Orkustofnun, Grensasvegur 9,
IS-108 Reykjavik, Iceland

Reports 2015
Number 13

THE THERMODYNAMICS BEHIND INITIATION OF FLOW FROM GEOTHERMAL WELLS

Jason G. Gotuato
Energy Development Corporation - EDC
38/F One Corporate Centre Building
Julia Vargas corner Meralco Avenue
Ortigas Center, Pasig City, 1605
PHILIPPINES
gotuato.jg@energy.com.ph / jasongotuato@yahoo.com

ABSTRACT

Air-lift pumping and air compression are two techniques used to initiate flow from medium- and high-temperature geothermal wells. This paper aims to explain further the thermodynamic concepts of these methods. Spreadsheet models were developed to gain understanding of the technical requirements for a successful well discharge, and in planning the aforementioned methods of stimulation.

1. INTRODUCTION

Geothermal wells are the conduit for geothermal fluids to flow from the reservoir to the surface. They can be characterized into: low temperature (< 150°C), medium temperature (150-200°C) and high temperature (> 200°C) wells. Figure 1 illustrates a typical schematic diagram of a casing program for a high-temperature geothermal well. The low-temperature wells are used for district heating or direct use and high-temperature wells for power generation. These wells can be further subdivided based on the formation pressure into two: artesian and non-artesian wells. Artesian wells are wells which have a water level above the surface and will flow when the wellhead valve is opened. Non-artesian wells have a water level below the surface and must be pumped or stimulated in order to self-flow. Some non-artesian wells will build up gas or steam pressure on top when shut-in and will flow when opened, due to boiling deep in the well (Steingrímsson, 2015). Figures 2 and 3 show typical pressure per depth plots of artesian and non-artesian wells for both low- and high-temperature wells, respectively.

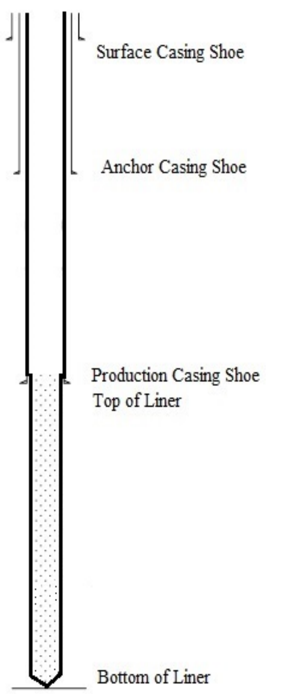

FIGURE 1: Schematic diagram of a geothermal well

Some high-temperature geothermal wells are capable of self-discharge or are simply self-flowing wells. These wells are usually from vapour-dominated systems and those within the naturally-two-phase regions of 1iquid-dominated reservoirs. Many wells, however, are non-artesian. Discharge of these wells can often be initiated by certain methods (Buning et al., 1998).

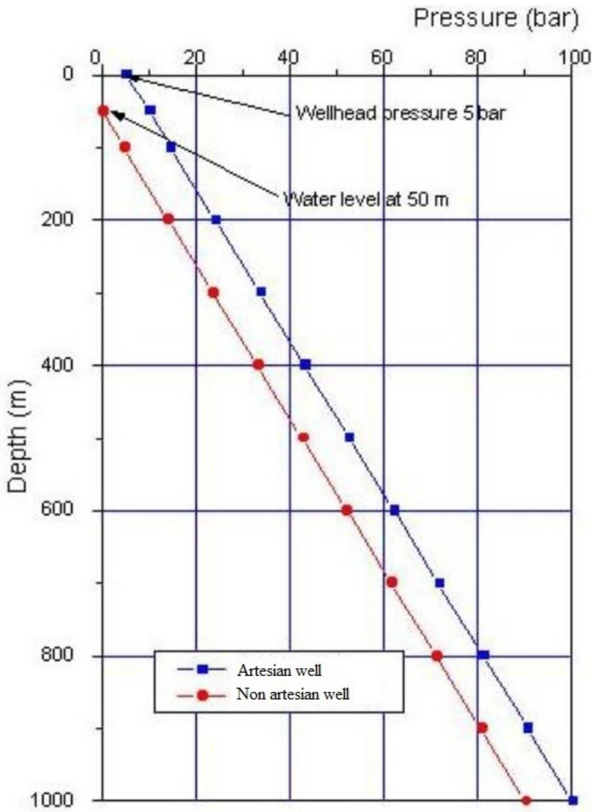

FIGURE 2: Artesian and non-artesian wells for low-temperature systems (Steingrímsson, 2015)

