Preliminary Study of Membrane Technology to Resolve Silica Scaling to Enhance Geothermal Binary Power Plant

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Abstract. Large amount of hot brines produced by liquid-dominated geothermal field should lead to utilization of binary power plant in order to increase the installed capacity. However, binary power plant system extract energy from the hot brine that could increased the possibility of silica scaling either at the surface or at the reservoir because of the temperature decrease. Methods such as acidizing, water jetting, or alkaline injection has been proven could solve or prevent the occurrence of silica scaling. Still, those methods have their own limitation to solve silica scaling problem, such as economical or technological issues. Therefore we assume that physical separation methods such as sedimentation and filtration should be done to decreased the silica scaling problems. Membrane technology seems could filled the spot, because by using membrane technology the silica content in thermal fluid could be separated completely and decreased silica scaling potential. At the end of the process, the concentration of silica could be decreased by large number. Although the silica scaling problem might not be solved completely, but the decreased potential of silica scaling still could be achieved and lead to increased installed capacity since silica scaling tend to limitate the production of thermal fluid.

1. Introduction
A liquid dominated geothermal fields are more common than a vapor dominated geothermal fields, especially around the geothermal system which is associated with volcanic-hydrothermal system. It is called liquid dominated geothermal field because the major reserves of the reservoir are in liquid phase thermal fluid with different characteristics between one field and the another. High amount of liquid phase in the thermal fluid make it necessary to separate the liquid phase and the vapor phase of the thermal fluid, that is required because most of geothermal power plant turbine only receives vapor thermal fluid due to it’s high enthalphy [1].

Sometimes, before the brine is reinjected to the reservoir, due to it’s medium-high temperature it is formerly used to increase the temperature of other working fluid that is used to generate additional power, called binary system power plant. Because of the contact with a cooler working fluid, the brine’s temperature decreased significantly which cause the silica scaling happens. However, the silica scaling not only happens because of the decreased temperature of the brine, but also because of the high concentration of silica in the brine [2].

Silica scaling in geothermal filed tend to be major problem nowadays, because it is very responsible to the decrease of installed capacity due to decreased thermal fluid flow rate. Then many methods has been proposed, to mitigate silica scaling before it is happening or after it is happens. Unlike mitigation
methods such as acidizing [3] and water jetting [4] which was proposed to mitigate silica scaling after it is happens, otherwise physical separation of silica particle in the brine could prevent the silica scaling from happening by using methods such as alkaline injection [5]. Membrane technology is one of many methods of physical separation. Principles of the membrane is to separate particle based on it’s size by diameter (Figure 1). Membrane is specified by it’s pore diameter which allow particles to go through due to smaller diameter than the membrane pore diameter or being detained due to larger diameter than the membrane pore diameter.

Figure 1. Particle separation by membrane pore principle (screen filtration) [6]

Figure 2. Silica scale of injection pipe in the initial phase of the commercial operation [7]

1.1 Low-medium Enthalpy Geothermal System
Most geothermal systems are liquid-dominated. They contain liquid water in all channelways and interstitial pores (Figure 3). Groundwater recharge is not as restricted as in the vapor-dominated case, although alteration zone may be extensive. Hot waters from reservoir commonly leak at the earth’s surface (Figure 4). Temperature and pressure will increase steadily with increasing depth. If the rate of upflow is rapid, boiling springs or geysers will form and temperature changes with depth will closely follow the boiling-point curve. That is why liquid dominated reservoirs have maximum temperatures of ≤ 370°C and have widely ranging salinities [8], which is made it more common to found low-medium enthalpy geothermal system.

