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Discharge stimulation of geothermal wells: Overview and analysis

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ABSTRACT

Power output from geothermal wells depends on the measured mass flow rate and flowing enthalpy during production (discharge) testing. Key question before testing the productivity is; will the well self-discharge or not after warm-up. This work demonstrates that the simplest and accurate methods to predict the well will self-discharge or not are the Af/Ac method and the new water level to feed zone method. Five well discharge stimulation techniques are discussed and recommendations were given to the well-to-well stimulation when there is a self-discharge well nearby, while the air compression method should be the first choice in remote wells.

1. Introduction

After drilling a new geothermal well, it is important to carry out completion (well) testing. Completion testing consists of several tests. These include water loss surveys to identify the loss (permeable) zones, injectivity test, pressure falloff test, temperature warm up surveys and finally production/flow test. Well discharge analysis should be carried out before the flow testing to assess whether the well will likely to self-discharge or not, before committing staff time, equipment and funds. Some hot and permeable liquid-dominated wells do not naturally self-discharge the reservoir fluid, thus they are called non-self-discharge wells. Non-self-discharge wells are common in conventional liquid dominated geothermal fields such wells have been reported in Indonesia (Bacquet et al., 2014; Mubarok, 2013; Mubarok and Saptadji, 2015), the Philippines (Algopera, 1980; Aqui, 1996; Sarmiento, 2011; Siega et al., 2005; StaAna, 1985), Costa Rica (Castro-Zuniga, 2015), Iceland (Kajugus, 2015), Iran (Khosrawi, 2015; Kousha and Ghaderi, 2015), Mexico (Luviano and Montes, 2015; Martínez and Armenta, 2015), Kenya (Saitet, 2015) and New Zealand, (authors experience).

Having a non-self-discharge well does not mean that the well will not produce nor has poor productivity. In fact, some non-self-discharge wells have high mass flow, flowing enthalpy and well head pressure (WHP) than some self-discharge wells. However, these wells should be stimulated (jump started/initiated) before discharging fluids. The poor ability of a well to naturally discharge can be related to several factors (Grant and Bixley, 2011; Sarmiento, 1993):

- Deep water levels (> 500 m) from the well head.
- Temperature recovery is very slow and wellhead pressure does not develop by itself.
- Cold water column (due to cold ground) on top of the hot reservoir fluid.
- Well damage during drilling.
- Poor reservoir permeability.
- High elevation terrain (lower water level).
- Small production casing size (higher pressure drop).

Geothermal wells in vapour dominated reservoirs that produce high enthalpy dry or almost dry steam do not encounter such problem, due to the low density of the produced steam, high energy content, generally shallow depth and the lack of cold water column. Geothermal wells, with reservoir pressure that is higher than the hydrostatic head of water are also not affected by this problem, since the reservoir pressure can overcome the water head in the wellbore. Non-self-discharge well is a problem in low to moderate enthalpy (1000–1700 kJ/kg) liquid dominated reservoirs where the reservoir pressure is less than the hydrostatic head of cold water column.

It is not uncommon to have geothermal wells that require discharge stimulation after they are shutdown. This can vary from field to field and we estimate that it affects more than 15–20% of conventional geothermal wells worldwide. The general field practice is to have these wells producing continuously even when they are not in use, this is to save discharge stimulation time and cost. Although this may sound very wasteful, the reality of geothermal energy utilization is that it not about thermodynamic efficiency but rather economic efficiency (viability).

