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Geothermal well behaviour prediction after air compress stimulation using one-dimensional transient numerical modelling

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Abstract. The non-discharges geothermal wells have been a main problem in geothermal development stages and well discharge stimulation is required to initiate a flow. Air compress stimulation is one of the methods to trigger a fluid flow from the geothermal reservoir. The result of this process can be predicted by using by the Af / Ac method, but sometimes this method shows uncertainty result in several geothermal wells and also this prediction method does not take into account the flowing time of geothermal fluid to discharge after opening the well head. This paper presents a simulation of non-discharges well under air compress stimulation to predict well behavior and time process required. The component of this model consists of geothermal well data during heating-up process such as pressure, temperature and mass flow in the water column and main feed zone level. The one-dimensional transient numerical model is run based on the Single Fluid Volume Element (SFVE) method. According to the simulation result, the geothermal well behavior prediction after air compress stimulation will be valid under two specific circumstances, such as single phase fluid density between 1 – 28 kg/m³ and above 28.5 kg/m³. The first condition shows that successful well discharge and the last condition represent failed well discharge after air compress stimulation (only for two wells data). The comparison of ρf values between simulation and field observation shows the different result according to the success discharge well. Time required for flow to occur as observed in well head by using the SFVE method is different with the actual field condition. This model needs to improve by updating more geothermal well data and modified fluid phase condition inside the wellbore.

1. Introduction
Geothermal energy developments in Indonesia are constantly faced with several challenges such as exploration and engineering aspects. In engineering, the main goal of geothermal energy utilization is to have it well discharging but sometimes the geothermal wellbore do not show any fluid discharges. This problem is caused by the presence of water column in the wellbore which is standing above the major permeable zone [1] and to initiate flow, a well discharge stimulation is required. One of the effective methods to stimulate non-flowing geothermal well is an air compression method. Basically, this method boosts the energy in the water column by conductive heating at the certain depth. The

(footnotes)

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liquid is depressed and it will increase the potential energy in the compressed gas [2]. Especially in air compression method, the prediction of “well behaviour” after stimulation process can be described by using the Af/Ac method [3]. This method calculates the ratio between two areas in static pressure and temperature profile (defined as Af and Ac) in order to find an association between successful and failed attempts of the well discharge capability after stimulation trial. Sometimes the result of air compress stimulation prediction using the Af / Ac method represents a different outcome than well discharges test trial [1]. The uncertainty result by using previous prediction might be minimized with numerical modelling which describes the geothermal well condition during stimulation process. The one-dimensional numerical modelling method which is used in this study is modified by using Single Fluid Volume Element method (SFVE) in siphon system [4]. The modified model will be adapted to geothermal well condition during air compress stimulation process. The simulation result of this condition model will be expected to predict geothermal well behaviour after air compress stimulation (based on static pressure and temperature profile data).

2. Basic Theory
In this section all theory involved in the geothermal well stimulation is listed and briefly explained, including geothermal wells principle, wells problem and wells stimulation. In this part also is described the simulation using modified Single Fluid Volume Element method (SFVE).

2.1. Geothermal wells principle and problem
The geothermal wells have the capability to produce heat from sub-surface. The main process of geothermal wells system are heat and mass transfer of geothermal fluid from the reservoir to the earth's surface [5]. Especially in liquid-dominated geothermal system, the produced fluid can flow under the following condition.

\[ P_{\text{reservoir}} > P_{\text{hydrostatic}} + P_{\text{air inside the well}} \]  

(1)

According to the Equation (1), in order to discharge, reservoir pressure must be greater than the sum of hydrostatic pressure of water column and the air pressure inside the well. Geothermal wells are divided into two types based on discharge capability such as artesian well and non-artesian well [1]. Artesian geothermal well refer to the natural geothermal fluid flow through well casing to the surface and fulfil Equation (1) condition after opening the wellhead valve. Conversely, the non-artesian well refer to the no discharge behaviour after opening the geothermal wellhead. It is caused by the shallow water column inside the wellbore. This type of wells located in the liquid dominated geothermal systems which have varying elevation and consequently the water column in each well show a different depth [1]. The presence of water column at the shallow level inside the geothermal well will increase the hydrostatic pressure.