Low-medium enthalpy geothermal system is a geothermal system whose reservoir temperature below 150°C [9]. It is widely distributed and available in many countries, which has huge potential to generate power as huge as high enthalpy geothermal system. What makes it is different is how to manage and control it. Also, low enthalpy geothermal is now become an option for power generation in many developing countries. The utilization of the low-medium enthalpy geothermal energy varies from direct use, heat pump, and also binary power generation to generate small capacity of electricity.
Scaling in Geothermal Field

Scaling, especially silica scaling could happen if the concentration of overall silica exceed the solubility of amorphous silica [9]. Which means that scaling could happens whenever some mineral composition exceed it’s solubility limit that could lead to mineral deposition, which is called scaling.
Theories has been added [10] which said that scaling from geothermal fluids has been recognized as a major obstacle in the development of geothermal energy. Following are different types of scaling which is could affect the power generation in geothermal system. First is the most common scaling in low enthalpy geothermal system, (1) calcium carbonate (calcite) scaling. Calcium carbonate (CaCO₃) forms a dense, extremely adherent deposit. It is by far the most common scale problem in low and medium temperature geothermal systems. The mechanism of CaCO₃ scale formation can be described as follows: almost all geothermal fluids contain significant quantities of dissolved CO₂(aq) and HCO₃⁻. The flashing of the vapour phase and the CO₂ release cause a pH increase. As a result, supersaturation conditions are established and CaCO₃ is deposited. Second type of the scaling in geothermal is (2) heavy metal sulphide scaling. The heavy metals at the high temperatures of the brines are mainly transported as chloride complexes. Additionally, the precipitation of metal sulphides is promoted by two other factors, i.e. the temperature decrease, since the solubility of most sulphides significantly increases with temperature, and the "enrichment" of the residual brine in heavy metals because of steam separation. In heavy metal sulphide scaling, a measure to mitigate the problem is the prevention and control of corrosion of the pipes. Last but not least type of scaling is (3) silica and metal-silicates scaling. Amorphous silica (SiO₂) is deposited from virtually all high temperature geothermal fluids and sometimes from some medium temperature fluids. The mechanism of silica deposition is neither simple nor well understood. Another characteristic of the silica deposits is that they are present in every part of the geothermal installation and they are not confined to a relatively short part immediately after the flashing point. A significant problem is encountered in brine reinjection systems, where the precipitated silica colloids can block the pores of the reinjection formation.

Solids formation is one of the most important factors that restrict in many cases rate and scales of using the geothermal system resources [11]. Previous research said that basic part of solids consists of the following components: oxides, sulphides of iron, calcium carbonate, and dioxide of silicium SiO₂ (silica) [12]. The content inside silica solids formation seems become the major cause that lead to scale formation, because of its natural characteristics to form a solid compaction.

Silica scaling is the largest problem that displays practically at all geothermal fields (Figure 2), especially at the high temperature, because fluid forms in contact with rocks where silicium is the basic rock-forming element. The solubility of silica is decreasing when temperature decreases. As opposed to carbonate, silica deposition is controlled by kinetics and can begin on the surface in several minutes or hours after reaching supersaturation. Silica scaling are hard to mechanical removal [12].

Geothermal field which is associated with volcanic-hydrothermal system such as most geothermal fields in Indonesia, has high temperature with high silica content in the thermal fluid, which means there is high possibility of silica scaling in many geothermal field in Indonesia. Silica that mostly found in geothermal field are quartz silica which is hard to overcome after it’s formed scale because it’s crystalline characteristic. Then if the silica scaling was already happened, acidizing using acid solution (usually sulphate acid, H₂SO₄) is the only way to resolve the scaling problem, mostly. This is because crystalline characteristic of quartz silica make it impossible to resolve silica scaling using mechanical removal. However, mechanical removal using water jetting combined with Coiled Tubing Unit (CTU) called RotoJet could resolve the problem of silica scaling after it’s happened [4].

Despite of that, after the silica scaling removed, silica still circulating inside the geothermal field and reservoir which means silica scaling still could happens in the future even after it was removed.