It is important to mention that some geothermal wells may start

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Nomenclature

A	Cross section area (m^2)
Ac	Area of condensation
Af	Area of flashing
BPD	Boiling point of depth (°C)
$CAPEX$	Capital expenditure
CHF	Casing head flange
CTU	Coil tubing unit
D	Diameter (m)
EGS	Enhanced geothermal systems
g	Gravitational acceleration (9.81 m/s^2)
GUI	Graphical user interface
h	Discharge enthalpy (kJ/kg)
H	Distance between water level until nitrogen target (m)
kh	Permeability thickness (Dm)
L	Distance between casing head flange until hydrogen injection target (m)
M	Total mass flow rate (kg/s)
$MAWP$	Maximum allowable working pressure (bara)
MPZ	Main permeable zone
$OPEX$	Operational expenditure
p	Pressure (bara)
PCS	Production casing shoe
PI	Productivity index (kg/Pa s^2)
Qf	Flowing quality
Qs	Static quality
r	Radius (m)
S	Saturation
Sr	Submergence ratio
STP	Standard temperature and pressure
T	Temperature (°C)
v	Velocity (m/s)
V	Volume (m^3)
$\bar{v}$	Average velocity of the mixture (m/s)
W	Mass flow rate of nitrogen (kg)
WHP	Wellhead pressure (bara)
x	Dryness (%)
$\frac{dP}{dz}$	Pressure drop gradient (bar/m)

Greek letters

α	Void fraction
μ	Dynamic viscosity (kg/m s)
ρ	Density (kg/m^3)
ϑ	Specific volume (m^3/kg)
Δp	Pressure difference from each point in the well (bara)
ΔZ	Depth difference (m)

Subscripts

a	Acceleration
ann	Annulus
c	Condensation
ch	Characteristic
f	Flashing
$fric$	Frictional
g	Gas (vapour)
gas	Nitrogen
$grav$	Gravitational
l	Liquid
mix	Mixture
res	Reservoir
sat	Saturated
$stat$	Static
sub	Submergence
w	Wellbore
wf	Well flowing
wh	Well head

their production life as self-discharge wells and later become non-self-discharge. This is when the reservoir pressure significantly decline, reservoir temperature reduce with cooling (e.g. reinjection breakthrough, ground water down flow), possibly due mineral scaling in the formation or some other effects. The opposite is also possible, but less likely; discussing this further is outside the scope of this work.

The objective of this study is to analyse and test existing and new well discharge prediction methods. This is including the ratio of flashing and condensation (*Af*/*Ac*) area method (StaAna, 1985), the liquid hold-up method, numerical reservoir simulation, wellbore simulation and the newly proposed ratio of water level to feed zone depth method. Once it is established that the geothermal well will not self-discharge, well discharge stimulation techniques will be considered to promote (jump start) the well. There are five established techniques for well discharge stimulation including air compression, well-to-well stimulation, nitrogen injection, air injection and injection of steam from a portable boiler.

The term stimulation can also refer to improving the permeability of the reservoir near the geothermal well. This is to enhance the productivity or injectivity (water take) of newly drilled wells or geothermal wells with damaged (blocked) formations (e.g. by drilling fluids) or mineral scaling. These techniques typically involve hydraulic fracturing (water enhancement), acidizing (matrix acidizing and acid fracturing), thermal fracturing and other geothermal stimulation techniques (casing perforation, high energy gas fracturing/deflagration, acoustic stimulation and electric stimulation) (Aqui and Zarrouk, 2011; Covell et al., 2016; Malate et al., 2015; McLean et al., 2016; Pasikki et al., 2010). This type of permeability stimulation/enhancement is outside the scope of this work.

2. Well discharge prediction

Discharge testing of a new geothermal well is the final and most important step in any exploration or drilling programme. It is the time when the productivity of the well is measured and the power output is calculated. When the power output is known for any field by the wells production testing, it will be easier for developers to obtain finances, effectively this is when the geothermal development becomes low risk and bankable.

Before embarking on the output testing whether through a vertical or horizontal discharge test setup. It is important to predict if the well is going to self-discharge or not. This is to save on discharge testing cost and time and to select the appropriate discharge stimulation technique, should the well is not predicted to self-discharge.

There are several discharge prediction methods used by the geothermal industry and some proposed in this work.

2.1. *Af*/*Ac* ratio method

This method was originally developed for liquid-dominated geothermal wells by StaAna (1985) to predict whether a well will self-discharge or not before applying air the compression discharge stimulation technique. It is by far the most commonly used method used for predicting well discharge. The tendency of the well to self-discharge or not is predicted by the empirically calculated *Af*/*Ac* ratio. StaAna (1985) showed that *Af* which is the area of steam flashed from liquid is