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Stimulation program of air compression and nitrogen injection in geothermal well

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Abstract

Non-self-discharge (non-artesian) well is one of the problems often faced in geothermal development. This problem can be identified using several methods. However, not all methods can be used because it requires data that only be obtained after a discharge test. The failure of self-discharge well is due to the presence of a water column above the main feed zone, which makes the hydrostatic pressure higher than the reservoir pressure at static conditions. Therefore, stimulation is needed to initiate the discharge of the well. There are many methods of well stimulation have been developed. This paper aims to program the stimulation of geothermal well using air compression and nitrogen injection methods with a case study on WBA well. The output parameter in air compression is the compression pressure needed to suppress the height of the water column, whereas in nitrogen injection is the amount of liquid nitrogen required to reduce the density of the water column.

Keywords: Non-artesian well, well stimulation, air compression, nitrogen injection

1. Introduction

In the completion phase of a geothermal well, the discharge test is the last step to prepare a well to become a production well. Before the test carried out, it is crucial to predict whether the well can self-discharge or not. Based on the chance of discharge, geothermal wells divided into two types: wells that can flow fluids to the surface naturally (artesian wells) and wells that cannot naturally flow fluids to the surface (non-artesian wells). Non-artesian wells often found in wells with a liquid dominated reservoir system. The leading cause of this well is the presence of a water column, which causes hydrostatic fluid pressure higher than the reservoir pressure when the well is shut-in. Therefore, well necessary to be stimulated (jump-start). This paper aims to provide an overview of geothermal well stimulation programs about what parameters need to be considered, and how to obtain them so that the well can return to self-discharge by limiting the discussion of two discharge prediction methods and the two stimulation methods used.

This paper is organized as follows. The second section describes Af/Ac method and Distance from the static water level to the feed zone method for discharge prediction. Then, section 3 explains about the air compression and nitrogen injection program. Section 4 is a case study of stimulation program. Last, conclusion for this study enclosed in section 5.

1.1. Nomenclature

Notation	Description	Unit
A_c	Area of condensation	grid block
$dP = P_2$	Difference between well pressure and saturation pressure in feed zone	mpa

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dP/dL	Pressure drop gradient	pa a/m
A_f	Area of flashing	grid block
BPD	Boiling point of depth	deg C
ρ_m	Mixture density	kg/m3
L_{sub}	Distance between water level until nitrogen target	m
dL= $L_{airpipe}$	Distance between casing head flange until nitrogen injection target	m
P_{MPZ}	Feed zone pressure	mpa
P_1	Gas pressure at standard conditions (0.101325)	mpa
T_{MPZ}	Feed zone temperature	deg C
T_1	Temperature gas at standard conditions (273)	K
T_2	Average water column Temperatu re	K
v_1	Specific volume of gas at standard conditions (0.7996)	m^3/kg
$v_2 = v_{ga}$	Specific volume of gas at wellbore	m^3/kg
v_{air} @ T_2	Specific volume of water at T_2	m^3/kg
v_m	Mixture specific volume	m3/kg
x	Dryness	fraction
v	Bubble velocity	m/s
D_{ch}	Diameter of pipe characteristics	m
R_i	Radius of tubing	m
R_o	Radius of casing	m
α	Void fraction	fraction
A_{ann}	Annular area	m^2
W	Nitrogen injection flow rate	kg/s
$V_{liquidN2}$	Required liquid volume of nitrogen	gallons
mMD	Meter measured depth	
masl	Meter above sea level	

2. Discharge Prediction

According to Mubarok & Zarrouk (2017), several methods can be used to predict geothermal well discharges, such as:

- Af/Ac method
- Liquid hold up method
- Analytical radial flow simulation
- Numerical radial modelling
- Distance from static water level to feed zone

Based on the five methods above, three methods, except the Af/Ac method and the distance from static water level to the feed zone method, require data that is not available before the discharge test. Although the research showed accurate prediction results using retrospective data, the usability of these methods, in practice, is not recommended as a first choice and also less commonly used.