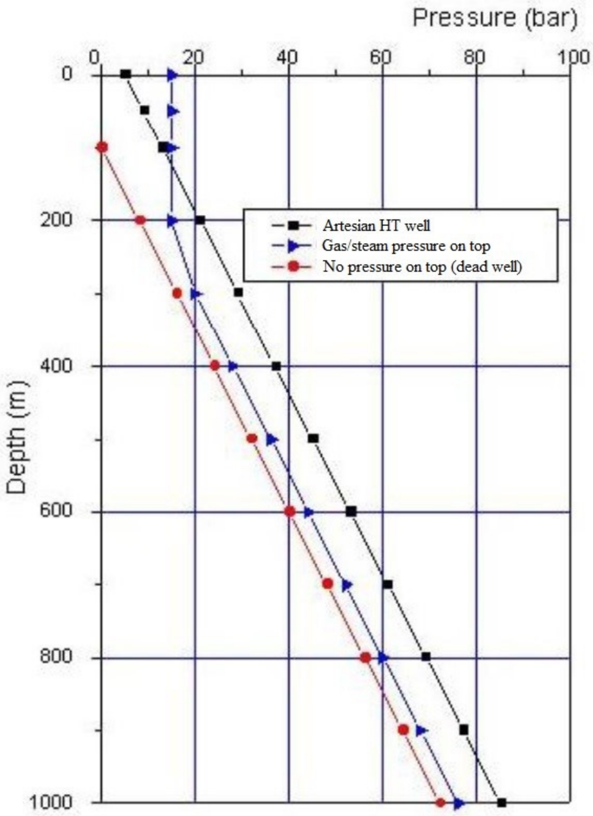

FIGURE 3: Artesian and non-artesian wells for high-temperature systems (Steingrímsson, 2015)

Air-lift pumping and air compression are two methods commonly employed to initiate discharge from geothermal wells. Both methods involve air injection into the well using an air compressor. With the air-lift pumping method, air is injected through a coiled tubing or a drill pipe run into the well to a depth below the water level. The low-density air will lift the water out the well to initiate self-flow, once it is hot enough so boiling of the water supplies sufficient steam to overtake the "air-lifting". With the air compression stimulation, air is injected through a valve (kill line) on the wellhead, depressing the water level. The cold water is pushed down into the hot part of the well to reach the formation temperature at that depth, eventually allowing the well to self-flow once the pressure is rather rapidly released and boiling in the water lifts the fluid to the surface.

2. OBJECTIVE

The objective of the study is to explain the thermodynamics behind the two methods: air-lift pumping and air compression. What are the technical requirements for a successful discharge by air-lifting and compressing of the well?

For the air-lift pumping the questions are, what submergence (distance below the water table) the coiled tubing or drill pipe is required, and what air-compressor rating (pressure and air flow) is necessary for a successful discharge? For air compression, the questions are; what air-compressor rating is required for a certain job and how long does it take to compress a well from zero (initial) to final pressure? What is the minimum water level suppression required to discharge the well successfully by compression alone? What other key factors need to be considered for a well to attain successful discharge and to maintain self-flow?

3. METHODOLOGY

The two methods, air-lift pumping and air compression, will be explained operationally and technically, using concepts learned from thermodynamics and fluid dynamics. Literature research will be the first step in describing these concepts. The discussion will focus on what is really happening inside the wellbore.

Spreadsheet models were developed as part of this report to aid in the analysis and guide the design of these two procedures. MS Excel will be used to develop these models together with X-Steam, an add-in function in Excel for steam properties (http://xsteam.sourceforge.net/). The first spreadsheet model for air-lift pumping aims to simulate success of the air-lift operation, if the flow will reach the surface after inputting certain parameters, such as air volume injected trough the coiled tubing below the water level in the well. The second spreadsheet model for the air compression aims to simulate how much air volume, or what capacity of compressor is needed to compress a well, given the initial and desired pressure and compressor time. The third spreadsheet model, also for air compression aims to simulate success of air compression, if the pressure profile attained immediately after the air discharge is sufficient for the well to self-flow, given the reservoir formation temperature and pressure. The fourth spreadsheet model was developed to simulate the flowing pressure and temperature profile from the bottom to the top of the well. This is a two-phase simulator that aims to answer whether the well will sustain self-flow or not. The HOLA wellbore simulator program (Björnsson et al., 1993) was also used to calculate the temperature and pressure profiles of flowing wells. The spreadsheet model results are compared to the HOLA results and to actual measurements made in flowing wells (dynamic logs).

Actual field data gathered from initiating jobs for wells to flow and flowing wells in the Philippines are used for this project to confirm the model predictions. Data, such as initial wellhead pressure, downhole temperature and pressure logs, duration of stimulation method, target wellhead pressure, compressor rating etc., will be used. The data are analysed and serve as an actual example after learning the physics behind the stimulation process.

4. AIR-LIFT PUMPING

In air-lift pumping or gas-lifting, coiled tubing, drill pipes, or hoses are run into the hole from the wellhead to depths below the water level in the well. Compressed air or nitrogen gas is then injected through the pipes, causing the water column in the annulus to bubble as the air flows back to the surface. The fluid density at the water/air column will then decrease, causing the aerated fluid level to rise. This method is commonly applied to freshwater wells, often referred to as air-lift pumping. In the oil industry, this type of method is also used for producing oil wells that have stopped producing because of severe pressure drawdown in the reservoir (Sarmiento, 2011). The schematic diagram for the typical air-lift pumping in freshwater wells is shown in Figure 4. The arrangement in geothermal wells is similar except the production casing serves as the eductor pipe and the wellhead diverter is more robust.

