phase flow consisting of steam and water in a separator. The application is, however, limited to the study of qualitative phenomena in the separator in terms of the quality of steam. For the case of wet scrubbing, liquid droplets exist as a dispersed phase in the steam. A detailed description of different phases and their interaction thus require Eulerian-Lagrangian approach for modeling. The approach consists of fluid flow equations as the continuous phase in the Eulerian field and the particles or the droplets are tracked independently in the Lagrangian field.

Nakeo et al.(1993) published a paper about the application of Eulerian-Lagrangian approach for studying the boiler water reactor dryer and a separator. The work uses a three-dimensional dispersed phase code for the analysis. Later, improvements in the model were made by Nakeo et al. (1998) by taking the effect of droplet diameter into consideration. Another work from Jia et al. (2007) describes the application of Eulerian-Lagrangian approach for studying the droplet behavior in a wave-type flow channel of a separator. Effect of droplet generation due to impingement on the wall was taken into consideration. Study on injection of droplets in superheated steam was done by Frydman et al. (1999). The model considers the effect of droplet heating and evaporation and is able to predict features such as temperature, flow velocity, droplet trajectories and deposition on the wall.

Simulating the process of aqueous salt solution droplets injection in superheated steam requires modeling an additional effect of salt solution concentration on boiling point elevation as discussed before. A thermodynamic model for calculating the boiling point elevation as a function of the concentration of the salt in the aqueous solution and temperature was presented by Chauhan et al. (2018). The current work presents Computation Fluid Dynamics (CFD) model development for simulating aqueous potassium carbonate droplets in superheated steam using OpenFoam (OpenFOAM, 2018) an opensource software. The work uses *sprayFoam* an existing model in OpenFoam as a base model and is modified further. To include the effect of droplet salt concentration, model from Chauhan et al. (2018) is implemented into the available CFD model. Available libraries for thermophysical properties of water are extended and modified as per the case study requirement. For validating the CFD model, experiments were carried out by injecting salt solution at different concentrations into the superheated steam and then measuring the steam temperature and salt concentration at the separator bottom.

2. PHYSICAL MODEL

The solver named *sprayFoam* in OpenFoam uses Eulerian approach for the gas phase and Lagrangian approach for the dispersed phase droplets. Modeling the gas phase (which in this study is the superheated steam) requires conservation equations for mass, momentum and energy. The discrete phase droplets require additional equations for breakup, dispersion, and evaporation. In addition the effect of salt concentration in the droplet needs to be considered. The model requires two-way coupling to include the effect of one phase on the other. The equations for the model are as follows:

2.1 Equations for the gas phase

The conservation equations for mass, momentum and energy for the gas phase are as follows:

$$\frac{\partial \rho_s}{\partial t} + \nabla \cdot \rho_s V_s = S_M \tag{1}$$

$$\frac{\partial \rho_s V_s}{\partial t} + \nabla \cdot (\rho_s V_s V_s) = \nabla \cdot \mu_{eff} \nabla V_s + \nabla \cdot \mu_{eff} \left[(\nabla V_s)^T - \frac{2}{3} tr((\nabla V_s)^T) I\right] + \rho_s g - \nabla p + S_V \tag{2}$$

$$\frac{\partial \rho_s H_s}{\partial t} + \nabla \cdot (\rho_s V_s H_s) = \nabla \cdot \lambda_{eff} \nabla H_s + \frac{Dp}{Dt} + S_H \tag{3}$$

where ρ_s and V_s are the respective density and velocity of steam, μ_{eff} is the effective dynamic viscosity, g is the acceleration due to gravity, p is the pressure, tr is the trance operator, I is the Identity matrix, T is the transpose operator and S_M, S_V *and* S_H are the source term for the mass, momentum and energy.

2.2 Equations for the dispersed phase

The droplet momentum, heat and mass balance equations are given as:

$$m_d \frac{d\vec{V}_d}{dt} = \vec{F}_D + \vec{F}_g \tag{4}$$

$$m_d \frac{dT}{dt} = hA_d(T_s - T_d) \tag{5}$$

$$\Delta H_v \frac{dm_d}{dt} = hA_d(T_s - T_d) \tag{6}$$

where m_d, V_d, T_d, and A_d are the respective droplet mass, velocity, temperature and surface area of the droplet, h is the heat transfer coefficient, ΔH_v is the latent heat of vaporization for water and F_D and F_g are the drag and net force due to gravitation and buoyancy. The expression for the forces can be found in the literature (Zhou et al., 2018).