2.2 Geothermal wells stimulation and previous prediction method
The problem of non-artesian geothermal wells can be solved by using several stimulation methods. The principle of those stimulation methods is to decrease hydrostatic pressure inside the wellbore by reducing the density or thickness of water column [1]. There are several methods of well stimulation for non-artesian type such as air (or gas) compression, gas lifting, and well-to-well two phase injection and all of these methods are usually used in liquid dominated geothermal systems. In particular, the air compression method boosts the energy in the water column by conductive heating at the certain depth to which the liquid is depressed [2]. The water column temperature is increased by this phenomena and it will change the fluid density of a water column (flashing). This condition will initiate a discharge mechanism [2]. All of the circumstances before air compress stimulation are shown in Figure 1 and after air pressure compress shown in Figure 2.
In air compression method, the successful prediction of the well discharge has been developed by a simple empirical formulation [3]. Basically, this formulation calculates the ratio between two areas such as Af and Ac. Af refers to the flashing area that is limited by the saturation temperature of the water column with wellbore temperature. Ac is the condensation areas including near the wellhead that is limited by the temperature curve in the well and the curve of 100 °C. The ratio between Af and Ac of some targeted wells were taken together with water column level before stimulation to find an association between successful and failed attempts, yet there are several limitations of this formulation. The first condition is an initial limiting case; the upper well temperature must be around 100 °C.

<table>
<thead>
<tr>
<th>Af/Ac</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Af/Ac &lt; 0.70</td>
<td>Low discharge probability</td>
</tr>
<tr>
<td>Af/Ac &gt; 0.85</td>
<td>High discharge probability</td>
</tr>
<tr>
<td>Af/Ac = 0.70 – 0.85</td>
<td>Uncertainty range</td>
</tr>
</tbody>
</table>

Following to the Table 1, a ratio of Af and Ac less than 0.7 refer to the low discharge probability and the wells with Af/Ac above 0.85 define as high probability to discharge. A ratio between both values (0.75 to 0.85) is an uncertain result [3]. Sometimes, this well discharge prediction shows different result with a field data information on several geothermal wells.
2.3 Single Fluid Volume Element (SFVE)

The uncertain results by using the Af/Ac ratio can be minimized by developing a simple well model which represents the condition of non-artesian well before and after air compress stimulation. The wellbore model will be simulated based on well data, such as pressure, temperature and mass flow for each depth. One of the methods to represent the well stimulation process are one-dimensional transient flow simulation and this method related to physical processes in geothermal wellbore. This study is conducted by simulation of transient fluid flow in self-siphons using Single Fluid Volume Element Method (SFVE). Basically, this study can be modified to predict the flow occurrence in the geothermal systems.

SFVE method is a finite difference based method, which is used to solve equations of motion of a single fluid volume element. This element represents the transient motion of the fluid along its channel. Details of illustration and derivation of this method for vertical, horizontal, inclined, and semi-circular pipes can be found in [4], while only required equations are presented in this work. The element will have pressure force of fluid above and below it.

\[ F_p = \rho g \left( z + \Delta h - z \right) A \]  

where \( A \) is well cross section, \( \Delta h \) thickness of the element, \( z \) position of the element, and \( \rho \) is the fluid density, which is in general

\[ \rho(T, p) = \frac{\rho_0}{1 + \beta(T - T_0)} \frac{1}{1 - (p - p_0) / E} \]  

with \( \rho_0 \) = initial density (kg/m\(^3\)), \( E \) = Bulk modulus fluid elasticity (N/m\(^2\)), \( \beta \) = Volumetric temperature expansion coefficient (m\(^3\)/m\(^3\) °C), \( T_0 \) = Initial temperature (°C). In this study, \( \beta \) coefficient is assumed in the water condition (0.0002 m\(^3\)/m\(^3\) °C at 20 °C) and the \( E \) coefficient is also assumed in the water condition (2.15 \times 10^9 N/m\(^2\)) [8]. The initial density, pressure and temperature are taken in the specific depth. Temperature and pressure are also functions of depth \( z \), which are provided by temperature- and pressure-depth profile. There is also force due pressure drop related to the position of the element relative to the initial position of shallow water column \( z_0 \).

\[ F_d = -\rho g \left[ z - z_0 \right] A \]  

Gravitation plays also a role of the element through

\[ F_g = -\rho g A \Delta h \]  