The common terms are the following:

- *Discharge level* is the level where the discharge line is.
- *Static water level* is the depth where the water level is at static condition.
- *Pumping water level* is the depth where the water level is during air-lift pumping.
- *Eductor pipe* is a temporary pipe installed in large diameter groundwater wells but is not practical to install in high-temperature geothermal wells.
- *Air line* is the coiled tubing, drill pipe, or hose installed from the wellhead to set depth below the water level.
- *Starting submergence* is the length of the air line submerged below the static water level.

- *Pumping submergence* is the length of the air line submerged below the pumping water level.
- *Total starting lift* is the distance from the discharge level to the static water level.
- *Total pumping lift* is the distance from the discharge level to the pumping water level.

To start and maintain air-lift pumping, air pressure and volume flow rate are essential. To overcome the initial pressure the air pressure must reach the starting submergence pressure at the lower end of the air line. The air volume flow rate injected becomes the most essential factor in the success of an air-lift pumping after the pressure has initiated flow (Australian Drilling Industry Training Committee, Ltd., 1997). Figure 5 shows how the addition of different volumes of air affects the water flow pattern in the borehole.

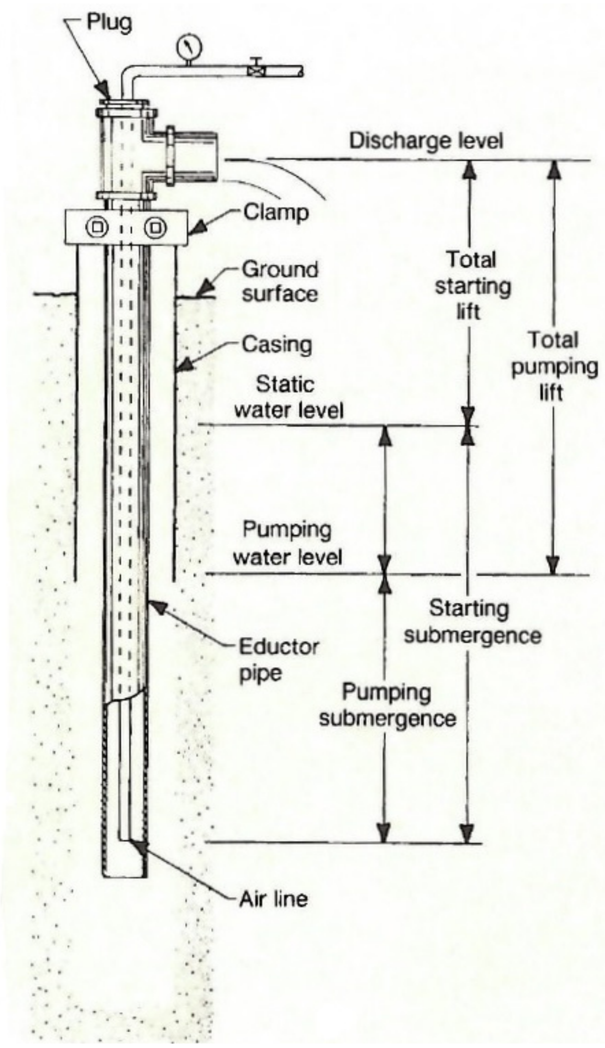

FIGURE 4: Schematic diagram of a typical air-lift pumping set-up with the common terms used (Ingersoll-Rand, 1971, in Driscoll, 1986)

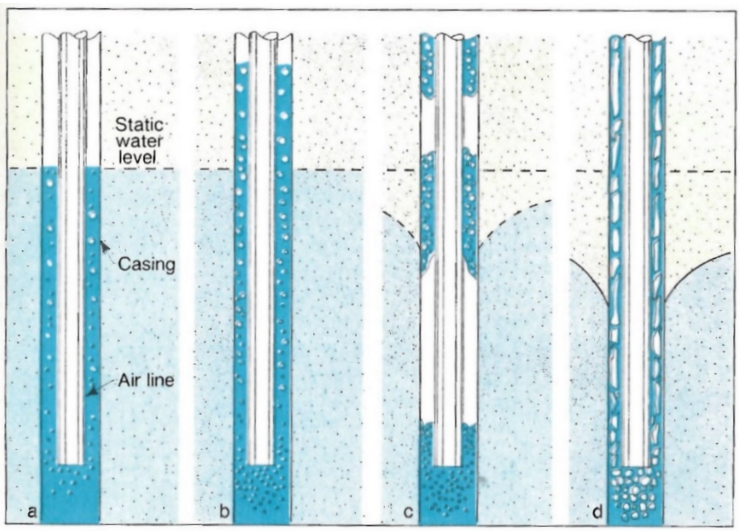

FIGURE 5: This diagram shows how the two-phase (air and water) flow behaves during air-lift pumping; (a) Introduction of air into the well shows no change at the water level because the first air injected is just enough to overcome the initial head exerted by the water column; (b) As the volume of injected air increases, the water becomes partly aerated as it rises up the well; (c) Aerated water surges or is lifted out of the casing irregularly as the air injected further increases; (d) If injected air is sufficient, aerated water will flow steadily out of the well, but note that excessive air volume might actually decrease the flow rate of water (Driscoll, 1986)