2.1. Af/Ac method

The ratio of Af/Ac is a method of predicting the success of geothermal well discharges developed empirically by Stock (1983) then applied directly to geothermal wells in the Philippines by StaAna (1985). The Flashing Area (Af) is the area in the curve bordered by the saturation temperature profile and the temperature profile in the wellbore. This area represents the extra energy contained above the saturation energy [1]. Whereas the Condensation Area (Ac) is the area near the wellhead, which is bordered by a temperature of 100 deg C and the temperature profile in the wellbore. This area represents the energy that must be overcome by the fluid as it moves upward toward the wellhead. The Af and Ac areas obtained by calculating grid blocks of the curve. The value criteria of the Af/Ac ratio to predict the success of well discharge shown in Table 1.

Table 1. Range criteria of Af/Ac ratio [2]

Value of Af/Ac	Explanation
Af/Ac < 0.7	Low Chance Well to Discharge
Af/Ac > 0.85	High Chance Well to Discharge
Af/Ac = 0.70 – 0.85	Uncertain Well to Discharge

2.2. Distance from static water level to feed zone method

This method is a new method developed by Mubarok & Zarrouk (2017) by researching geothermal wells in Indonesia with results, as shown in Fig 1. It is simple and requires the least amount of parameters to be able to analyze.

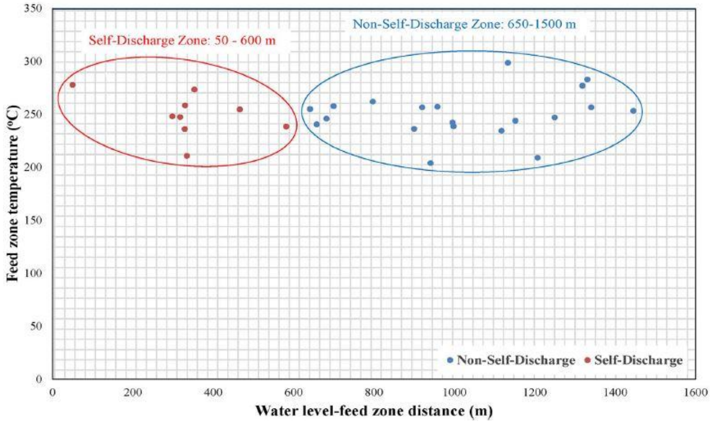

Fig. 1. The distance between the water level and the feed zone depth [1]

Based on the research, it concluded that shorter distance between water level and feed zone, the higher possibility of well to discharge. If the range is between 0 - 600 m, the well is capable self-discharge, whereas if it has a distance of more than 600 m, the well will not self-discharge. Nevertheless, this method only works for wells with a minimum feed zone temperature of 200°C.

3. Geothermal Well Stimulation

Well stimulation is an attempt to make non-artesian well to be able to self-discharge by reducing the hydrostatic pressure of the water column in the wellbore [3]. Five methods can be used to stimulate geothermal wells [1], such as:

- Air compression
- Well to well stimulation
- Nitrogen lifting
- Water lifting
- The steam injection uses a portable boiler.

3.1. Air compression

Air compression method operated by connecting the high-pressure air compressor to the valve (kill line) on the wellhead [4]. Facilities for well stimulation using an air compressor shown in Fig. 2. The parameter that needs to be determined in this stimulation program is compression pressure. The compression pressure calculated using the hydrostatic pressure formula as follows.