1.3 Membrane Technology
Membranes have gained an important place in chemical technology and are used in a broad range of applications. The key property that is exploited is the ability of a membrane to control the permeation rate of a chemical species through the membrane. In controlled drug delivery, the goal is to moderate the permeation rate of a drug from a reservoir to the body. In separation applications, the goal is to allow one component of a mixture to permeate the membrane freely, while hindering permeation of other components [6].
Based on [6], membrane are divided into two types of membranes which is isotropic membranes and anisotropic membranes. Isotropic membranes consists microporous membranes and dense membranes (Figure 5). Beside, anisotropic membranes consists of Loeb-Sourirajan membrane, and thin-film composite membrane (Figure 6).

![Symmetrical Membranes](image1) ![Anisotropic Membranes](image2)

**Figure 5.** Isotropic membrane principle types [6]  
**Figure 6.** Anisotropic membrane principle types [6]

In fact, the vast majority of membranes used commercially are polymer based. However, in recent years, interest in membranes formed from less conventional materials has increased. Ceramic membranes, a special class of microporous membranes, are being used in ultrafiltration and microfiltration applications for which solvent resistance and thermal stability are required. Dense metal membranes, particularly palladium membranes, are being considered for the separation of hydrogen from gas mixtures, and supported liquid films are being developed for carrier facilitated transport processes. Difference between microporous and dense membrane described by Figure 7 and Figure 8.

![Microporous membranes](image3) ![Dense solution-diffusion membranes](image4)

**Figure 7.** Microporous membranes separate by molecular filtration [6]  
**Figure 8.** Dense solution-diffusion membranes separate because of differences in the solubility and mobility of permeants dissolved in the membrane material [6]

In short, membrane technology often use to separate unwanted particle inside some solution, chemical or else. The separation are based on size of the particle. Different types of driving force of the separation process are used according to some reasons based on the membrane principle.

[13] mentioned that there are types of driving force uses in membrane transfer theory. There are driving force using pressure, concentration, thermal, electical, and hybrid. Membrane for physical separation as mentioned before commonly used membrane with pressure as it’s driving force. Membrane
with pressure as driving force basis are grouped by the size of it’s pore which is microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO).

In this paper, microfiltration (MF) membrane would be used according to it’s pore size that is match the size (smaller than the size of silica particle). We assume that the silica particle has average size of 100 μm so microfiltration (MF) membrane with pore size 10 μm could be used. The detailed information of microfiltration (MF) membrane can be seen in Table 1.

### Table 1. Comparison of membrane process with pressure based driving force [14]

| Parameter                | Reverse Osmosis | Nanofiltration | Ultrafiltration | Microfiltration |
|--------------------------|-----------------|----------------|-----------------|-----------------|
| Membrane                 | Asimetric       | Asimetric      | Asimetric       | Simetric        |
| Thin film thickness      | 150 μm          | 150 μm         | 10-150 μm       | 150 μm          |
| Pore size                | < 0.002 μm      | < 0.002 μm     | 0.2-0.02 μm     | 4-0.02 μm       |
| Reject                   | NaCl, Glucose, Amino acid | Mono-, di-, and oligosaccharides, negative ion polyvalen | Macro molecule, protein, polysaccharides | Particle, clay, bacteria |
| Membrane material        | CA, thin polyamide | Polyamide | Ceramic, PSO, PVDF, CA, thin film | Ceramic, PP, PSO, PVDF |
| Membrane module          | Tubular, spiral wound, plate and frame | Tubular, spiral wound, plate and frame | Tubular, hollow fiber, spiral wound, plate and frame | Tubular, hollow fiber |
| Operate pressure         | 15-150 bar      | 5-35 bar       | 1-10 bar        | < 2 bar         |

2. Methodology

Methodology flow chart (Figure 9) represent that first important thing to obtain is the thermal fluid data and characteristics, especially for brine that would enter the binary system. The data should consist silica concentration which is used to determine the value of Silica Saturation Index (SSI) and further binary power generation calculation later. Also, thermodynamic properties such as temperature and pressure of the thermal fluids are needed for thermodynamic calculation and kinematic scaling.