5. AIR COMPRESSION

Stimulation by air compression involves mobilizing and connecting a high-pressure air compressor to the wellhead. The air injected will cause the cold water column to be pressed down and into the hotter portion of the well. The well is then shut for hours or days to give ample time for the suppressed cold water to heat up. If the fluid heats up to a sufficient temperature, it should overcome pressure and heat losses as it rises up the wellbore and initiate boiling. Once the valve of the well is opened for discharge, the flow should reach the surface if the attempt for discharge is successful (Sarmiento, 2011).

Prior to the start of compression, the field engineer shall gather the relevant well information for the stimulation work, such as casing burst pressure, branch limit pressure, wellhead conditions, target wellhead pressure, temperature and pressure profile of the well, casing depth, etc. The engineer and operators shall mobilize the air compressor to the site with all the accessories: pressure rated hose, swivel joints and pipe, wing valve adaptor, fuel, stud bolts, seal ring and other necessary tools. The set-up of the air compressor, and the arrangement of the swivel joints and pipe from the valve of the well to be compressed to the discharge line of the air compressor, shall be planned accordingly and have whip-stop cables on connections for safety. After the installation of the pressure rated hose, swivel joints, and pipes, the connections should be checked for leakages and if they are securely in place. The installed pressure gauges at the wellhead must also be inspected to ensure that they are in good working condition and calibrated.

The wellhead pressure build-up should be monitored during the compression. The engine and the discharge line going to the well should be checked for any abnormal conditions. Leaks should also be checked and repaired immediately if any are observed. The pressure in the discharge line should be released before the repairs. The switch on the air compressor should be changed from load to unload after achieving the desired wellhead pressure of the well. The pressure build-up on the wellhead can take hours or days, depending on the capacity of the compressor and the wellhead pressure considered necessary to stimulate the well to flow. When the wellhead pressure is reached, the well is kept shut-in for a number of hours or days (sometimes a week) for heating up until the well is ready for discharging.

Figure 6 shows a hypothetical well pressure and temperature profiles prior to and after air compression. The wellhead pressure prior to air compression is 1 bar-a and the water level is at 500 m with a temperature of about 80°C, at that depth. During the air compression, the wellhead pressure rises up to 70 bar-a and the water level becomes depressed to 1500 m, to the production casing shoe, where the temperature is about 300°C. At around 1400-1600 m, the temperature profile overlaps with the boiling point depth curve, which indicates a tendency of boiling around that depth.

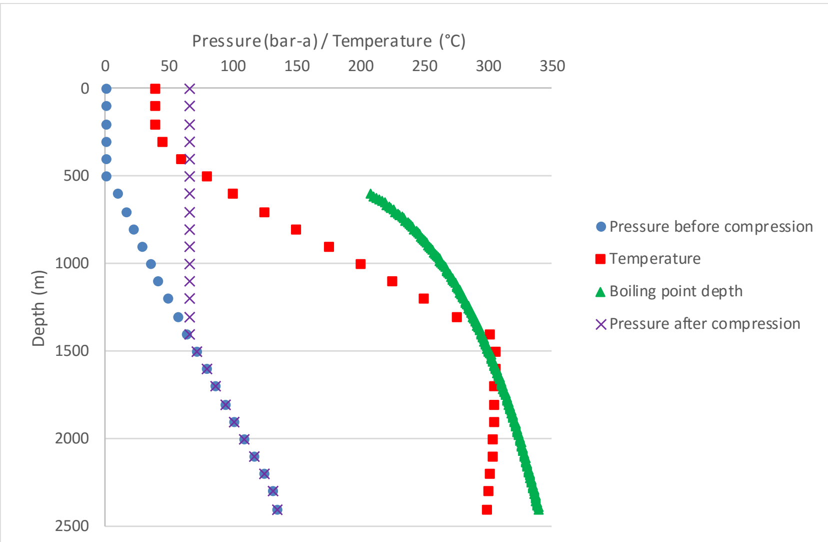

FIGURE 6: Temperature and pressure downhole profiles of a non-artesian well prior to air compression

The water column that is depressed encounters high formation temperature which increases its energy content (enthalpy). The rapid release of pressure is made by opening the valve at the wellhead and allowing the air to escape. Pressure reduction then occurs which causes the fluid to flow up the wellbore. Some of the water flashes to steam due to the energy released during pressure reduction (Colina et al., 2008). The boiling process for the model calculations is adiabatic (iso-enthalpic) as the heat loss is minor from the well to the formations.

The maximum depth to which the water level can be compressed is down to the first loss zone, but typically only down to the depth of the production casing shoe, because the next section is the open hole with a slotted liner, and air injected there will just diffuse out into the formation. Usually, the well is compressed to the maximum allowable pressure, taking in consideration the pressure rating of the discharge lines and of the wellhead.