The last considered force is viscous drag between the element and its channel

\[ F_v = -8\pi \eta \Delta v \]  

as in [4], which is modified from [6]. Parameter \( v \) is a velocity of fluid element and fluid viscosity \( \eta \) is also a function of temperature

\[ \eta(T) = \eta_0 \times 10^{27.8/\left(T - 140\right)} \]
with $\eta_0 = 2414 \text{ cP}$ and $T =$ fluid temperature (°K). Other forms [7] of Equation (7) can also be used. Then, using Newton second law of motion, acceleration of fluid element is

$$a = \frac{1}{\rho A \Delta h} \left( F_p + F_s + F_g + F_f \right)$$

Integration of Equation (7) will produce velocity, and integration will produce position. Numerical

The method used is the simple Euler method.

$$v(t + \Delta t) = v(t) + a(t) \Delta t$$

and

$$z(t + \Delta t) = z(t) + v(t) \Delta t$$

Iteration though Equations (2) - (10) from an initial time to final time will give transient dynamics of a fluid element with thickness $\Delta h$. Based on simulation process, there are two condition to represent well behaviour in this study. The well behaviour is divided into two types such as discharge well and no discharge well after air compress stimulation. For simulation purpose, two termination conditions can be implemented, which $z > z_{\text{well head}}$ for the first type and $v < \varepsilon$ for the second type.

3. Geothermal wells properties

Data from two different wells are used in this work for testing the simulation, where “Well-A” represents unsuccessful well and “Wells-B” represents successful wells after air compress stimulation [1]. Figure 3 and Figure 4 show profiles of temperature-depth and pressure-depth of both wells.
According to the Figure 3 and Figure 4, the pressure and temperature profile are represented by a blue and red line. The “Wells-A” has shallow water position at -350 m, temperature about 40 °C, pressure of 1 MPa, and it fails to discharge, where a “Wells-B” has shallow water position at about 200 m, temperature about 70 °C, pressure of 5.4 MPa, and it is successful to discharge.

4. Result & discussion
Simulation parameters in this study are $\Delta h = 10$ m and $\Delta t = 10^{-4}$ s. According to the simulation results which is given in Figure 5. It is found that the crossover between the flow and no flow states is located between values $\rho_f = 28$ kg/m$^3$ and $\rho_f = 28.5$ kg/m$^3$ for the well “Well-B”, while for the “Well-A” all values of $\rho_f$ give no flow. The $\rho_f$ parameter refer to the final density of fluid element after simulation process ended. Following to the simulation result, the $\rho_f$ value of single phase fluid also can be defined simply through

$$\rho_f = \alpha \rho_{\text{water}} + (1-\alpha)\rho_{\text{vapor}}$$  \hspace{1cm} (11)

or

$$\alpha = \frac{\rho_f - \rho_{\text{vapor}}}{\rho_{\text{water}} - \rho_{\text{vapor}}}$$  \hspace{1cm} (12)

In this study $\alpha$ is denoted as density fraction of water. The value of $\alpha$ is between $2 \times 10^{-4}$ and $2.72 \times 10^{-2}$ for the previous range of $\rho_f$ simulation result. It is very vapour-rich mixture of water and vapour. For the success discharge well after air compress stimulation, the $\rho_f$ can be measured in the geothermal well head. Based on “Well-B” observation data which is give a positive result after stimulation process, the $\rho_f$ value is approximately 990 kg/m$^3$. It means that the simulation result using SFVE method (match observation only for values 1 kg/m$^3 < \rho_f < 28$) is not approach the field data measurement. Time required for flow to occur as observed in well head is about 80 s simulation time, which is too short compared to real required time about more than 1000 second.

This unrealistic result that the density of the discharged fluid is too light and discharge time is too short shows that implementation of SFVE, which considers a single-phase fluid, does not work well. The advancement of this method by considering two-phase flow. The unrealistic result can be reached.
due to the assumed static pressure-depth profile, which in reality changes during performing the SFVE.

5. Conclusion
The prediction of well behavior after air compress stimulation using 1-dimensional transient numerical modeling based on two geothermal wells will be valid with two specific circumstances. The first condition is single phase fluid density ($\rho_f$) between 1 – 28 kg/m$^3$ and the second condition is above 28.5 kg/m$^3$. Based on simulation result, the first condition shows successful well discharge and the second condition represents failed well discharge after air compress stimulation (only for two wells data). The comparison of $\rho_f$ values between simulation and field observation shows the different result according to the success discharge well. Time required for flow to occur as observed in well head by using the SFVE method is different with the actual field condition. This model needs to be improves by modifying Single Fluid Volume Element (SFVE) method with two-phase flow assumption and collect more geothermal wells data with successful and failed discharge after stimulation.

Reference