# Application of Aqueous Salt Solutions with High Boiling Point Elevation for Scrubbing Particulate and Acid Gas Impurities from Superheated Geothermal Steam

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## ABSTRACT

The boiling point elevation properties of certain aqueous salt solutions enable water droplets to stay in the liquid phase in superheated steam flow. This work describes how aqueous salt solutions with high boiling point elevation can be applied for scrubbing particulates and acid gas impurities from superheated geothermal steam. To demonstrate the validity of the proposed technique, an experimental investigation was carried out to study the performance of the scrubbing process for superheated steam. Aqueous potassium carbonate, which has high boiling elevation, was injected into superheated steam containing silica particulates, to study how effectively the particles were removed. Results from the experiments show an increase in the degree of superheat retained and an increase in scrubbing efficiency with increase in aqueous salt concentration.

## 1. INTRODUCTION

In the geothermal industry, the conventional method of removing acid chloride and solid-state impurities from steam is wet scrubbing, which is applied by injecting water or brine into the steam to form a two-phase mixture. The impurities are then removed along with the liquid phase in a separator. For HCl abatement from steam, caustic alkali is also used as a scrubbing medium. Details of the method used for HCl abatement in the geothermal power plant are discussed by Paglianti et al. (1996). Conventional wet scrubbing offers an effective way of removing acid gas or solid impurities from the steam. The conventional wet scrubbing of superheated steam, however, has one major drawback. The method results in a complete quenching of the steam superheat in order to form a two-phase mixture as required for the separation process. The quenching of steam superheat causes loss in power output due to reduced turbine efficiency (DiPippo, 2008).

Researchers have proposed various techniques for scrubbing steam in a dry state without quenching the superheat to obtain increased power output. Alternatives to traditional wet scrubbing for removing impurities from superheated steam were proposed by Fisher and Jung (1996). Three conceptual techniques were proposed for cleaning of superheated steam, i.e. dry scrubbing using agent by adsorption or absorption, oil washing and hybrid washing using the liquid/solid mixture. Experiments for dry scrubbing using amines and calcite bed absorption were made by Hirtz et al. (2002). An effective way of removing HCl from the steam was achieved with minor loss in superheat. The methods proposed in the literature provide alternatives for HCl abatement from the steam without loss of superheat. The analysis, however, does not take the presence of solid impurities such as silica into consideration. The silica present in the superheated steam precipitates as the solubility decreases with decreasing pressure. Utilization of superheated steam thus also requires a method to remove silica in addition to HCl gas impurities from the steam without loss in superheat.

An efficient way of scrubbing superheated steam without significant loss in its superheat can be achieved by the application of aqueous salt solutions having boiling point elevation properties as proposed by Weres and Kendrick (2010). The researchers suggested injection of aqueous potassium carbonate solution into a borehole for neutralizing acid gas impurities present in the dry geothermal steam. As described by Ge and Wang (2009), the salt decreases the vapor pressure of the water, causing boiling point elevation. Numerical model development and analysis for the calculation of lifetime of small water droplets containing sodium chloride in a high-pressure steam environment were done by Gardner (1981). The result shows a reduction in droplet evaporation due to the boiling point elevation caused by the salt concentration. For geothermal applications, Weres and Kendrick (2010) suggested aqueous potassium carbonate as an optimal scrubbing fluid for mitigating acid gas impurities from the dry geothermal steam. The boiling point elevation property enables the salt solution to stay in steam with a high degree of superheat without precipitation. Figure 1 shows a plot from Kamps et al. (2007) showing a fitted curve for the total pressure above aqueous solutions of potassium carbonate at different concentrations. The total vapor pressure above the aqueous solution shown by the logarithmic scale on the y-axis decreases with increase in salt solution concentration. Also, the total pressure drop is found to increase with an increase in saturation pressure.