6. MODELS

Spreadsheet models are developed as part of this report for air-lift pumping, air compression, and two-phase simulation. The design, formulas, input and output parameters are discussed in the following sections. Practical guidelines or "rules of thumb" from handbooks/guidelines were used to select parameters to be used for a successful air-lift pumping. To verify the two-phase simulator model results a wellbore simulator program called HOLA, and dynamic well logging measurements were used.

6.1 Air-lift

6.1.1 Rule of thumb

Guidelines for designing air-lift pumping operations have been established based on field experience as described by Driscoll's "*Groundwater and wells* (1986 - 2nd ed.)" book and the manual from the Australian Drilling Industry Training Committee Ltd. (1997) entitled "*Drilling: the manual of methods, applications, and management*". The design procedure will be explained by the following example.

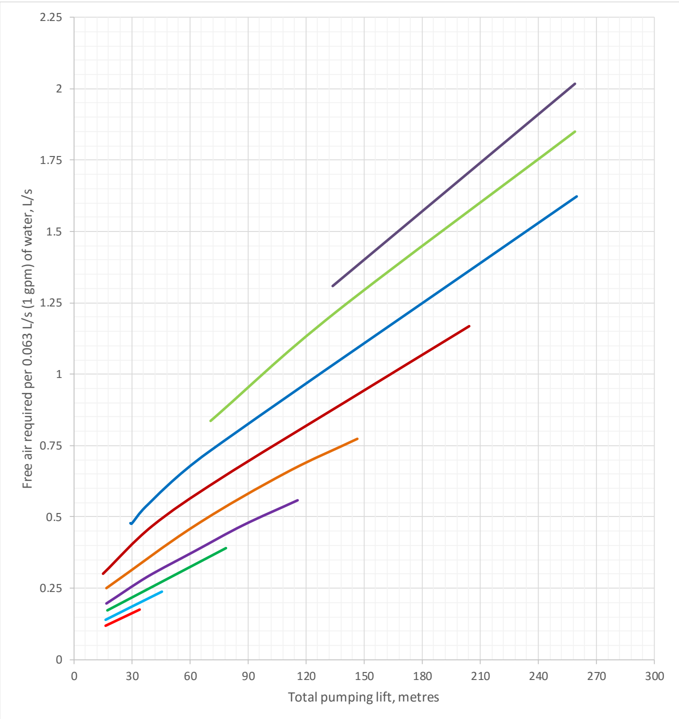

FIGURE 7: Air volume (cfm) required to pump 0.063 L/s (1 gpm) of water for various submergence percent and total pumping lift combinations (modified from Ingersoll-Rand, 1971, in Driscoll, 1986)

To overcome initial head created by the submergence of the air line into boreholes 90-120 m deep, the compressor used for air supply should have a minimum pressure of 8.6 bars. The air volume flow rate is the most important factor in successful air-lift pumping once the pressure initiates flow. The rule of thumb is that for each 0.063 L/s (1 gpm) of water, the proper compressor capacity for air-lift pumping is to provide about 0.35 L/s (3/4 cfm) of air.

The total pumping lift, the pumping submergence, and the cross-sectional area of the casing are the factors to be considered for the air volume requirement to operate air-lift pumping efficiently in freshwater wells. Figure 7 shows the graphical relation of some of these factors. For maintaining steady flow, the air-volume requirements will usually be greater than those given in the figure. The actual volume of air required may be two to three times the volume shown in the figure for deep boreholes with low static water levels. Table 1, on the other hand shows the suggested sizes of eductor pipes (not applicable as the casing is used) and air line for air-lift pumping, but some changes in sizes may be necessary for practical reasons.

TABLE 1: Recommended pipe sizes for air-lift pumping (modified from Driscoll, 1986)

Pumping rate*		**Size of well casing if eductor pipe is used**		**Size of eductor pipe (or casing if no eductor pipe is used)**		**Minimum size of air line**	
gpm	**L/s**	**in**	**mm**	**in**	**mm**	**in**	**mm**
30-60	1.8-3.79	4	102, or larger	2	51	½	13
60-80	3.79-5.05	5	127, or larger	3	76	1	25
80-100	5.05-6.31	6	152, or larger	3 ½	89	1	25
100-150	6.31-9.46	6	152, or larger	4	102	1 ¼	32
150-250	9.46-15.8	8	203, or larger	5	127	1 ½	38
250-400	15.8-25.2	8	203, or larger	6	152	2	51
400-700	25.2-44.2	10	254, or larger	8	203	3	64
700-1000	44.2-63.1	12	305, or larger	10	254	3	64
1000-1500	63.1-94.6	16	406, or larger	12	305	4	102

*Actual pumping rate is dependent on percent submergence

The length of the air line below the pumping water level, divided by the total length of air line suspended in the well, and multiplied by 100 is equal to the pumping submergence percentage. When the pumping submergence is about 50 percent, the air-lift pumping is quite efficient for wells with about 60-150 m of total pumping lift and 40 percent for 150-270 m. Figure 8 shows the guideline for optimum submergence for a given pumping lift.