To model the effect of salt concentration on droplet boiling point elevation, model from Chauhan et al. (2018) and is followed. To calculate the change in salt solution density, relation for the concentration dependence of the relative density is obtained using curve fit for the data from Liley et al., (1999).

3. EXPERIMENTAL SETUP AND PROCEDURE

Figure 1 shows the schematic diagram of the setup. The system consists of two sub-systems: Steam generating system and a salt solution injection system. The steam generating system consists of an 18kW electric boiler, used for generating steam and a cyclone separator (S_1) and a 500W superheat (SH) used to make the steam superheated. The salt injection system consists of a peristaltic pump and a Peas-Anthony type venturi unit. The salt injection is done at the throat section of the venturi unit using a cone shape injector connected to the peristaltic pump. The salt solution droplets are separated from the steam using a cyclone separator (S_2) placed after the venturi unit.

For performing experiments, wet steam was generated using an 18 kW heating capacity boiler and was made dry by passing it through a cyclone separator (S_1) and a throttle valve (T_v). The steam was then passed through a 500W superheater (SH) to attain superheat. Aqueous potassium carbonate solution was injected using a variable speed peristaltic pump into a venturi tube attached along the steam flow line. The venturi unit consists of a cone orifice at the throat section for solution injection. Injected solution droplets brake and disperse because of momentum exchange with the high-velocity steam and turbulence occurring due to the narrow throat section of the venturi. The salt solution droplets get collected at the bottom of the cyclone separator (S_2). The separated steam was passed through the condenser (C_1) for condensation in order to measure the flow rate before disposal. The system was well insulated to minimize heat loss, which could cause condensation. The experiment is carried out by injecting salt solution at a constant volume rate of 3.6 ml min^{-1} with concentration values of 0.02, 1.1, 1.81, 3.41 and 5.27 in mol kg^{-1} respectively. The inlet steam temperature and pressure after the superheater is 148℃ and 2.6 bar respectively. The steam flow velocity is 15 ms^{-1}. Temperature measurements are done at the separator bottom after a steady state is observed. The salt solution droplets are sampled after each run and the solution concentration measured with inductively coupled plasma atomic emission spectroscopy (ICP).

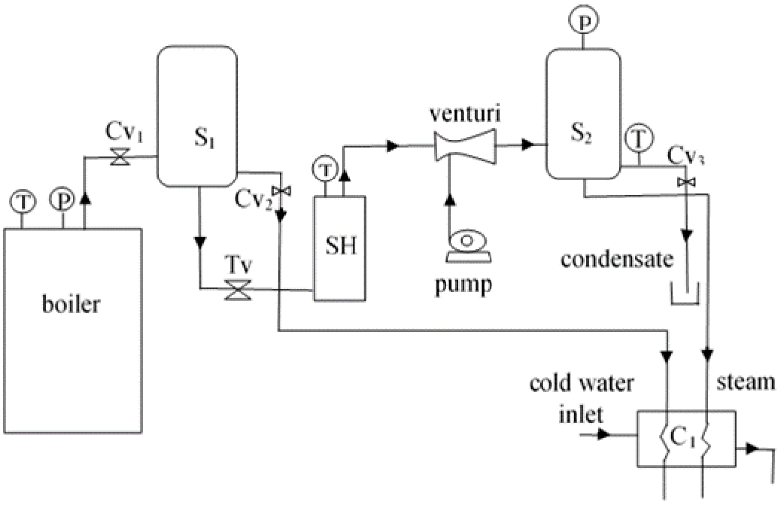

Figure 1: Schematic diagram of the experimental setup

4. SIMULATION METHOD

Figure 2 shows the geometry and the mesh structure for the model simulation. Table 1 shows the dimensions of the geometry. The work uses k-ε model for turbulence modeling in the gas phase. The simulation assumes rebounding wall boundary conditions for the droplets. Zero gradient for temperature and velocity are assumed at the wall for the gas phase, which infers that the system is adiabatic.