Initial calculation includes the calculation of SSI value and binary power generation before the silica rejected from the thermal fluids. The initial calculation has to be done first so the efficiency of silica rejection using membrane could be determined then.

After thermodynamic properties and silica concentration value obtained, membrane technology determination could be done. It is consist membrane pore size calculation, membrane module selection, and membrane material consideration. Membrane pore size and material are based on pressure and temperature data of the fluid in the field. When membrane module selection would be based on the thermodynamic data and the consideration of the research which is the best module to be used at the moment. In the end of the membrane determination process, there is membrane application to the thermal fluids in the system which is could correct the value of SSI and binary power generation too. However, membrane technology determination in this paper only based on ideal data, which is complex calculation are neglected.

Final calculation then could be conducted by using the corrected SSI value to calculate the improved binary power generation, by also double-check the data in initial calculation which enable the comparison between them.

At the end of the process, silica-free thermal fluid would be reinjected to the reservoir through reinjection well after passed through binary system. When the silica-rich thermal fluid that separated early by using membrane could be rejected at the surface and not reinjected along with the silica-free thermal fluid back to the reservoir.
2.1 Kinematic Scaling

First thing first, some data has to be there to prove that silica scaling is happening. Ratio between concentration of silica and concentration of amorphous silica then become the value of Silica Saturation Index (SSI) which indicates occurrence of the silica scaling if the value exceeds 1. Besides, silica scaling will only occur provided that SSI is greater than 1 and is generally not problematic for SSI values <1.4, depending on temperature [15].

Much work has been done to correlate the equilibrium solubilities of quartz and amorphous silica in water at different temperatures [16]. There seems to be good agreement in the literature for temperatures below 300°C. Two correlation that agree well with the literature are provided as equations (1) and (2), respectively, where the solubility dependence of quartz and amorphous silica with temperature are described. Equation (1) [16] and equation (2) [17] are the following:

\[
\log C = -\frac{1309}{T} + 5.19 \tag{1}
\]

\[
\log C = -\frac{731}{T} + 4.52 \tag{2}
\]

where C is the concentration of silicic acid (mg/kg or ppm) and T is the absolute temperature in Kelvin. Both equations are valid for systems at the temperature of 0-250°C. Meanwhile, [2] said there is simplified method to estimate silica scaling potential in geothermal power plants. The following correlation for amorphous silica solubility, s (T,m = 0), as a function of the absolute temperature, T (in kelvins) [18];

\[
\log_{10} s = -6.116 + 0.01625T - 1.758 \times 10^{-5}T^2 + 5.257 \times 10^{-9}T^3 \tag{3}
\]

To obtain s in mg/kg or ppm, one must multiply s as found from equation (3) by 58,400.

The concentration of silica found from equation (3) then could be used to reassure the concentration of silica in equation (1) and (2), so the actual temperature limit could be obtained.

Main purpose of the method is to decrease the overall concentration of silica in the thermal fluid, so the value of SSI could be reduced. By doing so, the thermal fluid could be used in binary power plant discussed later in the paper.

Figure 9. Methodology flow chart
2.2 Case Study

Published data by [19], average of overall data, SiO\textsubscript{2} content (quartz) in thermal fluid said that the concentration of silica exceeded 600 ppm with the temperature of brine 170°C. Current actual data published by [19] presented in Table 2. According to that, we assume the value of SSI = 1 means there is silica scaling potential at multiple possible location such as piping instrumentation or reinjection well, with the amorphous silica concentration is 600 ppm by assumption. Using the equation (2) we calculated the temperature limit of silica scaling occurrence is 419 K (146°C). To reassure the value of temperature limit, we used the temperature obtained from equation (2) to the equation (3) which we obtained concentration of silica 578 ppm. Since the concentration of silica are quite similar, we resumed the calculation.