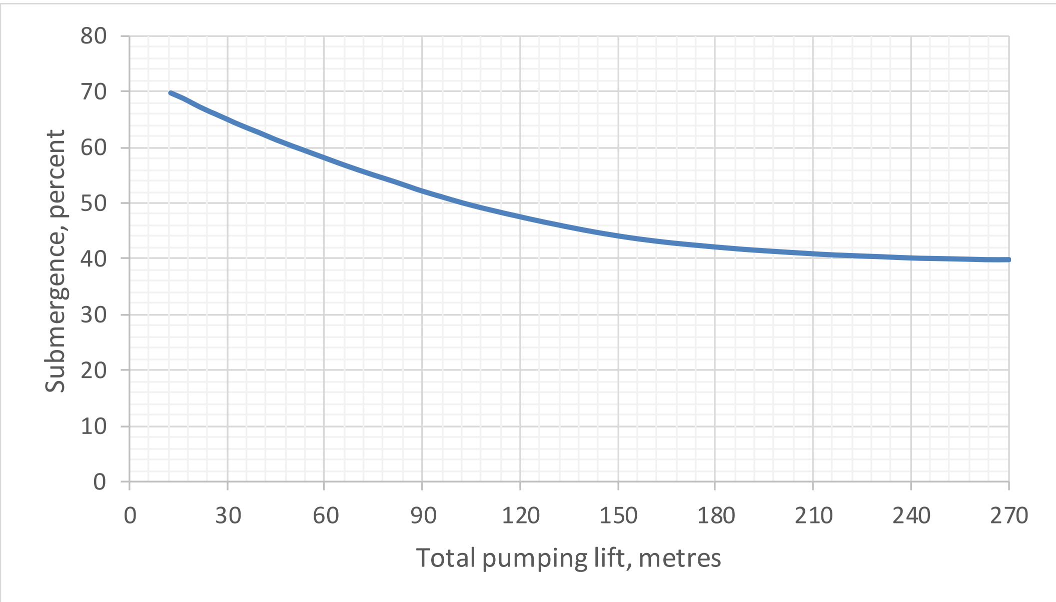

FIGURE 8: This graph serves as a guideline of pumping submergence for optimum air-lift efficiency (modified from Ingersoll-Rand, 1971 in Driscoll, 1986)

Not taking time to analyse and consider the operational characteristics of an air-lift may lead to inefficient pumping, lost time, and in some cases, failure to pump any water. The example below from

Driscoll's book "Groundwater and wells", shows the factors that should be considered for designing a successful air-lift pumping operation.

Figure 9 shows, as an example, a 254-mm (10-in) diameter cased well with a total depth of 123 m and screened from 110 to 123 m. Static water level is at 30 m. It is decided to air-lift pump at a rate of 38 L/s (600 gpm), 20 percent above the design rate of 31.5 L/s (500 gpm). Pumping water level would be at 61 m. The following are the steps for selecting the proper size of equipment for air-lift and for estimating the potential efficiency of the system:

- Step 1 is to determine the diameter of the eductor pipe, if required, and the air line. Use Table 1 for this step. It shows that a 203-mm (8-in) eductor and a 76-mm (3-in) air line should be used for the 254-mm (10-in) casing. A smaller diameter eductor can be chosen, but the air-pressure requirements would rise because of the additional friction effects.
- Step 2 is to determine the length of the eductor pipe and the air line. The bottom of the eductor pipe is set at 122 m, reasonable distance above the bottom of the screen, with the air line set at 120 m.
- Step 3 is to determine the submergence.

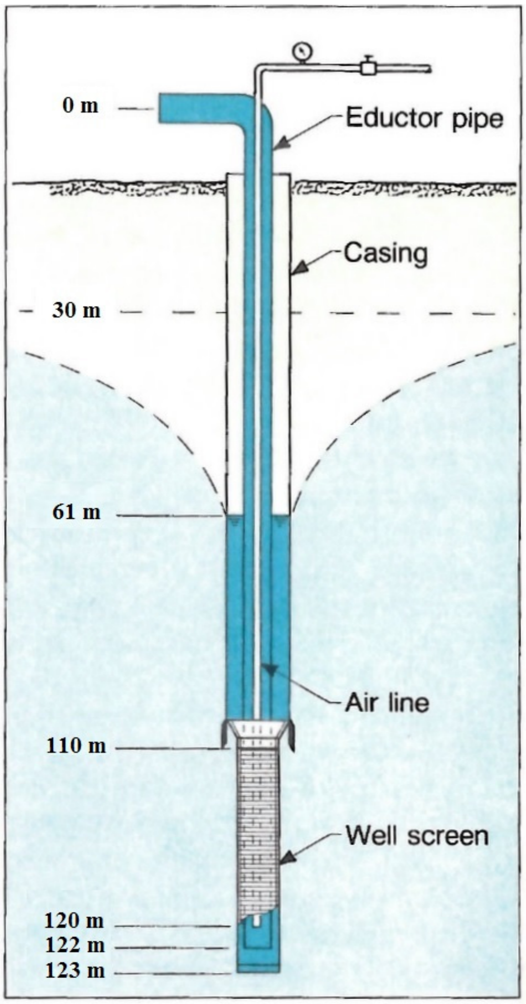

FIGURE 9: Sample well for air-lift designing (modified from Driscoll, 1986)