Weres and Kendrick (2010) suggest the injection of aqueous potassium carbonate solution into boreholes for neutralizing acid gas. During the process of borehole injection, the hydrogen chloride gas present in the superheated steam on coming in contact with the salt solution droplet surface causes the following reaction to occur:

$$K_2CO_3(aq) + 2HCl \Rightarrow 2KCl(aq) + H_2O + CO_2 \tag{1}$$

Treatment by injecting the salt solution in boreholes as proposed by Weres and Kendrick (2010) works well for neutralizing acid chloride impurities without losing superheat. Injection in boreholes, however, suffers from two major drawbacks. First, eliminating potassium chloride formed as the by-product of the reaction shown by equation 1 is difficult. The potassium chloride by-product precipitates once the saturation limit is achieved, because of its low boiling point elevation. Second, the silica present in gaseous form is left untreated and precipitates whenever pressure drop occurs, hence adding to the problem of deposition. To overcome these drawbacks, Chauhan et al. (2018) proposed treatment of superheated steam using aqueous potassium carbonate above the surface and simultaneously removing the by-product and scrubbed impurities using a separation process.

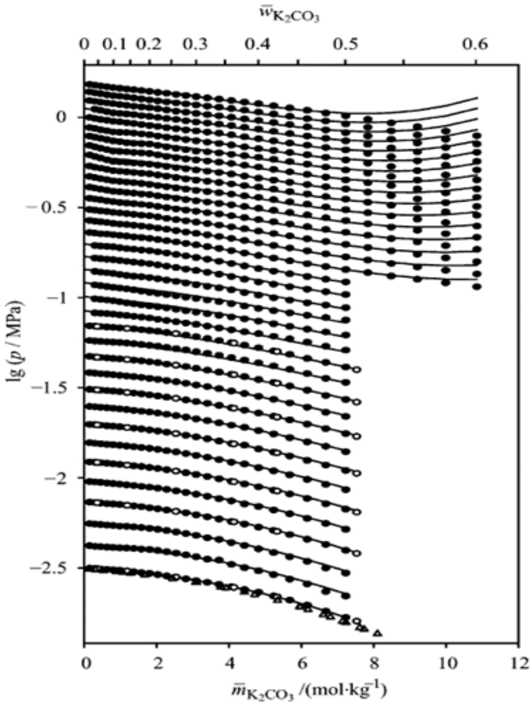


**Figure 1: Plot from Kamps et al. (2008) showing fitted curves for the total vapor pressure above aqueous solutions of potassium carbonate at different concentration: ● experimental data by Aseyev (1998); o experimental data from Puchkov and Kurochkina (1970); ▲isopiestic data by Sarbar el al. (1982)**

Scrubbing superheated steam above the surface follows similar processes and mechanisms for the neutralization of acid gas impurities as that of traditional wet scrubbing applied in the geothermal industry. The only difference lies in the scrubbing medium used. In the geothermal industry, HCl removal is done by applying wet scrubbing using caustic alkali. Details of the methods used for HCl abatement in the geothermal power plant are well described by Paglianti et al. (1996). The method using salt solution is thus supposed to deliver similar performance as that of wet scrubbing for acid gas removal and therefore not discussed any further. The other impurity to be taken into consideration is the silica. In this work the performance analysis of using salt solution for scrubbing silica particle impurities from the superheated steam is studied.

For solid impurities, scrubbing occurs by the mechanism of diffusion, interception and inertial impaction. The scrubbing efficiency for the process involving spraying liquid in a gaseous medium is governed by parameters and mechanisms such as droplet size, density, breakup, diffusion, collision, and dispersion. A detailed study of the effect of different parameters affecting scrubbing performance was published by Pak and Chang (2006). For scrubbing solid impurities from the superheated steam using salt solution, an additional parameter affecting the scrubbing performance is the salt concentration. A change in droplet salt concentration causes boiling point elevation and density to change. These parameters affect the scrubbing efficiency and the degree of superheat retained by the steam.