$$P_c = \rho_{air} g h_c \quad (1)$$

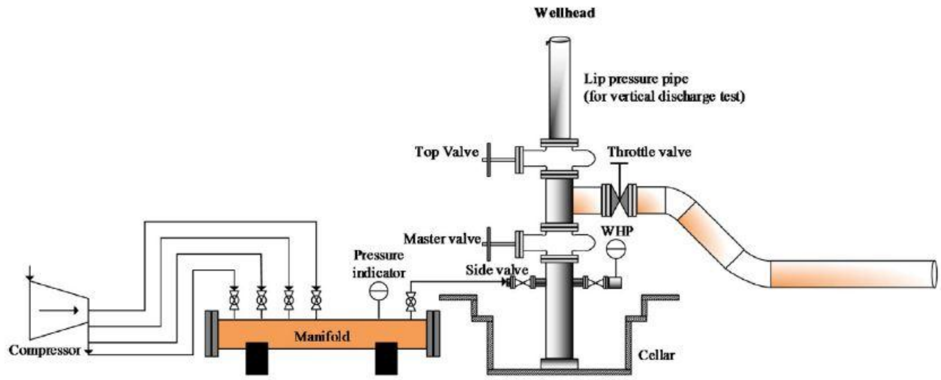

Fig. 2. Facilities for air compression stimulation [1]

Compressed air will press and push the water column into the formation where the maximum depth of suppression, in practice, only to the bottom of the casing shoe production, because the next section is an open hole with a slotted liner [5]. The success of air compression injection developed using empirical equations [3]. It is done by trial and error the Af/Ac method to obtain a ratio > 0.85. The success of the stimulation program ensured by calculating the hydrostatic pressure of the water column where if it is smaller than the reservoir pressure, the well can self-discharge. Air compression stimulation is the simplest and cheapest method with a high proven success rate [1]. Besides, this method does not require complicated facilities, mobilization, or installation [4].

3.2. Nitrogen injection

Nitrogen injection stimulation method performed by injecting nitrogen into the well through a coil tubing unit (CTU). Injecting is conducted below the water level to reduce the density of the water column. A schematic graph of nitrogen injection stimulation presented in Fig. 3.

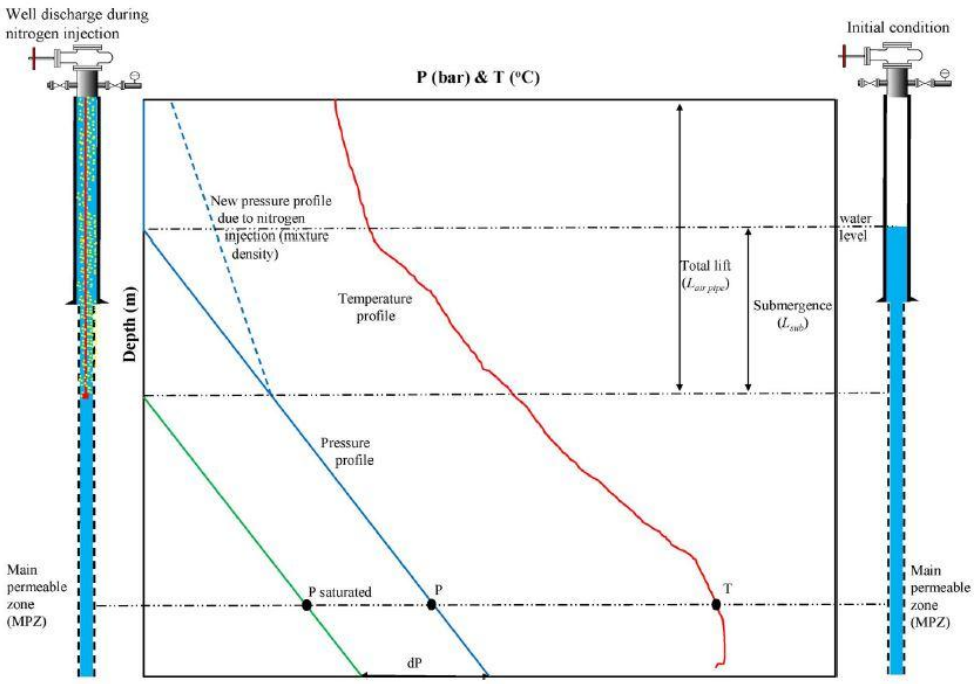

Fig. 3. Schematic graph of nitrogen injection [1]

The actual injection of nitrogen up to well discharged takes the time 30 minutes to 3 hours. However, the preparation of well and equipment requires a minimum time of a week [6]. The nitrogen injection stimulation method is not an inexpensive operation [6]. The high cost of this method makes it the last option when other cheaper plans (air compression and well to well stimulation) do not succeed in initiating well discharge [7]. Therefore, if this method fails, the well will not discharge [1].