The pumping submergence is given by this formula:

$$\%\,pumping\ submergence = \frac{length\ of\ air\ line\ below\ pumping\ water\ level}{total\ length\ of\ air\ line} \cdot 100 \qquad (1)$$

$$= \frac{120 - 61}{120}$$

$$\approx 50\%$$

Figure 8 shows that at this pumping submergence, the air-lift will be reasonably efficient considering that the volume of water pumped is acceptable.

- Step 4 is to determine the air-volume requirements. Figure 7 shows that for a total pumping lift of 61 m and pumping submergence of about 50%, 0.47 L/s (1 cfm) of air is required to pump 0.063 L/s (1 gpm) of water. Thus, 283 L/s (600 cfm) of air are required to pump 38 L/s (600 gpm) of water.
- Step 5 is to determine whether the compressor has sufficient pressure to initiate flow in the air line.

$$Minimum\ pressure\ requirement\ (bar) = \frac{density\ of\ water\ \cdot 9.8 \cdot (length\ of\ air\ line - static\ water\ level)}{100000} \qquad (2)$$

$$= 1000 \cdot 9.8\,(120.4 - 30.48)/100000$$

$$= 8.8\text{ bar}$$

The minimum pressure requirement to start the air-lift for the starting submergence chosen is at 8.8 bar, and a safety factor of 25% is usually added to this pressure figure. The pressure requirement decreases almost by half once the flow has been established as the head acting on the air line decreases.

To have some assurance that the air-lift development procedures will work as desired, the steps mentioned above must be done properly. The steps, including the design and operational parameters, however, are not mathematically precise. Thus, the air-lift design may have to be changed depending on the well condition or available equipment. The engineer must be prepared to make appropriate adjustments. Generally, the air-lift pumping will be most efficient if the static water level is high, the casing diameter is relatively small, and the capacity of the compressor is adequate.

6.1.2 Spreadsheet model

A spreadsheet model was made as a part of this report to simulate the success of an air-lifting operation. The input parameters are: the volume rate of air to be injected, air line setting depth, pressure and temperature at the air line setting depth, and the expected water flow from the wellbore. After inputting the said parameters, the model will calculate the pressure versus depth up to the surface based on the density profile. It will show whether the input parameters are sufficient to make the fluid flow to the surface or not. A successful discharge will yield a minimum of 2 bar-a, at the wellhead.

The pressure at depth h is calculated by using the formula:

$$P = P_o - \rho g h \tag{3}$$

where P = Pressure (bar-a);
P_o = Pressure at deeper depth (bar-a);
ρ = Density of two-phase flow (kg/m^3);
g = Acceleration of gravity (9.8m/s^2);
h = Depth (m).

The air volume per depth is calculated using the ideal gas law:

$$PV = nRT \tag{4}$$

By isolating the air volume (V), the equation will be:

$$V = \frac{nRT}{P} \tag{5}$$

where V = Air volume per second (L/s);
n = Number of moles per second (n/s);
R = Universal gas constant (0.08314 L bar/K mol);
T = Temperature (K);
P = Pressure (bar-a).

The number of moles per second is calculated from the input parameters of the air volume injected. After inputting the air volume at standard cubic feet per minute (scfm) for the compressor, it will be converted to litres per second (L/s) and then finally to number of moles per second. One mole of an ideal gas will occupy 22.4 L at standard temperature (0°C) and pressure (1 atm) so the volume in L/s will be divided by 22.4 L to get the number of moles. The output rating of air compressors is reported in standard cubic feet per minute (scfm) but the criteria for "standard" temperature varies, either 0°C (STP) or in the United States 68°F but the pressure is always 1 atm. The former criterion is used in this report.

The density of the two-phase flow is calculated using the formula:

$$\rho = \frac{M}{V} \tag{6}$$

where ρ = Density of two-phase flow (kg/L);
M = Total mass flow of air and water (kg/s);
V = Total volume of air and water (L/s).

The total mass flow is equal to the sum of the air injected in kg/s and the mass flow rate of water. The density of water is retrieved from steam tables (X-Steam) based on the temperature given. The total volume is found by adding the air volume injected and the assumed water flow.

The submergence depth is calculated using the formula:

$$S = h - \frac{P}{\rho g} \tag{7}$$

where S = Submergence depth, length of air line submerged in water (m);
h = Air line setting depth (m);
P = Pressure at the air line setting depth (bar-a);
ρ = Density of water (kg/m^3);
g = Acceleration of gravity (9.8 m/s^2).

The pumping submergence percentage is calculated by dividing the submergence depth by the air line setting depth, then multiplying it by 100.