| Separator     | Cl (ppm) | SiO\textsubscript{2} (ppm) | pH  | Temperature (°C) | SSI |
|---------------|----------|-----------------|-----|-----------------|-----|
| SEP 1A        | 1137.00  | 673.00          | 7.76| 173.5           | 0.96|
| SEP 1B        | 995.00   | 610.00          | 8.60| 175.3           | 1.27|
| SEP D         | 1092.00  | 727.00          | 8.84| 178.3           | 1.38|
| FLASH 1A+1B   | 1196.08  | 720.12          | 8.20| 120.0           | 1.93|
| FLASH D       | 1219.92  | 825.34          | 8.48| 120.0           | 2.59|
| BINARY 1A+1B | 1057.62  | 638.03          | 8.20| 100.0           | 1.98|
| BINARY D      | 1092.00  | 727.00          | 8.84| 100.0           | 2.92|

Using microfiltration (MF) membrane with pore size 10 μm [14] and using assumption of rejection rate ± 25% could ideally change the concentration of overall silica that has approximately greater than 100 μm [16] from 600 ppm to 450 ppm (with the assumption that concentration of amorphous silica are constant due to could not be rejected by membrane). Then we resume to calculate the temperature limit using equation (2) which yield temperature 391 K (118°C). Equation (3) then used to reassure the temperature limit, where the concentration of silica are quite similar, which is 430 ppm. The value of SSI then not exceeded 1, that is become 0.75, assumed would not has silica scaling potential.

Main benefits of using membrane as prevention strategies for silica scaling was the enhanced potential of developing binary cycle power plant as bottoming unit. Binary cycle power plant used heat from brine which will decrease the temperature of the brine. As been discussed before, temperature is a key factor to silica scaling problem. The lower the temperature, the higher the potential for silica scaling. But, when membrane is used to the brine pipe system, lower limit of temperature could be used, which means there is much more heat that could be used for binary cycle power plant.

In this study, a binary cycle power plant model was made to see how much the improved generated power when the membrane was installed into the brine piping system. There are 5 main components in this binary cycle, preheater, evaporator, turbine, condenser, and pump as shown in Figure 10. Each component is calculated using basic thermodynamic equation.
2.2.1 Preheater and Evaporator. Preheater and evaporator are basically a heat exchanger that transfer the heat from heating fluid to working fluid. In binary cycle, this component is essential because the steam of working fluid formed here before generate electricity by transfer its energy in the turbine. The two heat exchangers may be analyzed separately as follows:

Pre-heater:
\[ \dot{m}_{hf} C_{hf} (T_B - T_C) = \dot{m}_{wf} (h_5 - h_4) \]  

Evaporator:
\[ \dot{m}_{hf} C_{hf} (T_A - T_B) = \dot{m}_{wf} (h_1 - h_5) \]

2.2.2 Turbine. In the turbine, there is an isentropic expansion process of the steam. The assumption used is neglecting potential and kinetic energy, adiabatic and steady. The equation of the process in a turbine can be analyse as follows:

Turbine:
\[ W_T = \dot{m}_{wf} (h_1 - h_2) = \dot{m}_{wf} \eta_T (h_1 - h_{2s}) \]

2.2.3 Condenser. Condenser is a heat exchanger with opposite function with preheater and evaporator. Unlike the pre heater and evaporator, in condenser the working fluid is releasing the heat energy to another fluid, can be water or air. The heat transfer between working fluid and the cooling fluid analyzed as follow:

Condenser:
\[ Q_{2-3} = \dot{m}_{wf} (h_2 - h_3) = \dot{m}_{cf} C_{cf} (T_x - T_y) \]
2.2.4 Pump. The power to be transferred to working fluid from the pump can be analyzed as follow:

\[
W_p = \dot{m}_{wf} (h_4 - h_3) = \dot{m}_{wf}(h_4 - h_3) \eta_p
\]  

