DEVELOPMENT OF MATHEMATICAL MODEL TO PREDICT SULFIDE SCALING IN GEOTHERMAL WELLS

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ABSTRACT

Scaling or solid deposition generally occurs inside geothermal wells which produce two-phase geothermal fluid. This occurrence will lead to the blockage of fluid flow in geothermal wells. Certain geothermal fields encounter sulfide scaling inside the production wellbore, for example the Dieng geothermal field. The solution to overcome sulfide scaling is by doing workover operation. However, the growth of sulfide scaling inside the wellbore has never been modeled. The necessity for modeling the growth of scaling is important, as by knowing the scaling growth inside the wellbore, we would know the depth of scaling. Moreover, workover operation can be conducted before scaling occurs and fills up the production well completely. This study is attempted to develop mathematical models to find a solution for predicting the sulfide scaling in the geothermal wells, focusing on galena and sphalerite. The mathematical model was developed by integrating the solubility-temperature corelation and two-phase pressure drop correlation in a vertical production well. The outcome of this study would visualize the increasing thickness of sulfide deposition inside the wellbore per annum. Then, sensitivity analysis was applied in several parameters, for example pH, the amount of Pb^{2+}, Zn^{2+}, bottomhole flowing pressure and mass flowrate. The results showed that the amount of Pb^{2+}, Zn^{2+} and mass flowrate had an effect on the amount of deposition, whereas the change of the bottomhole pressure would change the initial depth of deposition.

1. BACKGROUND

Scaling is the process of solid deposition which may occur in the production wells, surface pipelines, turbines and injection wells. The deposition reduces both the volume of open space in the well and in the surface pipeline thus inhibits the flow of geothermal fluid from the bottomhole to the turbine. This may lead to supply shortage of steam turbine to generate electricity. As a result, the company's revenue will decrease accompanied by increasing in maintenance costs for cleaning the production wells, surface pipelines, turbines and injection wells.

Factors affecting the occurrence of scaling are pressure and temperature. During the production of geothermal fluid from the bottom of the well to the surface, the fluid pressure and temperature decreases. Decreasing pressure and temperature will influence in the solubility of the chemical content dissolved in the geothermal fluid. Chemical constituents of geothermal fluid consist of cations, the positively charged ions and anions, as negatively charged ions.

Cations and anions have a tendency to react with each other to form a neutral ionic compound that is dissolved in the geothermal fluid. The ionic compounds have unique solubility and differ from one another. Solubility of ionic compounds is expressed as product solubility constant (K_{sp}). K_{sp} is an equilibrium constant of a solid dissolving in the fluid at a given temperature. Product solubility constant vary with changes in pressure and temperature experienced by the geothermal fluid. To be able to determine whether an ionic compound soluble or not at a given temperature, then the comparison between the equilibrium constant ionic compounds (K_c) with K_{sp} is conducted. There are three possibilities that could occur from comparison between the K_{sp} and K_c:

- $K_c < K_{sp}$= undersaturated solution
- $K_c = K_{sp}$= saturated solution
- $K_c > K_{sp}$= supersaturated solution

Solid deposition or scaling is dominated by silica and calcite in geothermal wells. But in certain cases, sulfide scaling can occur in the production wells, for example in the Dieng geothermal field. In the Dieng geothermal field the wells are worked over to remove scale. Till now no predictive estimates of the deposition rate have been done. However by knowing the amount of deposition at different depths in the wells, the potential deposition point in the well can be estimated. In addition, the workover scheduling for each well will be better, because it can be done without waiting for the deposition to fill up the well completely.

Based on the things that have been described above, we have developed a mathematical model which can predict the sulfide deposition in the well. The development of the mathematical model was trialed theoretically using a test well and the sulfide compounds that will be the focus of the study are galena (PbS) and sphalerite (ZnS).

2. METHODOLOGY

Mathematical model developments are divided into three stages. They are data preparation, pressure drop modelling inside the wellbore and solubility modeling of galena and sphalerite.