To study the effect of injected salt solution concentration on steam superheat and scrubbing efficiency, an experimental investigation of the scrubbing process was done. A laboratory scale setup was designed and constructed forthe experiment. Measurements were made for silica particle concentration, injected solute ion concentration at the endpoint and superheat retained for different solution injection concentrations.

## 2. EXPERIMENTAL SETUP AND PROCEDURE

The experimental system consists of three major sub-systems: steam generation and superheating system, particle feeding and injection assembly and salt solution injection system, as shown in Figure 2. An 18 kW Chromalox electric boiler was used for generating steam which was passed through a 500 W capacity Chromalox superheater (SH) to gain superheat. The system enables steam flow to gain superheat of up to 40 degrees at a pressure of 1.3 bar. Particle injection to the superheated steam is done with the help of a micro screw feeder and an ejector. The particles falling from the feeder are made to enter along with a small volume flow rate of air into the steam flow line using an ejector. The present work uses silica fume having a density of 2200 kgm$^{-3}$ and size range from 3μm to 20μm as a particle medium for the experiment. The silica fume resembles amorphous silica particles present in geothermal systems in terms of physical properties such as density and size distribution. The salt solution injection is done using a peristaltic pump which enables a constant volume rate of injection of the salt solution into the superheated steam. A Pease-Anthony type venturi with cone injection was placed along the steam flow line for this purpose. The salt solution droplets were injected in the throat section of the venturi where they should to break up and collide with the injected silica particles. The salt solution droplets along with the attached silica particles were separated using a cyclone separator placed after the venturi unit. To measure the concentration of silica and salt solution which remains unseparated from the superheated steam, a sampling probe was attached to the steam flow line after the cyclone separator. The endpoint of the probe was connected to the sampling flask with a condenser at the outlet to collect the incoming steam consisting of the leftover impurities.

The experimental setup is run with the steam flow in the beginning without silica particle and salt solution injection until a steady-state condition in terms of temperature and flow rate was obtained. Silica particle injection was then initiated at a constant feed rate.

Pure water without salt was then injected using the pump injection assembly in order to scrub the silica particles. This corresponds to the normal wet scrubbing method. Steady-state temperature was measured in the separator once the thermal equilibrium was achieved. Condensate sampling is done for 20 minutes which was used for measuring silica and salt concentration carried over with the steam after the separation in S2. The experiment was then run for different concentrations of aqueous potassium carbonate solution and a similar procedure was followed for sampling and measurement. The silica and salt concentration in the condensate was measured using inductively coupled plasma atomic emission spectroscopy.

