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MODEL DEVELOPMENT OF SILICA SCALING PREDICTION ON BRINE FLOW PIPE

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ABSTRACT

Silica scaling is one of problems in the geothermal fields, where its deposition can occur in some geothermal power plant equipment such as pipe surface to the injection wells. Deposition of amorphous silica causes blockage in pipes that drain off the geothermal fluids, for example as happened in the pipes that drain off brine fluid from separator. Problems in the injection pipeline will disrupt the brine fluid to be injected back into the earth, whereas the importance of doing the injection brine is to maintain pressure in the reservoir and to prevent adverse effect on the environment.

Long distances from separator or pond to the injection well will affect to brine flow in the pipe. In the geothermal field that has high silica content, construction and insulator of pipe will change the temperature of brine. This condition has impact to changes solubility of silica contained in the brine. Changes of pressure and heat loss causes change in enthalpy and brine flow rate and decrease in the inner diameter of the pipe caused by deposition of silica. Currently attempting to build a prediction model of silica scaling based on physical changes of brine flow in pipe.

INTRODUCTION

To prevent the decline of mass production caused by the drop in the reservoir pressure is used injection techniques. Fluid injection is done with the aim of re-filling the pore volume of rock. In addition, fluid injection serves to prevent heat pollution and also chemical pollution on the environment caused by certain chemical constituents contained in the brine production. Location of injection wells are generally far from production wells, typically located at the reservoir boundary area. This is to avoid thermal breakthrough and drastic temperature drop in production wells (Sanyal et al, 1995).

Distance far from the injection wells and the pond from the separator will have an impact on the construction of a long pipeline. This condition will affect the brine saturation conditions in the pipe containing silica. Temperature decreases cause changes solubility of silica and silica scaling is likely to occur. Along the pipe flow, brine will have changes in pressure and temperature. This condition will causes the change in enthalpy brine and brine mass flow rate caused by flashing, condensation, or mass reduction due to precipitation of amorphous silica brine. All conditions affecting each other so that it can be stated that the changes in pressure and temperature along the pipe can cause silica scaling.

Heat loss and drop pressure causes changes in enthalpy, brine flow rate changes due to the vapor fraction (except in compressed liquid), and drop temperature. This change will cause mass deposition of amorphous silica in the brine flow in the pipe. Changes in temperature and pressure along the pipeline flow can be modeled by theories such as pressure drop calculation method (Zhao et al, 2000) and heat loss (Cangel, 2003). Deposition of amorphous silica will be deposited on the inside of the pipe radially (Karim, 2005; Klein, 1995). This precipitation will change the size of the pipe diameter becomes smaller as a function of time and will also affect the ability of brine flow. From these results we can predict changes in the inner diameter of the pipe and the flow rate of brine in the pipeline given time.

SILICA DEPOSITION

Silica is one of the chemical components found in many earth fault. At the regional manifestations, silica is commonly found in soil and water output surface of the earth. Silica can be formed in a variety of forms called polymorphs such as quartz, chalcedony, cristobalite, and amorphous (Edward, 1977).

Temperature is a dominant factor that affects mineral solubility geothermal system. Change of enthalpy, salinity, and pressure has impact to solubility, although not dominant. In a geothermal system, there are 3 properties of the effect of temperature on solubility (Nicholson, 1993), ie

1. Solubility increases with increasing temperature
2. Solubility increases with decreasing temperature
3. Solubility increases with increasing temperature but increased solubility only up to its maximum value and then decreases with increasing temperature.

Silica has the third properties because it has a maximum value. Each polymorph has a value different solubility at a given temperature as shown in Figure 1. Among these polymorphs, quartz and amorphous forms of silica are very interesting in relation to the deposition of silica.