2.1 Data Preparation

The development of mathematical model to estimate the solubility of galena and sphalerite requires the following data:

1. Well completion data
2. Production perfomance data, such as reservoir pressure, bottomhole flowing pressure, reservoir fluid enthalpy and mass flowrate
3. Chemical content of the reservoir fluid data, in particular H_2S, Pb^{2+} and Zn^{2+} content and pH

2.2 Pressure Drop Modeling

The first step was to model the pressure-drop profile inside the wellbore. The model was developed using drift-flux correlation Hasan and Kabir (2010) because of its advantage in overcoming the discontinuity at the transition from one flow pattern to another pattern by introducing a flow smoothing parameter. Pressure loss calculations were performed from the bottom to the top of the well at three-meter intervals. A three-meter depth interval will give good results in the advanced computation (forward calculation) and iterative calculation (Situmorang, 2012). A flowchart of the pressure loss modeling process is presented in Figure 1.

The results to be obtained from the modeling of the pressure loss in the wellbore are pressure, temperature, dryness profile with depth and flow pattern formed inside the wellbore.

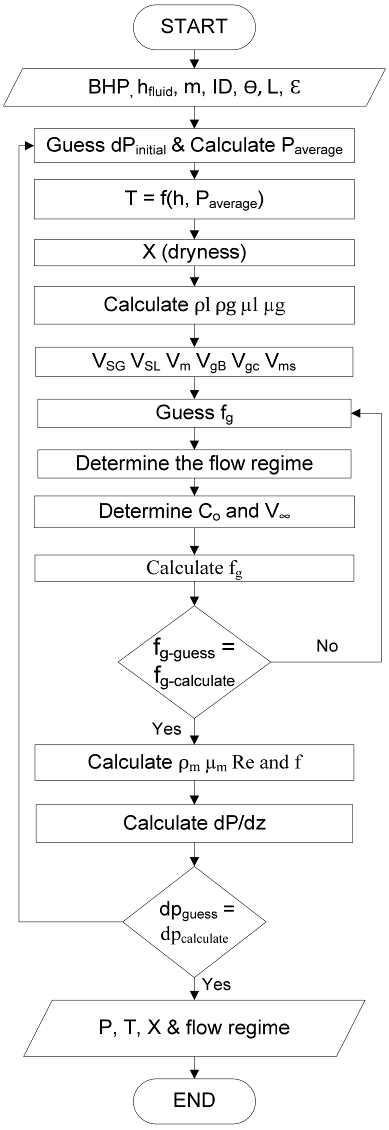

Figure 1: Pressure Drop Modeling Flow Chart

2.3 Solubility Modeling

Modeling the solubility of galena and sphalerite inside the wellbore can proceed after the pressure drop calculations. The data required for the calculation is temperature and dryness profile with depth.

The flow diagram for modeling the solubility of galena and sphalerite is presented in Figure 2.

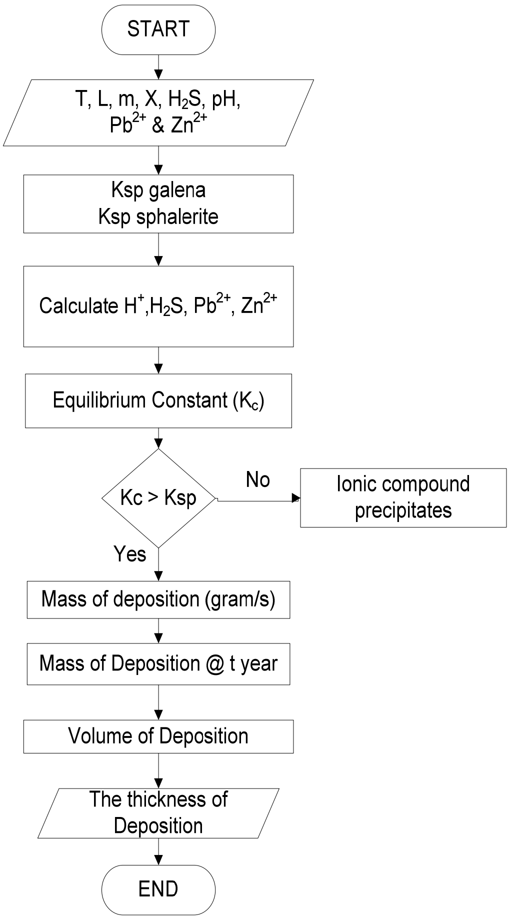

Figure 2: Solubility Modeling Flow Chart

2.3.1 Product Solubility Constant (K_{sp}) Calculation

Calculation of solubility product constant for galena is based on the following equation:

$Pb^{2+}_{(aq)} + H_2S_{(aq)} \longleftrightarrow PbS_{(s)} + 2H^+_{(aq)}$....................(1)

The reaction above occurs through three stages:

$H_2S_{(aq)} \longleftrightarrow H^+_{(aq)} + HS^-_{(aq)}, K_1 = K_{a1}$......................(2)

$HS^-_{(aq)} \longleftrightarrow H^+_{(aq)} + S^{2-}_{(aq)}, K_2 = K_{a2}$..........................(3)

$Pb^{2+}_{(aq)} + S^{2-}_{(aq)} \longleftrightarrow PbS_{(s)}, K_3 = 1/K_{sp}$.....................(4)

+

Final reaction:

$Pb^{2+}_{(aq)} + H_2S_{(aq)} \longleftrightarrow PbS_{(s)} + 2H^+_{(aq)}$........................(5)

Where, $K_{sp} = (K_{a1} . K_{a2)}/ K_{sp}$

$PbS_{(s)} + 2H^+_{(aq)} \longleftrightarrow Pb^{2+}_{(aq)} + H_2S_{(aq)}$.......................(6)

Where, $K_{sp\text{-}corr} = K_{sp} /(K_{a1} . K_{a2})$

The first and second stage reactions are the dissociation reactions of H_2S with dissociation constant for each stage of K_a1 and K_a2, with values given in Table 1 in standard condition 298 K.

Table 1: Acid dissociation constant (Weast, 1977)

Acid Constant	Value
K_{a1}	9.1×10^{-8}
K_{a2}	1.1×10^{-12}

The third stage is the forming of galena with product solubility constant (K_{sp}) of 3.4×10^{-28} (Kartohadiprojo, 1994) under standard condition 298 Kelvin. The galena product solubility constant that has been corrected for the effect of H_2S ($K_{sp\text{-}corr}$) and is equal to 3.396×10^{-9}. By using the van't Hoff equation, we can estimate the product solubility constant of galena at the temperature of interest. Van't Hoff equation is formulated as follows (Moore, 1983)**:**

$$\log \frac{K_{sp2}}{K_{sp1}} = \frac{\Delta H^0}{2.303R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \quad \text{.......(7)}$$

By using the value of ΔH^0 for reaction (1) and $K_{sp\text{-}corr}$ into the equation above, the final equation to determine the solubility of galena is as follows:

$$\log \frac{K_{sp2}}{3.396\,10^{-9}} = \frac{65.75}{2.303R}\left(\frac{1}{298} - \frac{1}{T_2}\right) \quad \text{.......(8)}$$

The reaction for sphalerite is the same as for galena, but substituting "Pb" with "Zn" for sphalerite. The third stage K_{sp} for sphalerite is equal to 1.6×10^{-24} (Kartohadiprojo, 1994) and the final equation to determine the solubility of sphalerite as follows:

$$\log \frac{K_{sp2}}{1.898\,10^{-5}} = \frac{15.99}{2.303R}\left(\frac{1}{298} - \frac{1}{T_2}\right) \quad \text{.......(9)}$$