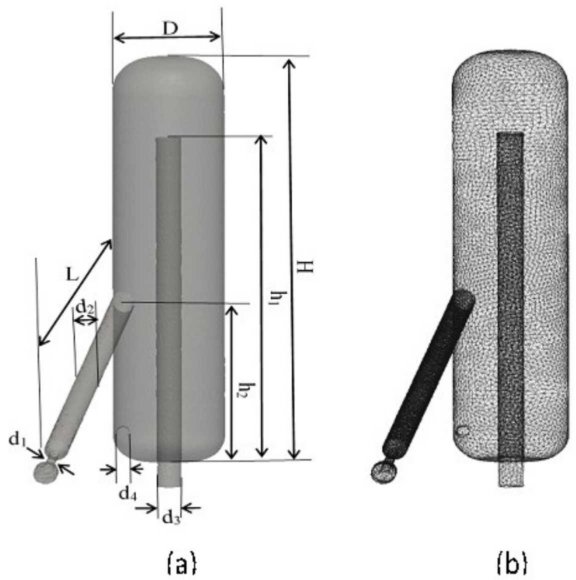

Figure 2: Schematic and grid representation of the injection and separation assembly considered: (a) 3D view of the geometry (b) 3D view of the CFD grids

Table 1: Geometry of the injection and separation system (D = 70 mm)

H/D	d_1/D	d_2/D	d_3/D	d_4/D	h_1/H	h_2/H	L/D
4.28	0.02	0.05	0.05	0.0266	0.4	0.8	5

5. RESULT

The model requires grid independence verification and validation before application. To verify grid independence, simulations were run for three different mesh grids of size 45082, 57698 and 70970 and change in temperature after the start of injection was observed. The effect of mesh refinement on temperature development is shown in Figure 3 (Left), It can be seen that the temperature increases as the number of cells increases from 45082, but very little difference is observed as the grid is refined further by increasing cell number to 70970. Thus A grid size with 70970 cells is selected for the simulation. The model validation was done by comparing the steady state temperature at the separator bottom obtained from the simulation with that from the experiments for different injection concentrations of the salt solution. As shown in Figure 3 (right), results from the simulation show good agreement with the experimental measurements, thus verifying the physical model.

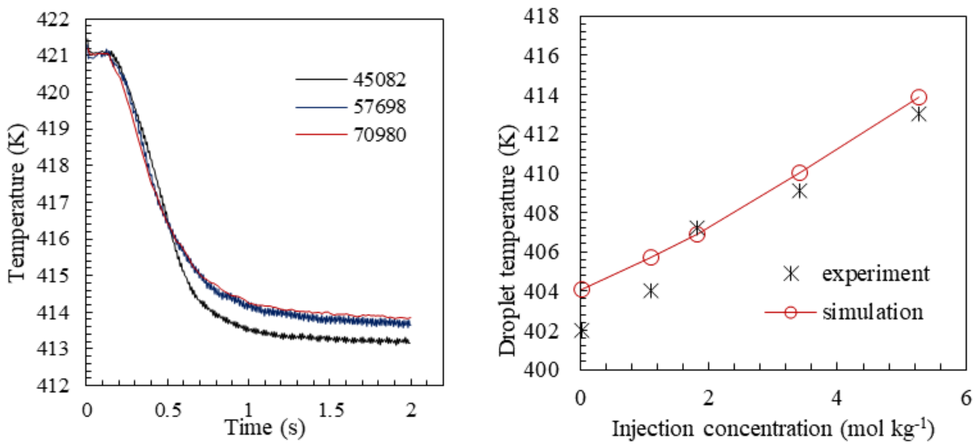

Figure 3: (Left) Grid independence verification (Right) Simulation and experimental results for the steady-state temperature

A better insight into the process of injecting aqueous potassium carbonate droplets in superheated steam can be obtained from the study of temperature and concentration fields in the geometry. Figure 4 shows the temperature profile of the separator at a steady state for different injection salt solution concentrations. As shown in the figure, an increase in the concentration of the injected salt solution causes an overall increase in the separator temperature. This occurs due to an increase in the boiling point elevation of the injected solution due to the increase in salt concentration, thus reducing heat transfer from the superheated steam to the droplets. The variation in temperature can be observed more clearly from the temperature profile at the bottom of the separator, as shown in figure 4.