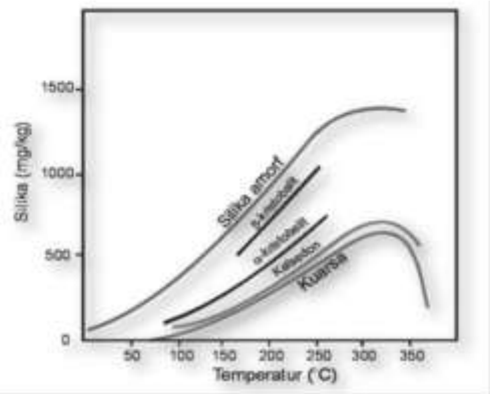

Figure 1 : Silica Solubility
(Source : Herdianita, 2011)

Solubility of the geothermal fluid in the reservoir is controlled by quartz. Whereas the temperature fluid is decreased to quite low (such as brine coming out of the separator) then solubility controlled by amorphous. Silica quartz solubility can be written in the following equation :

$$SiO_{2(s)} + 2H_2O_{(l)} = H_4SiO_{4(aq)} \qquad (1)$$

This reaction is dependent on temperature and follows the equation :

$$\log C = -\frac{1309}{T} + 5{,}19 \qquad (2)$$

Where C = concentration of silica (mg/kg) and T = absolute temperature (K).

Above equation valid for temperatures between 0 to 250°C.

For temperatures above 250°C, quartz solubility equation can be shown as follows :

$$T = -42{,}198 + 2{,}8831 * 10^{-1} * C - 3{,}6686 * 10^{-4} * C^2 + 3{,}1665 * 10^{-7} * C^3 + 77{,}034 * \log(C) \qquad (3)$$

Solubility of amorphous silica has been measured at saturation vapor pressure of water by Fournier and Rowe (1977), which is shown by the equation :

$$\log C = -\frac{731}{T} + 4{,}52 \qquad (4)$$

From Figure 1 can be shown that the solubility of amorphous silica is higher than the silica in the form of quartz at the same temperature. It is possible to prevent the precipitation of amorphous silica on the surface by keeping the temperature below its solubility values. However, when the brine discharged from the separator to the injection wells, the temperature will decreases. This condition causes the silica deposition along the brine flow pipe (Di Pippo, 2008).

PHYSICAL CALCULATION OF BRINE FLOW IN PIPE

For modeling the brine flow in the pipeline requires calculations that show the physical phenomenon of the brine flow. Physical calculations such as fluid thermodynamic properties (eg enthalpy, density, etc.), loss of pressure in the pipes, and decreases in temperature due to heat loss.

Characteristics of Geothermal Fluid

Geothermal brine is generally in the form of water. Water properties such as enthalpy, density, and viscosity is required in the calculation of the changes in pressure and temperature of brine in the pipeline. Tortike and Ali (1989) developed a polynomial equation for the independent variable is the pressure or temperature to determine the saturation value, enthalpy, density, and viscosity.

Saturation Temperature

Saturation temperature is the temperature value when fluid phase will change on specific pressure value. Tortike and Ali (1989) formulated a polynomial equation of saturation temperature (T_s) as a function of pressure (P) as follow

$$T_s = 280{,}034 + 14{,}0856 * \ln P + 1{,}38075 * (\ln P)^2 - 0{,}101806 * (\ln P)^3 + 0{,}019017 * (\ln P)^4 \qquad (5)$$

This equation valid for 0,611 kPa ≤ P ≤ 22,12 MPa.

Entalphy

Enthalpy is the total of energy in a material and energy used to do work. Enthalpy value is affected by pressure and temperature. Tortike and Ali (1989) showed the liquid phase enthalpy (h_f) and vapor phase (h_g) as a function of temperature (T) with the following polynomial equation.

$$h_f = 23665{,}2 - 366{,}232 * T + 2{,}26952 * T^2 - 0{,}00730365 * T^3 + 1{,}30241 * 10^{-5} * T^4 - 1{,}22103 * 10^{-8} * T^5 + 4{,}70878 * 10^{-12} * T^6 \qquad (6)$$

This equation valid for 273,15 ≤ T ≤ 645 K.

$$h_g = -22026{,}9 + 365{,}317 * T - 2{,}25837 * T^2 + 0{,}00737420 * T^3 - 1{,}33437 * 10^{-5} * T^4 + 1{,}26913 * 10^{-8} * T^5 - 4{,}96880 * 10^{-12} * T^6 \quad (7)$$

This equation valid for 273,15 ≤ T ≤ 640 K.