2.3.2 Equilibrium Constant Calculation

The equilibrium constant for galena and sphalerite is formulated as follows:

$$K_c = \frac{[M^{2+}][H_2S]}{[H^+]^2} \quad \text{.......(10)}$$

Where the $[M^{2+}]$ is defined as the concentration of metal (galena or sphalerite) in moles per litre which depends on temperature by:

$$[M^{2+}]_{T1} = \frac{[M^{2+}]_{T2}}{(1-(f1-f2))} \quad \text{.......(11)}$$

f_1 and f_2 are defined as dryness value from first segment to next segment inside the wellbore. The concentration of $[H_2S]$ and $[H^+]$ in liquid depends on temperature and equilibrium constant which will decrease as the fluid flashing. The concentration of $[H_2S]$ and $[H^+]$ can be estimated by using this equation:

$$[H^+]_{T1} = \left(1-(f1-f2)\right) x\, [H^+]_{T2} \quad \text{.......(12)}$$

The amount of deposition (in moles per litre) that occurs can be approximated by the following equation:

$$Deposition(mole^{-1}) = [M^+] - \left[[M^+]\, x\, \frac{K_{sp}}{K_c}\right] \quad \text{.......(13)}$$

3. IMPLEMENTATION

The methodology that has been previously described has been implemented in a test well. The well specifications are presented in Table A1, A2 and A3 with an illustration of the test wells A in Figure A1 (see Appendix).

The configuration and specification of test well A was chosen on the basis of a literature review and considerations such as the characteristics of water-dominated reservoirs in general, the well production data as well as chemical constituents in geothermal areas experiencing sulfide scaling.

Determination of target depth in the well A was done by considering general reference that geothermal reservoirs are usually located at a depth of about 1 to 3 kilometers from the surface (Grant & Bixley, 2011). Reservoir pressure is estimated to be around 100-300 bars for a water-dominated reservoir, also the reservoir temperature is varied as in Awibengkok at around 240°-310°C, Dieng at around 280°-310°C, and Lahendong at around 260°-330°C (Fauzi, 2005). The top of liner in well A is at a depth of 500 meters, with production capabilities based on the big bore production wells KA-45, KA-46 and KA-47 at the Kawerau geothermal field (Bush & Siega, 2010), at lastly the chemical content is taken from geothermal fluid from the Reykjanes (Hardardottir, 2005).

4. RESULT AND ANALYSIS

4.1 Pressure Drop Modeling

Modeling result shows the wellhead pressure around 49.54 bars with the vapor fraction at the wellhead is 0.102. At a depth of 2000 meters to 1208 meters, the geothermal fluid flows in the liquid phase (compressed liquid). Then, from a depth of 1208 meters up to the surface, the vapor fraction increases making two-phase flow. From the modeling result, flashing occurs at a depth of approximately 1208 meters.

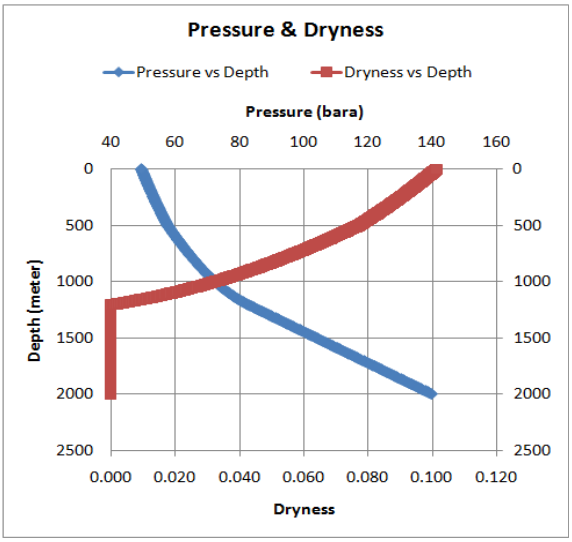

Figure 3: Pressure & Dryness Profile with Depth

Figure 4 illustrates the flow pattern profiles that occur in the well as the result of pressure drop modeling. There are three flow patterns that occur in well A. Compressed liquid flow pattern occurs at a depth of 1208-2000 meters, bubble flow pattern occurs ranging from 971-1208 meters depth and a pattern of slug flow occurs from a depth of 971 meters up to the surface.