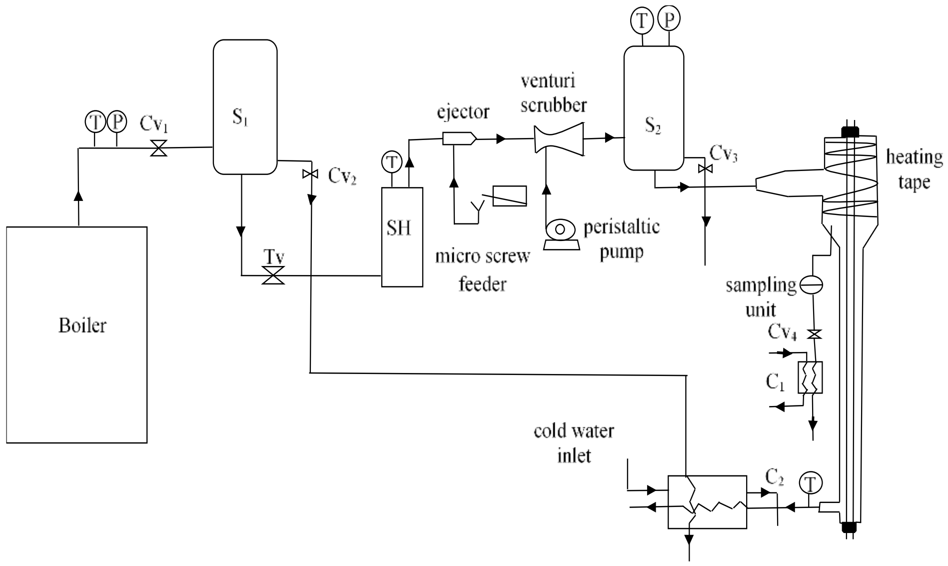


**Figure 2: Schematic diagram of the experimental setup**

## 4. RESULTS AND DISCUSSION

Measurements in of the degree of superheat retained, silica scrubbing efficiency and droplet separation efficiency were made during the experiment to evaluate the performance of the aqueous potassium carbonate solution as a scrubbing medium. Experiments were performed by injecting the salt solution with different concentrations. Figure 3 shows the variation of measured steam temperature in $S_2$ and the corresponding superheat retained by the steam with the concentration of the injected salt solution. The first point corresponds to the saturated state obtained during wet scrubbing by injecting sufficient amount of water droplets without any salt dissolved. The degree of superheat retained was found to increase with the injected salt solution concentration. Since the volume rate of salt solution injection was kept constant, as the salt concentration in the injected droplets increased, boiling point elevation increased. This caused less mass transfer due to evaporation from the droplets or less heat transfer from the superheated steam to the droplets, thus enabling steam temperature to retain a higher value. A maximum superheat of up to 34 degree was achieved during the experiment at a maximum injection concentration of 50%.

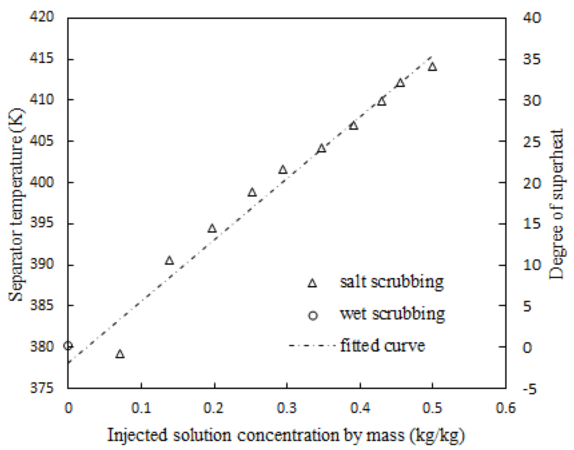


**Figure 3: Variation of steam temperature with injected solution concentration**

The concentration of the unseparated silica carried with the steam from the separator was measured in order to estimate the scrubbing efficiency for different injection concentrations. The silica concentration injected was kept constant at 40 ppm. Figure 4 (left) shows the measured silica concentration in the separated steam and the scrubbing efficiency (Figure 4, right) corresponding to the measured concentration for different injected salt solution concentrations. The first point on the figures corresponds to the silica concentration and the scrubbing efficiency obtained during wet scrubbing by injecting sufficient amount of water droplets without any salt dissolved. As shown in Figure 4 (right), the scrubbing efficiency was found to increase with the increase in the concentration of the injected salt solution. This can be explained by the fact that the increase in the concentration of salt in the injected droplets causes an increase in boiling point elevation, which further causes less evaporation in the droplets. The droplets, therefore, retain their size causing high droplet-steam volume ratio in the flow. This increases the scrubbing efficiency. Scrubbing efficiency of up to 99.5% is obtained at the maximum injected salt solution concentration of 0.5 kg/kg.