The parameter that needs to be determined in this stimulation program is the volume of liquid nitrogen before it is gasified and injected into the well with the calculation proceeds as follows:

- Calculate the delta pressure

$$dP = P_{MPZ} - P_{sat@MPZ} \tag{2}$$

- Calculate the length of the water column that needs to be removed

$$L_{sub} = \frac{dP}{(g\rho_{water})} \tag{3}$$

  Besides using the formula, L_{sub} obtained from the zero point distance between the pressure profile and the saturation pressure profile obtained using Equation 1.
- Calculate coiled tubing unit depth

$$L_{airpipe} = L_{sub} + h_{waterlevel} \tag{4}$$

- Calculate the pressure drop

$$\left(dP/dL\right) = \left(dP/L_{airpipe}\right) \tag{5}$$

- Calculate mixture density

$$\rho_m = \frac{dP/dL}{g} \tag{6}$$

- Calculate the specific volume of gas at standard conditions, which is calculated by the mixture gas law (Boyle, Charles and Gay-Lussac's laws)

$$v_{gas} = \frac{P_1 v_1 T_2}{dP T_1} \tag{7}$$

- Calculate the specific volume of the water column at the average temperature condition using a steam table
- Calculate mixture specific volume

$$v_m = \frac{1}{\rho_m} \tag{8}$$

- Calculate the mass fraction of nitrogen

$$x = \frac{v_{mix} - v_{water}}{v_{gas} - v_{water}} \quad P_c = \rho_{air} g h_c \tag{9}$$

- Calculate the diameter characteristics of the pipe [8]

$$D_{ch} = \pi\left[R_i + \left(\frac{R_o - R_i}{2}\right)\right] \tag{10}$$

- Calculate the bubble velocity through the casing

$$v_{gas} = 0.2935\left(2gD_{ch}\right)^{\frac{1}{2}} \tag{11}$$

- Calculate Rise Time [9]

$$RiseTime = \frac{L_{sub}}{v_{gas}} \tag{12}$$

- Calculate the Void Fraction, using the following formula

$$\alpha = \frac{1}{1+\frac{\left(1-x\right)^{0.8}}{x}\frac{v_{water}}{v_{gas}}^{0.515}} \tag{13}$$

- Calculate the area of the annulus

$$A_{ann} = \pi R_o^{\,2} - \pi R_i^{\,2} \tag{14}$$

- Calculate the nitrogen gas flow rate.

$$W = \frac{A_{ann}\left(1-\alpha\right)}{\vartheta_{gas}} v_{gas} \tag{15}$$

- Calculate the required volume of liquid nitrogen [10]

$$V_{liquidN_2} = W.RiseTime \tag{16}$$

4. Case Study: WBA Well

WBA well planned as a production make up well to supply steam to PLTP 2 of the "XT" geothermal field. This well is a directional well with a kick-off point at 400 mMD, a deviation angle of 40 deg, an altitude of 627 masl, and an atmospheric pressure of 0.925 bar. The WBA well has three sets of casings and two sets of slotted liners. WBA well profiles presented in Table 2.

WBA well is in the completion stage, with the latest status has been completed heating-up test. Some of the critical data obtained from the test, such as the main feed zone location at 1227.96 mMD with a static pressure of 64.69 bar, a static temperature of 246.81 deg C, and saturation pressure of 37.7 bar. Besides, WBA wells occurred boiling at a depth of 580 mMD with water levels of 508.28 mMD and average temperatures of 109.84 deg C.

After a heating up test for several months, the well will be carried out a discharge test to determine the well's output and to plan a suitable surface production facility. However, before doing that test, the prediction of the success discharge needs to be analysed early to determine whether the well stimulation necessary to do or not.