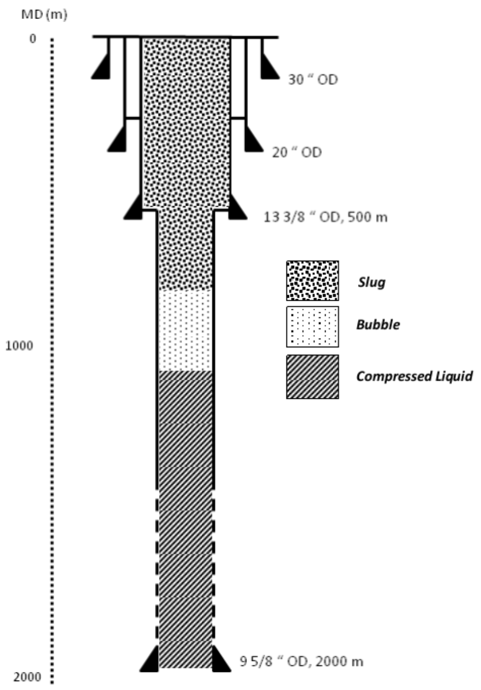

Figure 4: Flow Pattern in Well A

4.2 Solubility Modeling

Figure 5 shows the relationship between the equilibrium constant (K_c) for galena and product solubility constant (K_{sp}). From Figure 5 it can be seen that the equilibrium constant (K_c) is relatively constant at compressed liquid flow around the depth of 1208-2000 meters. This is because the amount of $[Pb^{2+}]$, $[H_2S]$ and $[H^+]$ which are dissolved in the geothermal fluid do not change significantly. At the depth of 1208 meters, the amount of $[Pb^{2+}]$, $[H_2S]$ and $[H^+]$ start to change as the flashing begins.

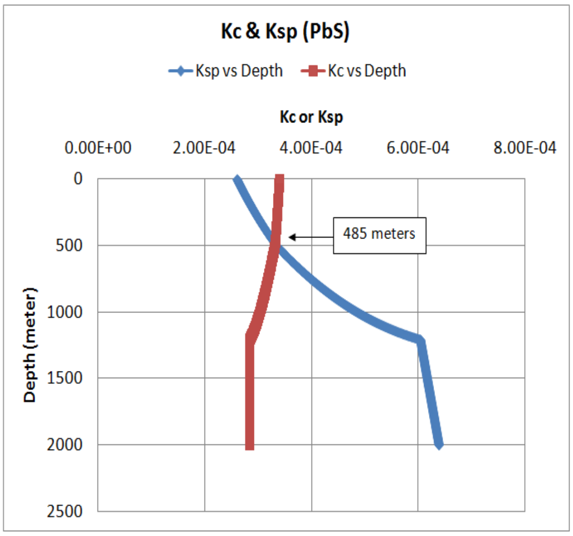

Figure 5: K_c & K_{sp} (Galena)

Flashing will increase the content of $[Pb^{2+}]$ as well as decrease the content of $[H_2S]$ and $[H^+]$ which is dissolved in the geothermal fluid. The content of $[Pb^{2+}]$ will increase because of the non-volatile cations that remain dissolved in the liquid phase as flashing begins. While $[H_2S]$ is so volatile which are carried off in vapour. $[H^+]$ is not volatile but as the acidic gases are flashed off the pH will increase so $[H^+]$ will decrease.

Product solubility constant (K_{sp}) of galena is relatively constant in compressed liquid condition. This is because the solubility product constant is a function of temperature. As the temperature in a single phase flow is unlikely to change, so the product solubility constants do not change significantly. Once past the flashing depth, product solubility constant of galena decreases significantly. This is because the mass of the geothermal fluid that can dissolve galena decreases. From Figure 5, K_c and K_{sp} intersect at the depth of 485 meters. At that depth, the saturation solubility of galena is exceeded so deposition of galena occurs.

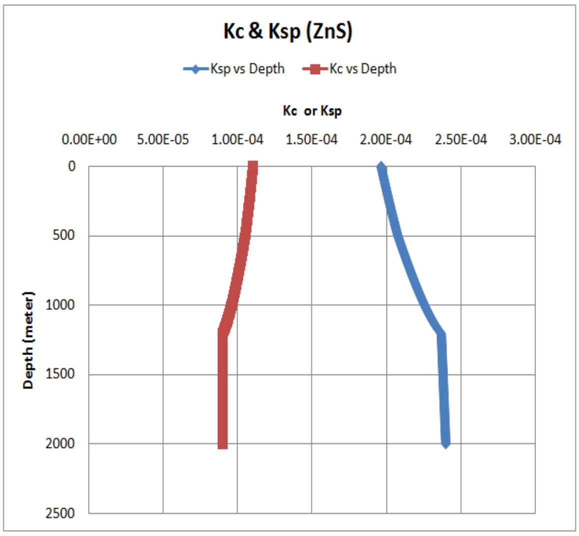

Figure 6: K_c & K_{sp} (Sphalerite)