(8)

2.2.5 Calculation Result. In this study, the heating fluid temperature is 170°C at 8.5 bar. The heating fluid flow rate is 772.22 kg/s tapped from reinjection pipe of the main plant. Table 3 shows the calculation of ORC model using isopentane as the working fluids. The limitation is on the brine output which is 146°C. That number comes out from the SSI calculation above.

| State  | Brine | Working Fluid |
|--------|-------|---------------|
|        | A     | C             | 1 | 2 | 3 | 4 | 5       |
| T(°C)  | 170   | 146.3         | 156.8 | 78.2 | 31 | 32.1 | 156.8   |
| P (bar)| 8.5   | 8.5           | 20.9 | 1.1 | 1.1 | 20.9 | 20.9    |
| H (kJ/kg)| 719.1 | 616.5         | 534.2 | 441.8 | 7.3 | 11.4 | 352.8   |
| S (kJ/kg.K) | 2.04 | 1.81           | 1.38 | 1.41 | 0.024 | 0.026 | 0.95    |
| (kg/s) | 772.2 | 150           |     |     |     |     |         |

After the membrane was installed to the system, the limitation of the brine output temperature can be decreased. Temperature limit with installed membrane was decreased from 146°C to 118°C. Table 4 shows the calculation of the ORC model with lower brine output temperature limit. The parameter that is changed to utilize the lower temperature limit of brine is the working fluid mass flow rate used in the ORC model.

| State  | Brine | Working Fluid |
|--------|-------|---------------|
|        | A     | C             | 1 | 2 | 3 | 4 | 5       |
| T(°C)  | 170   | 121.8         | 145.8 | 75.0 | 31.0 | 31.9 | 145.8   |
| P (bar)| 8.5   | 8.5           | 17.4 | 1.1 | 1.1 | 17.4 | 17.4    |
| H (kJ/kg)| 719.1 | 511.9         | 521.5 | 428.2 | 7.3 | 10.6 | 316.4   |
| S (kJ/kg.K) | 2.04 | 1.55           | 1.36 | 1.39 | 0.02 | 0.03 | 0.87    |
| (kg/s) | 772.2 | 310           |     |     |     |     |         |

Table 5 shows the comparison of temperature limit for binary cycle model when a membrane was installed into the brine piping system.

| T_L (°C) | Brine T_in (°C) | Brine T_out (°C) | \( \dot{m}_{wf} \) (kg/s) | Power Generated (MWe) |
|----------|-----------------|------------------|---------------------------|------------------------|
| 146      | 170             | 146.3            | 150                       | 13.46                  |
| 118      | 170             | 121.8            | 310                       | 26.13                  |

Where \( T_L \) is temperature limit or the lowest temperature of brine before the SSI value become 1 and \( \dot{m}_{wf} \) is mass flow of working fluid. Power generated is the net value, calculated by subtracting the gross power generated by the generator to required power for the pump and fan. The working fluids used in this study is isopentane.
Assumed parameters for the binary cycle model is turbine outlet pressure or condenser pressure that set to 1.5 bar for isopentane. Turbine inlet pressure and working fluid flow rate is optimized depend on temperature limit of heating fluid. Pinch point temperature of the heat exchanger was set to 5°C, and efficiency for pump, turbine, and generator are 75%, 85%, and 95% respectively.

3. Result and Discussion
This paper concludes that the use of membrane technology seems possible and very promising to solve silica scaling problem in order to enhance binary power plant energy output, by assuming:
   (1) The condition we calculated in this paper are in ideal condition, where silica with higher size (approximately 100 μm) than the pore size of microfiltration membrane (10 μm) are assumed completely rejected.
   (2) Overall assumption and condition of the membrane are not complex detailed where the technical and economical details were neglected.