Density

Fluid density is defined as the mass of fluid per unit volume. Density can vary greatly on different fluid. At the same fluid, pressure and temperature differences cause little change in density. Tortike and Ali (1989) showed the polynomial equation for the liquid phase density (ρ_f) and vapor phase (ρ_g) as a function of temperature (T) as follows :

$$\rho_f = 3786{,}31 - 37{,}2487 * T + 0{,}196246 * T^2 - 5{,}04708 * 10^{-4} * T^3 + 6{,}29368 * 10^{-7} * T^4 - 3{,}08480 * 10^{-10} * T^5 \quad (8)$$

This equation valid for 273,15 ≤ T ≤ 640 K.

$$\rho_g = \exp\left(-93{,}7072 + 0{,}833941 * T - 0{,}00320809 * T^2 + 6{,}57652 * 10^{-6} * T^3 - 6{,}93747 * 10^{-9} * T^4 + 2{,}97203 * 10^{-12} * T^5\right) \quad (9)$$

This equation valid for 273,15 ≤ T ≤ 645 K.

Viscosity

Viscosity is the resistance of a fluid to shear force. Viscosity can be divided into two types: dynamic and kinematic viscosity. Dynamic viscosity is a fluid property that relate shear stress to the fluid motion. Kinematic viscosity is the ratio of the density to fluid dynamic viscosity. Dynamic viscosity value is strongly influenced by temperature. Tortike and Ali (1989) made a polynomial equation of dynamic viscosity on the liquid phase (μ_f) and vapor phase (μ_g) as a function of temperature (T) as follows :

$$\mu_f = -0{,}0123274 + 27{,}1038 * T^{-1} - 23527{,}5 * T^{-2} + 1{,}01425 * 10^7 * T^{-3} - 2{,}17342 * 10^9 * T^{-4} + 1{,}86935 * 10^{11} * T^{-5} \quad (10)$$

This equation valid for 273,15 ≤ T ≤ 645 K.

$$\mu_g = -5{,}46807 * 10^{-4} + 6{,}89490 * 10^{-6} * T - 3{,}39999 * 10^{-8} * T^2 + 8{,}29842 * 10^{-11} * T^3 - 9{,}97060 * 10^{-14} * T^4 + 4{,}71914 * 10^{-17} * T^5 \quad (11)$$

This equation valid for 273,15 ≤ T ≤ 645 K.

Pressure Drop

For pressure drop calculation, need to consider the type of brine fluid flow in the pipeline. Brine from the separator is generally a single phase fluid. However, if the brine temperature exceeds the saturation temperature, then vapor fraction is formed so that the brine into a two-phase fluid. One method of pressure drop calculations performed by Harrison and Freeston. Harrison and Freeston shows the pressure drop calculations due to friction and acceleration by the following equation (Saptadji, 2011) :

$$\left(\frac{dp}{dp}\right)_{f\&acc} = \frac{4\tau_\omega}{D(1-AC)} \quad (12)$$

Where :

$$\tau_\omega = \frac{\lambda V_f^2}{8\upsilon_f}$$

With τ_ω is shear stress, AC is acceleration correction, λ is friction factor, V_f is the fluid phase velocity, m is the brine flow rate, dan υ_f is the specific volume of liquid phase.

Zhao et al (2000) made a new correlation for void fraction α. The void fraction provides a better compatibility between the pressure drop data prediction results against measurement data on two-phase fluid flowing in the pipe. Zhao et al (2000) gives the value of the void faction in the form of equation :

$$\frac{1-\alpha}{\alpha^{7/8}} = \left[\left(\frac{1}{x} - 1\right)\left(\frac{\rho_g}{\rho_f}\right)\left(\frac{\mu_f}{\mu_g}\right)\right]^{7/8} \quad (13)$$

In prediction of pressure drop in two phase flow, void friction parameter α is an important fundamental. This value affects the other parameters of two phase liquid such as the liquid phase velocity Vf. Zhao et al (2000) shows the phase velocity of liquid in the form of equation :

$$V_f = 1.1(1-x)\frac{m(1-x)v_f}{(1-\alpha)A} \quad (14)$$

Equation for the pressure drop due to elevation :

$$\left(\frac{dp}{dz}\right)_g = \rho g \sin\theta \quad (15)$$

with g is the gravitational acceleration and ρ is the density of the fluid.