Figure 6 shows the relationship between K_c and K_{sp} for sphalerite with depth which is quite different from Figure 5. The K_c and K_{sp} lines above do not intersect each other. It shows that there is no sphalerite deposition in the wellbore as the equilibrium constant of sphalerite is lower than the product solubility constant of sphalerite so sphalerite is undersaturated in the fluid.

Spontaneous deposition does not occur at a depth of 1208 meters at the start of the flashing zone. This is because the flashing is still is still minor so the amount of $[Pb^{2+}]$, $[H_2S]$ and $[H^+]$ have not changed significantly. Galena deposition takes place at a depth of 485 meters with vapor fraction is around 0.078 in slug flow pattern (Figure 4).

Solubility equilibrium reaction for both galena and sphalerite occur dynamically (two-way) heading towards the saturation point of galena or sphalerite solubility with temperature. The amount of galena or sphalerite deposited in the wellbore will be the difference between the actual dissolved amount and the saturation solubility. The residual amount of dissolved galena or sphalerite will be carried to the next segment, if the saturation is exceeded then some more of the galena or sphalerite will be deposited, this process is repeated until all the excess galena and sphalerite is deposited.

Figure 7 and 8 illustrate the growth of mass and thickness for galena during 10 years of production in well A. There is no deposition for both galena and sphalerite at depths below 485 meters.

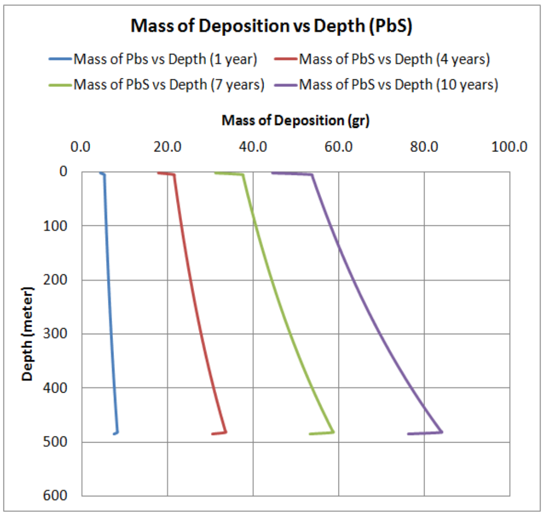

Figure 7: Mass of Galena with Depth

Deposition mass and thickness is greatest at a depth of 485 meters which then gradually decrease to the surface.

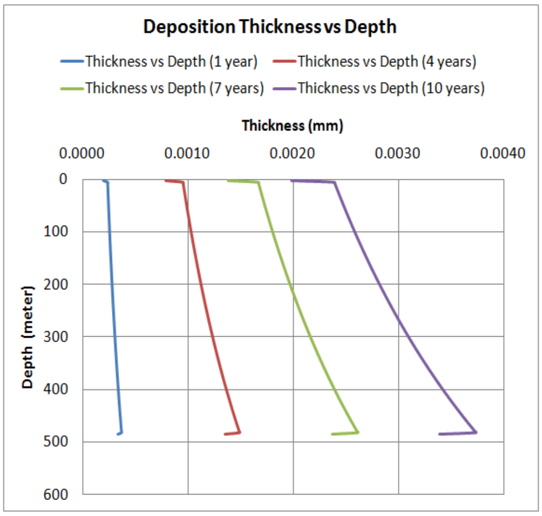

Figure 8: Thickness of Galena with Depth

4.3 Sensitivity Test in Well A

Sensitivity analysis was performed on well A by varying the chemical content of the fluid, pressure and mass flow rate in the interval of one year. The chemical parameters which were varied were pH, [Pb^{2+}] and [Zn^{2+}]. More detail about the sensitivity results is presented in Table A4 and Table A7 (see Appendix).