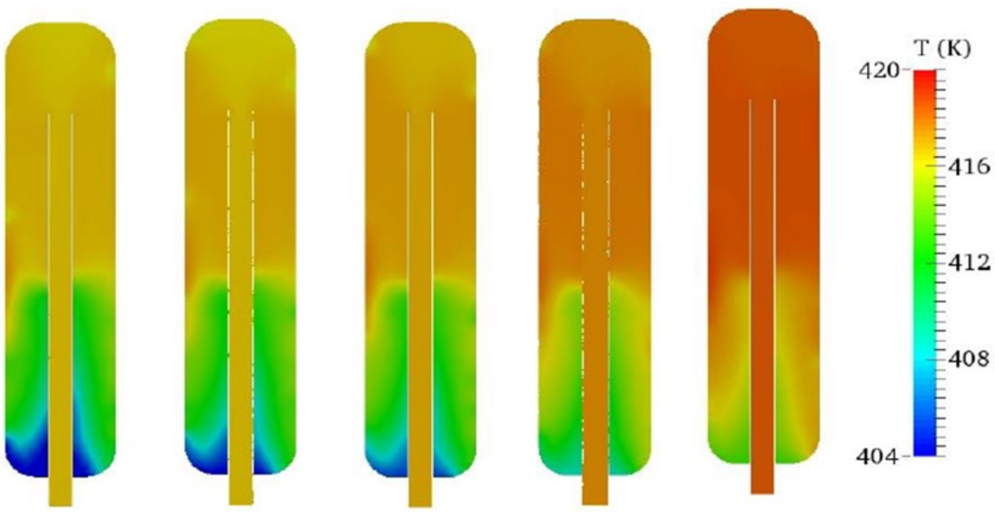

Figure 4: Steady-state temperature fields in the separator for different injected K_2CO_3 concentrations: (a) 0.02 mol kg-1 (b) 1.1 mol kg-1 (c) 1.81 mol kg-1 (d) 3.41 mol kg-1 (e) 5.27 mol kg-1

Figure 5 shows the profiles for the injected droplets salt concentration. As shown in the figure, the droplet salt concentration increases along the flow. This occurs due to the mass of water evaporating from the droplet as it flows, which causes the concentration of the salt in the droplet to increase.

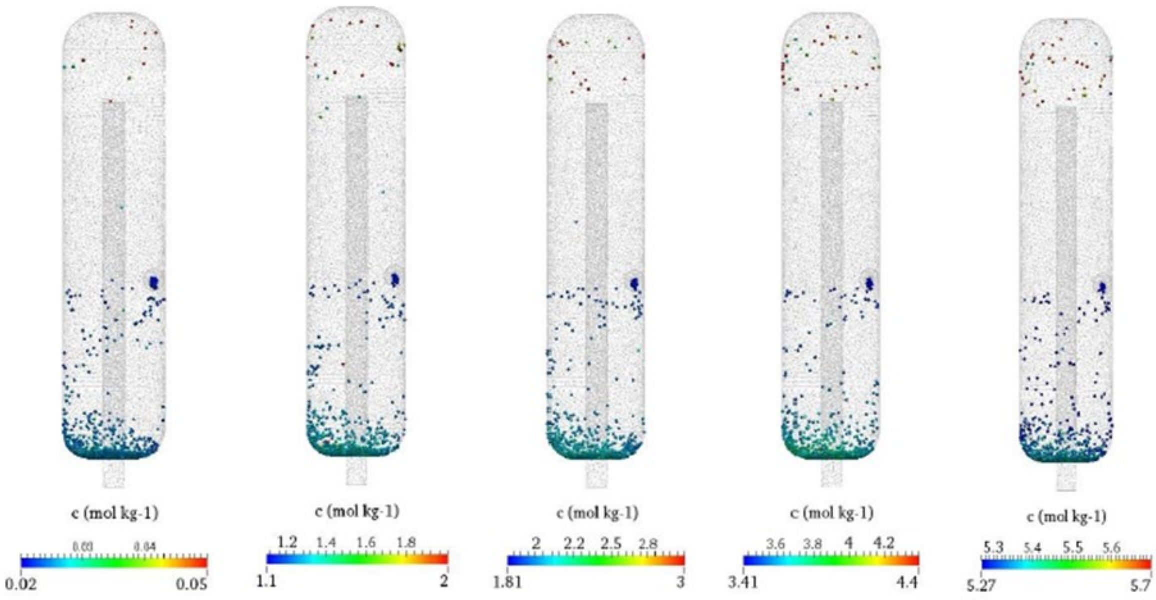

Figure 5: Droplet K_2CO_3 salt concentration along the flow for different injection concentration: (a) 0.02 mol kg-1 (b) 1.1 mol kg-1 (c) 1.81 mol kg-1 (d) 3.41 mol kg-1 (e) 5.27 mol kg-1

Simulation results for the salt concentration in the droplets collected at the bottom of the separator were compared with that obtained from the experiment, shown in Figure 6. Results from the simulation show a deviation of up to 20%. The deviation is expected to occur due to rebounding wall boundary conditions assumed for the droplets. The actual impaction process of the salt solution droplets on the separator wall has chances to make the fraction of the droplets stick to the wall. The droplets sticking then have higher residence time for heat and mass exchange before falling down to the separator bottom by gravitation.