Heat Loss

Calculation of the rate of heat loss on pipe with multiple layers as shown in figure 2 can be solved by taking into account one by one thermal resistance R of the fluid in the pipe until the brine into the air. Thermal resistance is described in layer network of pipes as shown in figure 2 (Cengel, 2003).

R1 and R5 is the convection thermal resistance, and R2, R3, and R4 is the conduction thermal resistance. The magnitude of the rate of heat loss from the brine temperature $T_{\infty1}$ through the pipe wall layers to the air temperature $T_{\infty2}$ can be written in the form of equations :

$$\dot{Q} = \frac{T_{\infty1} - T_{\infty2}}{R_{total}} \quad (17)$$

With :

$$R_{total} = R_1 + R_2 + R_3 + R_4 + R_5$$

$$R_{total} = \frac{1}{h_1 A_1} + \frac{\ln(r_2/r_1)}{2\pi L k_1} + \frac{\ln(r_3/r_2)}{2\pi L k_2} + \frac{\ln(r_4/r_3)}{2\pi L k_3} + \frac{1}{h_2 A_4}$$

where $A_1 = 2\pi r_1 L$ and $A_4 = 2\pi r_4 L$. L is length of pipe.

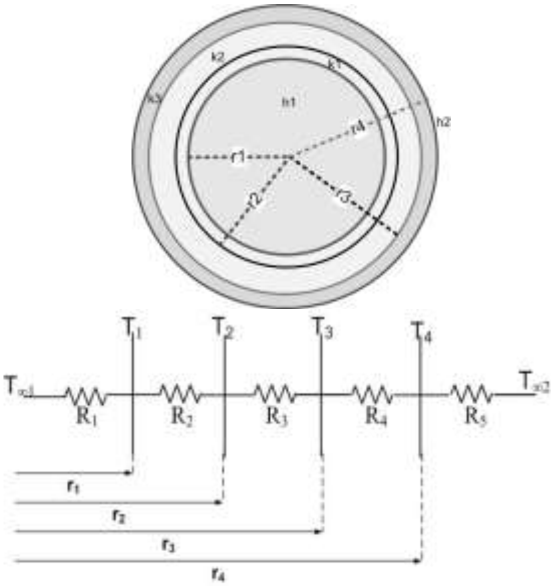

Figure 2 : (a) Cross section of layers in the pipe, and (b) Network thermal resistance on the pipes

MODELING METHODS OF SILICA SCALING EFFECT TO BRINE FLOW IN PIPE

For accurate calculation, the model is divided into segments pipe, where the pipe segment divided by the average per unit length meter and based on elevation. In each segment of pipeline done calculated as the pressure drop calculation, decrease the temperature, enthalpy change, mass amorphous precipitated silica, changes in flow rate, and changes in the diameter of the pipe flow of brine.

Modeling of Brine Pressure in Injection Pipe

For modeling the pressure drop, used the method from Zhao et al (2000) who developed Harrison Freeston method.

Modeling of Brine Temperature in Injection Pipe

Temperature modeling using the method of heat loss in pipes by conduction and forced convection in brine (Cangel, 2003). The amount of brine exit temperature of the pipe segment can be obtained from following equation :

$$T_{out} = T_{in} - \frac{Q_{loss}}{\dot{m}.C_p} \qquad (18)$$

Where T_{in} is the entrance brine temperature, m is the flow rate of brine, and Cp is the specific heat constant from brine.

Enthalpy Changes of Brine

Enthalpy change for the pipe segments can be obtained by the following equation :

$$h_2 = h_1 - \frac{Q_{loss}}{\dot{m}_1} \qquad (19)$$

Mass Silica Deposition and Brine Flow Rate Changes in Pipe

Decrease in temperature due to heat loss cause brine solubility of amorphous silica to be changed. Mass rate of silica deposition can be obtained by calculating the difference ΔC amorphous silica concentrations due to changes in temperature.