Table A4 shows that increasing pH causes the deposition occur earlier and so deeper in the well. The deposition increases due to the lower pH in the geothermal fluid. Decreasing amount of [H^+] then will increase the equilibrium constant (K_c) for galena and sphalerite. The change in pH is only one factor that controls whether deposition occurs or not. At alkaline pH values, the deposition tendency to occur will be higher than if the pH is acidic.

Table A5 shows that the higher amounts of [Pb^{2+}] ions in the geothermal fluid will also cause the deposition to occur deeper the well. In addition, increasing amount of [Pb^{2+}] is directly proportional to the amount of deposition. The same also occurs with [Zn^{2+}] (Table A6) although deposition of galena and sphalerite occur at different depths. Galena at a depth of 485 meters, whereas sphalerite at 2000 meters.

Table A7 presents the result of the flow rate and bottomhole pressure sensitivity. Increasing bottomhole pressure will cause the deposition to occur at shallower depths and will lower the amount of deposition. This is because the increasing bottomhole pressure will shift the flashing zone that occurs at shallower depths (Table A8). By shifting the depth of flashing the amount of [Pb^{2+}], [Zn^{2+}], [H_2S] and [H^+] will change at comparable depths, so the product solubility constant and the equilibrium constant of the reaction will intersect at shallower depth.

Increasing bottomhole pressure will result in decreasing deposition inside the wellbore. At high bottomhole pressures, the mass flow rate of fluid production will decline because the pressure difference between the reservoir pressure and bottomhole flowing pressure (drawdown) is getting smaller. If the pressure difference is multiplied by the productivity of the well, a lower flow rate will be obtained. The mass flow rate is related to the flux of [Pb^{2+}], [Zn^{2+}], [H_2S] and [H^+]. If the mass flow rate is lower, then the mass flux of ions [Pb^{2+}], [Zn^{2+}], [H_2S] and [H^+] will also be lower.

5. CONCLUSION

A mathematical model has been successfully developed by integrating the concept of pressure drop with solubility of galena and sphalerite in geothermal fluid, which can estimate galena (PbS) and sphalerite (ZnS) deposition. The mathematical model has successfully theoretically implemented in test well A in order to estimate the depth of the deposition, the growth of mass deposited and the thickness of deposition after a certain time interval. In addition, several conclusions were reached during the process of implementing the mathematical model and the sensitivity analysis as follows:

1. Flashing led to increased amounts of [Pb^{2+}] and [Zn^{2+}] accompanied by decreased levels of [H_2S] and [H^+]. As a result, K_{sp} will decrease after flashing depth while K_c will increase.
2. pH has no effect on the amount of deposition that occurs. pH only affects the equilibrium of the reaction that controls whether the deposition will occur or not.
3. The amount of deposition is influenced by ion concentration [Pb^{2+}] and [Zn^{2+}] in the geothermal fluid and the fluid mass flow rate of the geothermal wells.
4. A change of deposition depth is influenced by a change in bottomhole flowing pressure.

6. RECCOMENDATIONS

Some suggestions for further studies are:

1. It is necessary to test the validity of the mathematical model that has been developed on real geothermal field data where there are galena and sphalerite scaling problems.
2. The mathematical model needs to be developed to allow variation of bottomhole flowing pressure and flow rate value which is then integrated with the well production history.
3. Actual chemical content of reservoir fluid is required (downhole sampling) to determine accurate fluid composition and chemistry.
4. Caliper log data is necessary to know the thickness of deposition and overall size of the inside wellbore diameter.