Instead, this paper gives review about the possibility to maximize binary power plant energy output (in ideal condition) by the use of membrane technology that is to increase the limitation of decreased temperature after used by binary cycle which is described in many aspects, and also solving the silica scaling problem along the way. What makes the membrane technology more promising in solving silica scaling problem is that there is a chance to completely reject the silica inside the thermal fluid to the surface so it would not come back to the reservoir or the power plant systems. By doing so, prevention of silica scaling problem in the future would not just an expectations, and the sustainable geothermal industries could be achieved in any liquid dominated geothermal field.

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References
[1] Ellis A J and Mahon W A J 1977 Chemistry and geothermal systems Academic Press New York
[2] DiPippo R 1985 A simplified method for estimating the silica scaling potential in geothermal power plants Geothermal Resources Council BULLETIN
[3] Kaya T, Parlaktuna M, Demirici N, Giiney A, Dedeoğlu V, and Kaya R 2010 Effectiveness of the acidizing and mechanical reaming of geothermal production well in Kizildere geothermal well in 2009 Proc. of the World Geothermal Congress 2010
[4] Putra B R, Souvanir T, Abu Dawud H, Arstianti H, and Purba E 2018 Work over breakthrough: coiled tubing unit cleaned out totally plugged scales Proc. of 7th ITB Int. Geothermal Workshop 2018
[5] Setiawan F A, Panthron P M H, Alfredo D, and Perdana, I 2015 Mitigation of silica scaling from Dieng’s geothermal brines using Ca(OH)2 Proc. of Indonesia Int. Geothermal Convention & Exhibition 2015
[6] Baker R W 2012 Membrane technology and application 3rd ed. John Wiley and Sons West Sussex UK
[7] Engineering and Consulting Firms Association (ECFA) Japan 2006 Preventions and solutions for the scale problem at the geothermal power plant and CDM study in Indonesia Tohoku Electric Power Co. Inc
[8] Sirgudsson H 1999 Encyclopedia of volcanoes Academic Press A Harcourt Science and Technology Company
[9] Brown K 1998 Scaling and geothermal development Geothermal Institute The University of Auckland New Zealand
[10] Andritsos N, Karabelas A J, and Koutsoukos P G 2002 Scale formation in geothermal plants Conf. Paper of Int. Summer School on Direct Application of Geothermal Energy

[11] Thomas D M and Gudmundsson J S 1989 Advances in the study of solids deposition in geothermal systems Geothermics 18 5-15

[12] Kashpura V V and Potapov V N 2000 Study of the amorphous silica scales formation at the mutnovskoe hydrothermal field (Russia) Proc. of 25th Workshop on Geothermal Reservoir Engineering

[13] Wenten IG, Khoiruddin, Hakim, A N, and Aryanti, P T P 2012 Teori perpindahan dalam membran Teknik Kimia Institut Teknologi Bandung Bandung, Indonesia

[14] Mulder M 1996 Basic principle of membrane technology 2nd ed, Klower Academic Publisher

[15] Brown K 2011 Thermodynamics and kinetics of silica scaling Proc. from the Int. Workshop on Mineral Scaling

[16] Ngothai T, Lane D, Kuncoro G, Yanagisawa N, Rose P, and Pring A 2012 Effect of geothermal brine properties on silica scaling in enhanced geothermal systems GRC Transactions 36

[17] Fournier RO and Rowe 1977 The solubility of amorphous silica in water at high temperatures and pressures American Minerologist 62 1052-1056

[18] Fournier R O and Marshall W L 1983 Calculations od amorphous silica solubilities at 25° and 300°c and apparanant cation hydration numbers in aqueous salt solutions using concept of effective density of water Geochim. Cosmochim. Acta. 47 587-596

[19] Agani M, Patangke S, Hartanto D B and Silaban M 2015 Opportunity and barriers to develop a bottoming unit by utilizing separated hot brine in Ulubelu, Indonesia Proc. of World Geothermal Congress 2015 Melbourne