By calculating the mass flow of steam and condensation, the vapor phase brine flow rate $\dot{m}_{2g}$ can be obtained. From the mass balance relationships in the pipeline segment, the brine flow rate of liquid phase m_{2f} can be obtained too.

Changes of Inner Diameter in Pipe

Assuming radially deposited amorphous silica, then the radius of the pipe will be reduced during a certain time interval. Silica thickness (h_s) in the pipeline with a length l and radius (rp) on the interval (t) can be obtained given by the equation :

$$h_s = r_p - \sqrt[2]{r_p^2 - \frac{m_{dep}.t}{\rho_{sa}\pi l}} \qquad (20)$$

m_{dep} is a mass deposition rate of amorphous silica on the inner pipe wall. Mdep magnitude can be obtained by the following calculation :

$$m_{dep} = FP * m_{sa} \qquad (21)$$

FP is the fraction of amorphous silica which precipitated from a silica scale formed.

From precipitated silica thickness radially on the pipe wall, it can be obtained new inside diameter (ID) pipeline at any given time.

$$ID_{new} = ID_{old} - 2h_s \qquad (22)$$

Brine Flow Modeling Due to Silica Scaling Along Pipe

Simulation of calculations are performed on pipeline segments by calculating changes in pressure, temperature, enthalpy, flow rate, and diameter of the pipe. The calculation is performed along the pipeline.

EFFECTS OF SILICA SCALING TO FLOW RATE CORRELATION AND INSIDE DIAMETER IN PIPE

brine in the compressed liquid state does not causes the vapor fraction. So that the process of silica scaling is only due to a decrease in brine temperature in the pipeline. Decrease in temperature causes changes in solubility of silica in the brine. Decrease in temperature due to heat loss from the brine (by convection and conduction).

Heat loss will occur along the brine flow pipeline. The amount of heat loss is directly proportional to the mass of silica. The amount of heat loss in the pipe that has been divided into segments of pipe will be high value in the first part of the pipe segment and the smaller value of heat loss in the subsequent pipeline segments. This will have an impact on the greater mass of silica formed on the first pipe segment compared to subsequent pipeline segments.

Simulation calculations show that silica deposited at the end of the pipe segment more than the first pipe segments. This is due to the amorphous silica formed on the first segment of pipe is only partially precipitated in the first pipe segment. Residual silica is then accumulated with that amorphous silica is formed on the second pipe segment and the next segment. Thus the diameter of the pipe in the pipe segment farther away will be smaller than diameter of the first pipe segment. Can be stated that the deposition of amorphous silica causes the pipe diameter is reduced every time.

Calculation due to the reduction in the pipe diameter of silica scaling can be analyzed. diameter of the pipe at the second time (D_2) can be obtained by equation :

$$D_2 = \sqrt{{D_1}^2 - \frac{4F_p}{\pi.\rho_{sa}}\left(\frac{\dot{m}_{sa}}{L}\right).t} \qquad (23)$$

$\left(\frac{\dot{m}_{sa}}{L}\right)$ shows the rate of amorphous silica mass per unit length pipe. This equation can be used to obtain the diameter of the pipe at all time.

Based on data diameter, flow rate of brine enters to pipe at the second can be obtained from equation :

$$m_2 = k.\left(\frac{D_2}{D_1}\right)^{5/2}.m_1 \qquad (24)$$

constant k is to show the effect of uniformity of pipe diameter. k = 1 when a change in the diameter of the pipe is only dependent on the deposition of amorphous silica in the pipe segment. Constant k varies when taking into account residual the amorphous silica is not deposited on the pipe, where it accumulates with amorphous silica on the next segments.

CONCLUSIONS

1. Model of silica scaling prediction can be developed with analyze the physical changes that occur on brine in the injection pipe.
2. Models that have been developed have parameters such as deposition fraction. Amorphous silica deposition fraction values will be different on different pipe conditions and brine flow.
3. Precipitation of amorphous silica that occurs radially in the pipe to make reductions in pipe diameter and a decrease in the flow rate of brine which can be analyzed as a function of time.

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