Table 2. Well profile of WBA well

Parameter	Value
CHF Elevation, masl	627
Casing 30", m	0-48
Casing 20", m	0-480
Casing 13-3/8", m	0-1064
Casing 10-3/4" (Slotted Liner), m	1016-1861
Casing 10-3/4" (Slotted Liner), m	1852-2069
Well Status Info	Heating-up Test
Kick-off Point, m	430
Total Displacement, m	457
True Vertical Depth, m	1830
Total Depth, m	2069
Well Direction	N 297 ºE

4.1. Discharge prediction of WBA well

The prediction was done using the Af/Ac method and the distance from the static water level to feed zone method. In the Af/Ac method, the prediction made by plotted a static PT graph, saturation temperature (BPD), and an iso-temperature line of 100 deg C, as shown in Fig 4.

The value of Af is difficult to determine because the area formed is tiny, while the value of Ac is four so that the ratio of Af/Ac is close to zero. Besides, it is known that the distance between the water level and the main feed zone is 719.69 mMD from the water loss test data. Based on two methods of success discharge prediction above, WBA well cannot discharge naturally with an Af/Ac ratio <0.85 and the distance of the water level to the feed zone is more than 600 m. The prediction results then validated with a hydrostatic pressure profile that higher than the static pressure profile. In order to make a WBA well can self-discharge, well stimulation is necessary. In this paper, well stimulation program of WBA well using air compression and nitrogen injection methods.

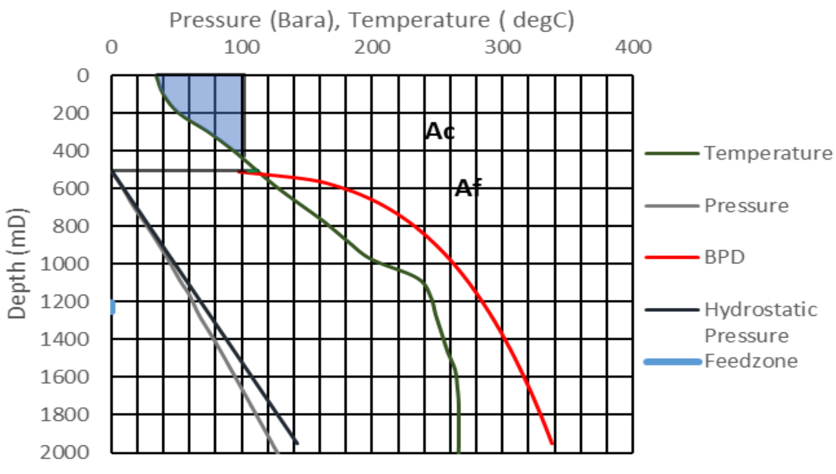

Fig. 4. Success discharge prediction using Af/Ac method

4.2. WBA well stimulation

- Air Compression
  Air compression stimulation operated using a compressor to inject compressed air into the well. The injection conducted until the wellhead pressure of WBA well reaches the targeted compression pressure, which is calculated by trial & error method. Trial & error applied to the depth segment of the water column, which is suppressed by computing the area of Af and Ac formed. The final depth of the water column is changed to obtain the value of Af/Ac ratio higher than 0.85. The profile results of WBA well stimulation program using air compression method presented in Fig 5.

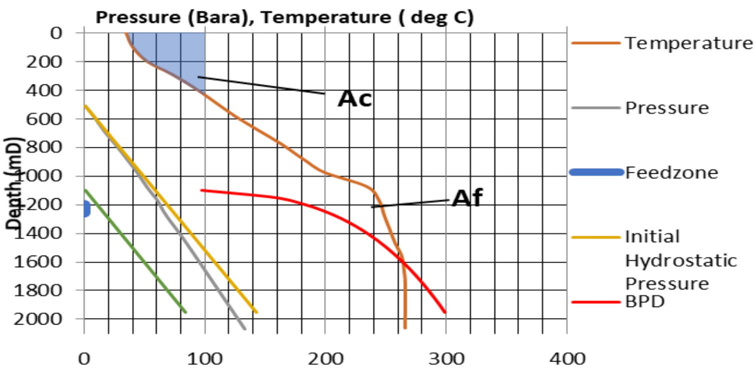

Fig. 5. Result of air compression program

When the water column pressed to a depth of 1100 mMD, an Af value is 3.5, and an Ac value is 4. Thus, the Af/Ac value is 0.875 where the value is higher than 0.85. The compression pressure needed to press the water column to that depth as follows.