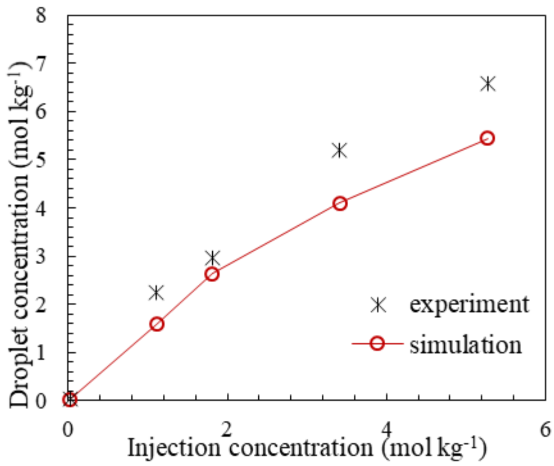

Figure 6: Concentration of K_2CO_3 in collected droplets with different injection concentration plotted along with results from computational simulations

6. CONCLUSION

A computational model was developed to simulate the behavior of droplets composed of an aqueous potassium carbonate solution, injected into superheated steam in the context of possible utilization of the aqueous salt solution for the scrubbing of superheated geothermal steam. The computation model was validated experimentally. Comparison of the model simulation from the experimental results for the separator temperature shows agreement up to a good extent. A deviation in the values of concentration measurement is observed may be attributed to the rebounding wall boundary conditions for the salt solution droplets. The results from the study indicate that the model can be applied for design of a scrubbing system with salt solution injection for superheated steam.

ACKNOWLEDGEMENTS

The work was funded by the Icelandic Research Fund through GEORG, Landsvirkjun, Reykjavik Energy, HS Orka, Orkustofnun and the IDDP project. The authors wish to thank Finnbogi Oskarrson and Iceland Geological Survey (ISOR) for providing valuable support and technical advice required for sample analysis.

REFERENCES

Armannsson, H., Fridriksson, T., Gudfinnsson, G.H., Olafsson, M., Oskarsson, F., Thorbjornsson, D.: IDDP—The chemistry of the IDDP-01 well fluids in relation to the geochemistry of the Krafla geothermal system, *Geothermics,* 49 (2014), 66-75.

Chauhan, V., Gudjonsdottir, M., Saevarsdottir, G.: Thermodynamic analysis of superheated geothermal steam scrubbing using aqueous potassium carbonate solution. *Geothermal Resources Council Transactions*, 42 (2018).

DiPippo, R.: Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact, *Second ed. Butterwort-Butterworth-Heinemann*, (2008).

Hjartarson, S., Sævarsdottir, G., Ingason, K., Palsson, B., Harvey, W.S., Palsson, H.: Utilization of the chloride bearing, superheated steam from IDDP-1, *Geothermics*, 49, (2014), 83–89.

Jia, L., Suyi, H., Xiaomo, W.: Numerical study of steam-water separators with wave-type vanes, *Chinese Journal of Chemical Engineering*, 15(4), (2007), 492-498.

Liley, P.E., Thomson, G.H., Friend, D.G., Daubert, T.E., Buck, E.: Section-2: Physical and Chemical Data In: Perry´s chemical engineers handbook, *7th ed. New York, NY: McGraw-Hill*, (1999).

Nakao, T., Sooma, H., Kawasaki, T., Sumida, I., Analysis of droplet behavior in a dryer with wave-type vanes. *Journal of Nuclear Science and Technology*, 30(12), (1993), 1303-1305.

Nakao, T., Saito, Y., Souma, H., Kawasaki, T., Aoyama, G.: Droplet behavior analysis in the BWR dryer and separator, *Journal of Nuclear Science and Technology*, 35(4), (1998), 286-293.

Frydman, A., Vasseur, J., Ducept, F., Sionneau, M., Moureh, J.: Simulation of spray drying in superheated steam using computational fluid dynamics. *Drying Technology: An International Journal*, 17, (1999), 1313-1326.

OpenFOAM, Userguide (2nd ed.) *OpenCFD Ltd*. (2014).

Srikantiah, G.S., Wang, S.S.: Numerical modeling of phase separation in steam separators by a three-dimensional two-fluid model, *Proceedings*, 4th International Topical Meeting on Nuclear Reactor Thermal-hydraulics, Karlsruhe, F.R.G., 1, (1989), 1031-1036.

Zhou, Z.F., Lu, G.Y., Chen, B.: Numerical study on the spray and thermal characteristics of R404A flashing spray using OpenFOAM, *International Journal of Heat and Mass Transfer*, 117, (2018), 1312-1321.