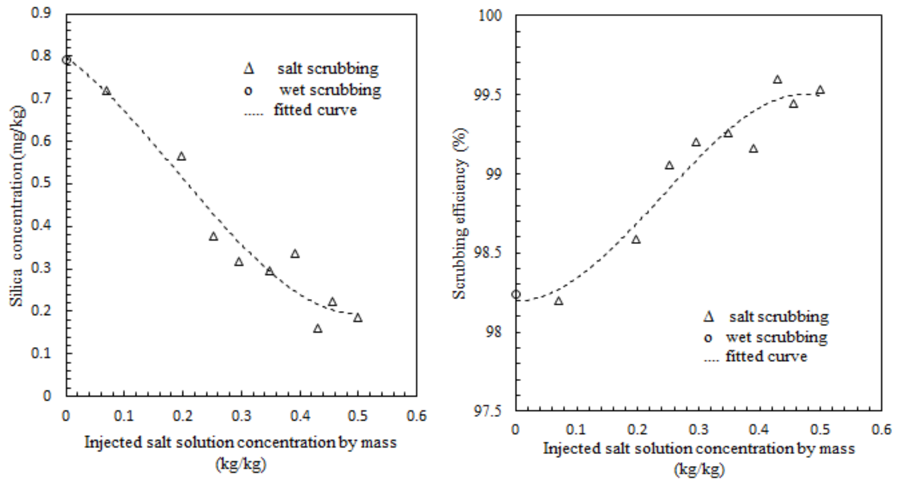


**Figure 4: Variation of silica concentration (left) after steam separation and scrubbing efficiency (right) obtained with injected solution concentration for a constant inlet silica concentration of 40ppm**

Salt solution concentration in the separated steam was measured to study the effect of change in injected salt concentration on droplet separation efficiency. As shown in Figure 5, the potassium ion concentration in the separated steam decreases with increase in injected salt solution concentration. The first point in the figure with very minute salt concentration corresponds to wet scrubbing using pure water without any salt dissolved. The salt solution concentration at the outlet is expected to increase with an increase in injected salt solution concentration. An opposite trend is, however, observed because of less reduction in the droplet size due to reduced evaporation with increasing boiling point elevation, as explained previously. Since the removal efficiency in the cyclone separator is proportional to the droplet size, the increase in mean droplet size causes an increase in droplet removal efficiency.

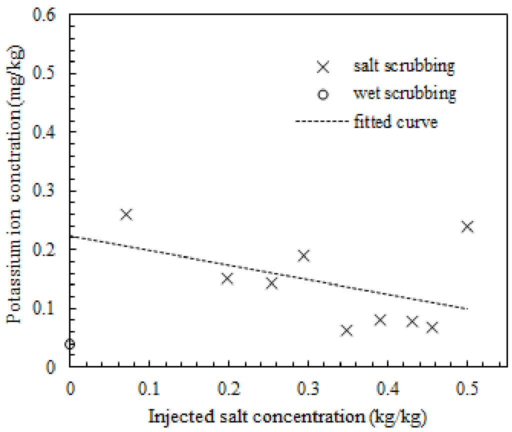


**Figure 5: Variation of Potassium ion concentration in the collected steam after separation with injected solution concentration**

## 5. CONCLUSION

The study shows how aqueous potassium carbonate can be an efficient scrubbing medium for removal of silica impurities. Experiments were done to evaluate the performance of aqueous potassium carbonate for scrubbing superheated steam. Measurement of the separator temperature during the experiment shows an increase in the degree of superheat retained with increasing injected salt solution concentration. Superheat of up to 34 degrees was achieved at the maximum injected salt solution concentration of 50%. Measurement for the silica particle concentration shows an increase in scrubbing efficiency with increase in injected salt solution concentration. A maximum scrubbing efficiency of 99.5% was obtained at maximum injected salt solution concentration. Measurement for the salt solution concentration in the separated steam shows a decrease in concentration or increased droplet removal efficiency with an increase in injected salt solution concentration. The overall study, therefore, shows aqueous potassium carbonate as an efficient scrubbing medium for removing impurities from the superheated steam. This potential method should be considered when acid gas, silica or other impurities need to be removed from superheated steam which can be the case when utilizing high enthalpy geothermal resources.

## ACKNOWLEDGEMENTS

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