Pc = 1000 x 9,806 x (1100-508)

= 5802820 Pa

= 58.02 bar

- Nitrogen Injection

The coiled tubing unit used for nitrogen injection is 2 inches with the production casing ID of 13,375 inches. Input parameters and calculation results in the nitrogen injection stimulation program shown in Table 3 and Table 4.

Table 3. Input parameters of nitrogen injection stimulation program

Parameter	Value	Unit
T_1	273.00	K
P_1	0.101325	Mpa.a
V_1	0.7996	m^3/kg
T_2	382.838	K
R_1	0.0254	m
R_0	0.16986	m
Water Level	508.277	m
T_{MPZ}	246.80667	deg C
P_{MPZ}	6.46977	Mpa.a
Psat	3.77	Mpa.a

Table 4. Calculation results of nitrogen injection stimulation program

Parameter	Value	Unit
$dP = P_2$	2.79636	Mpa.a
L_{sub}	285.14906	m
$dL = L_{airpipe}$	793.42606	m
dP/dL	0.00352	MPa.a/m
	3524.40782	Pa.a/m
ρ_m	359.38958	kg/m^3
v_{gas}	0.04063	m^3/kg
$v_{air@T2}$	0.00105	m^3/kg
v_m	0.00278	m^3/kg
x	0.04374	fraction
D_{ch}	0.30672	m
vg	0.71987	m/s
Rise Time	396.11257	s
α	0.3576	fraction
A_{ann}	0.08862	m^2
W	1.00867	kg/s
$V_{liquidN2}$	399.54493	kg
	130.62946	gallon

Based on calculations, the Coil Tubing Unit is run in the hole until a depth of 793.42606 mMD with the expectation of a water column that can be removed is 285.14906 mMD as also shown in Fig 6. The time required for bubbles to rise is 396.11257 second with a mass flow rate of 1.00822 kg/s. Thus, Nitrogen injection stimulation program requires a liquid volume of nitrogen of 130.62946 gallons.

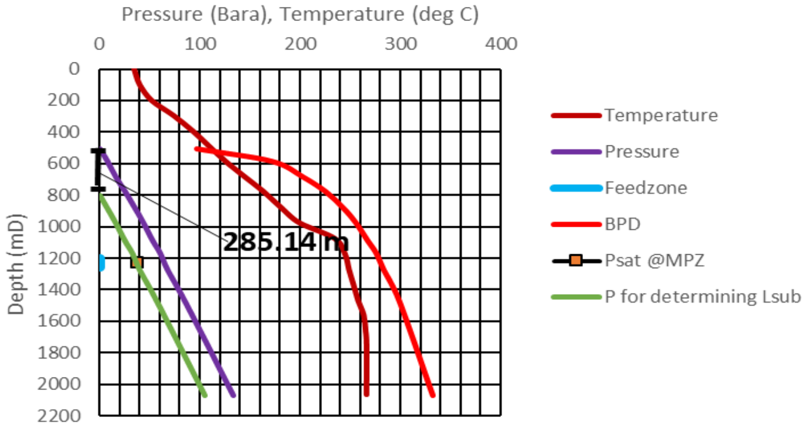

Fig. 6. Lsub determination

5. Conclusion

- WBA well is predicted not to self-discharge because it has a very small Af/Ac ratio (<0.85) and the distance of the water level to the main feed zone is more than 600 m (719.69 m).
- Well Stimulation program using air compression method requires a compression pressure of 58.02 bar to a depth of 1100 mMD to obtain an Af/Ac ratio> 0.85 (0.875).
- Well stimulation program using nitrogen injection method requires a liquid volume of nitrogen of 130.62946 gallons.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

E Budirianto, W A Nugroho, and B N Jayanto conducted the research and analysed the data; W A Nugroho and B N Jayanto wrote the paper; E Budirianto, D R Ratnaningsih and A H Lukmana revised the paper; all authors had approved the final version.

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