7. REFERENCE

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APPENDIX

Table A1: Completion of Well A

Casing 13 3/8” OD	12.415” ID	0-500	mVD
Liner 9 5/8” OD	8.618” ID	500-2000	mVD

Table A2: Production Data of Well A

Static Pressure @ 2000 mVD	150	bara
Static Temperature @ 2000 mVD	300	Celsius
Bottomhole Pressure	140	bara
Reservoir Fluid Enthalpy	1338	kJ/kg
Mass Flowrate	100	kg/s
Productivity Index	10	kg/s.bar

Table A3: Chemical Content of the Reservoir Fluid

Pb^{2+}	0.001	mg/L
Zn^{2+}	0.0001	mg/L
H_2S	10	mg/L
pH	4	-

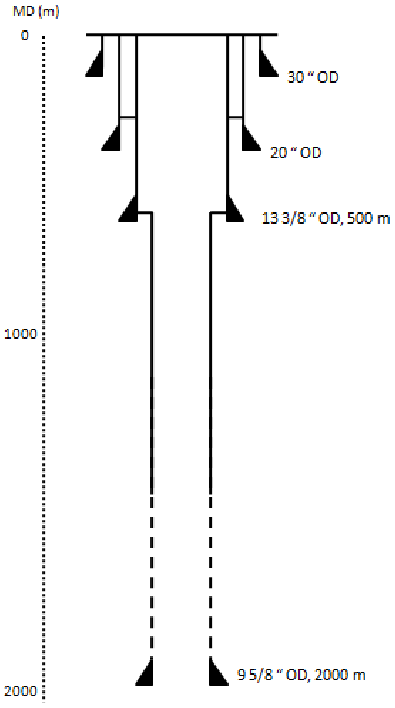

Figure A1: Illustration of Test Well A

Table A4: Effect of pH against Total Depth and Deposition Volume

$[Pb^{2+}]$ = 0.001 mg/L, $[Zn^{2+}]$ = 0.0001 mg/L, H_2S = 10 mg/L, t = 1 year			
pH	4	5	6
Depth of Deposition (meter)	0-485 (PbS)	0-2000 (PbS & ZnS)	0-2000 (PbS & ZnS)
Deposition Volume (m^3)	$1.43\ 10^{-4}$	$9.4\ 10^{-4}$	$9.4\ 10^{-4}$

Table A5: Effect of $[Pb^{2+}]$ against Total Depth and Deposition Volume

pH = 4, $[Zn^{2+}]$ = 0.0001 mg/L, H_2S = 10 mg/L, t = 1 year			
$[Pb^{2+}]$ (mg/L)	0.001	0.01	0.1
Depth of Deposition (meter)	0-485 (PbS)	0-2000 (PbS)	0-2000 (PbS)
Deposition Volume (m^3)	$1.43\ 10^{-4}$	$6.88\ 10^{-3}$	$7.65\ 10^{-2}$

Table A6: Effect of $[Zn^{2+}]$ against Total Depth and Deposition Volume

pH = 4, $[Pb^{2+}]$ = 0.001 mg/L, H_2S = 10 mg/L, t = 1 year			
$[Zn^{2+}]$ (mg/L)	0.0001	0.001	0.01
Depth of Deposition (meter)	0-485 (PbS)	0-2000 (ZnS) 0-485 (PbS)	0-2000 (ZnS) 0-485(PbS)
Deposition Volume (m^3)	$1.43\ 10^{-4}$ (PbS)	$1.39\ 10^{-3}$ (ZnS) $1.43\ 10^{-4}$ (PbS)	$1.84\ 10^{-2}$ (ZnS) $1.43\ 10^{-4}$ (PbS)

Table A7: Effect of BHP and Mass Flowrate against Total Depth and Deposition Volume

pH = 4, $[Pb^{2+}]$ = 0.001 mg/L, H_2S = 10 mg/L, $[Zn^{2+}]$= 0.0001 mg/L, t = 1 year			
BHP (bar)/ Flowrate (kg/s)	145/50	140/100	135/150
Depth of Deposition (meter)	0-323 (PbS)	0-485 (PbS)	0-674 (PbS)
Deposition Volume (m^3)	$4.99\ 10^{-5}$	$1.43\ 10^{-4}$	$3.43\ 10^{-4}$

Table A8: Depth of Flashing

Bottom Hole Pressure (bar)	Mass Flowrate (kg/s)	Depth of Flashing (meter)
135	150	1292
140	100	1208
145	50	1121