In addition to the plot of pressure versus depth in the wellbore, the pressure inside the air line is also plotted. The initial pressure required at the wellhead to be supplied by the compressor is calculated by adding the pressure drop to the pressure at the submergence depth. The pressure drop in the compressed air line is calculated by using the empirical formula (modified from The Engineering Toolbox, 2015):

$$dp = \frac{7.42q^{1.85}L \cdot 10^4}{d^5 p} \tag{8}$$

where dp = Pressure drop (bar);
q = Air volume flow at atmospheric conditions (m^3/min);
L = Length of pipe (m);
d = Inside diameter of pipe (mm);
p = Initial absolute pressure (kg/cm^2)

The air volume flow from the given parameter is converted to m^3/min. The length of the pipe is equal to the depth where the air line is set. The inside diameter of the pipe is as per the design. The initial absolute pressure is equal to the absolute pressure at the submergence depth, converted to kg/cm^2.

6.2 Air compression

6.2.1 Spreadsheet model (for planning)

A spreadsheet model was made as a part of this report to calculate how much total air volume is required, and what capacity of compressor is required in order to stimulate a high-temperature well to flow. The input parameters are: the production casing diameter size, static water level in the well, production casing shoe depth, the initial wellhead pressure, the target or final wellhead pressure during the air compression, the initial and final temperature in the airspace, and the compression or pumping time. After inputting the parameters, the model will calculate the initial and final casing air volume, the initial and final number of moles, the amount of moles that need to be injected into the wellbore, and finally, the corresponding air flow to be injected in litres per second (L/s) and in standard cubic feet per minute (scfm). The user can play around with the model by changing the necessary parameters. For example, if the user only has a low flow capacity compressor, he or she can change the length of pumping time in order to reach the target wellhead pressure.

The initial casing volume with air is calculated using the formula:

$$V_i = \pi r^2 h_i \tag{9}$$

where V_i = Initial casing volume with air (m^3);
r = Casing radius (m);
h_i = Water level (m).

The final casing volume with air is calculated using the formula:

$$V_f = \pi r^2 h_f \tag{10}$$

where V_f = Final casing volume with air (m^3);
h_f = Casing shoe depth or maximum water level suppression for target pressure (m).

The initial number of moles is calculated using the ideal gas law. By isolating the moles on the other side of the equation, the formula becomes:

$$n = \frac{P_i V_i}{R T_i} \tag{11}$$

where n = Number of moles;
P_i = Initial wellhead pressure (bar-a);
V_i = Initial casing volume with air (m^3);
R = Universal gas constant (0.08314 L bar/K mol);
T_i = Initial temperature (K).

The final number of moles is calculated using the formula:

$$n = \frac{P_f V_f}{R T_f} \tag{12}$$

where P_f = Final wellhead pressure (bar-a);
V_f = Final casing volume with air (m^3);
T_f = Final temperature (K).

The difference between the final and initial number of moles is equal to the total air that needs to be injected by the compressor. One mole of an ideal gas will occupy 22.4 L at standard temperature and pressure (STP) so the number of moles can be converted to litres per second (L/s) by multiplying it by 22.4. The volume in L/s is also converted to standard cubic feet per minute (scfm) for ease in finding compressor capacity suitable for actual operation.

This model can also be used in reverse. The volume flow capacity and the time it takes to compress a well from initial to final state can be interchanged so the volume capacity will be the input parameter and the time will be the output. The same concept and formulas will be used. After inputting the air volume capacity of a sample compressor in standard cubic feet per minute (scfm), it is converted to L/s and then eventually to number of moles per second by dividing it by a factor of 22.4. Finally, the time is calculated by getting the difference between the final and initial number of moles, and dividing this number by the number of moles per second. The time is calculated in seconds, then converted to hours. This can help in planning out an air compression job. The user can now have an estimate of how long the compression job will take just by knowing the condition of the well, the target wellhead pressure, and the compressor capacity.

6.2.2 Spreadsheet model (for predicting success)

A spreadsheet model was made for this report to simulate if the well will successfully discharge by attaining a certain pressure at the wellhead after releasing the air. The input parameters are the depth, static temperature and pressure profiles and target wellhead pressure. After inputting the parameters for a static well, the model will predict (or calculate) after the air release. The calculation of flowing pressure and temperature profile, steam quality, and density per depth is based on shifting the deep water up into the shallow portions of the well. The shift corresponds to the pressure of compression, by how much the water moves up. The model will then, based on the reassigned enthalpies vs. depth, calculate new values of pressure, temperature, steam quality, and density up to the surface. The pressure vs. depth is calculated by using Equation 3. The spreadsheet results will tell us if the well will successfully discharge by building up a certain wellhead pressure during the initial discharge just modelled. A criterion for successful discharge should be a minimum of 2 bar-a, at the wellhead.

6.3 Two-phase simulator

After stimulating the well to flow either by air-lift pumping or air compression successfully, the well will continue to discharge and self-flow. A spreadsheet model was created to determine if the well has sufficient pressure and enthalpy to flow successfully. The simulator program HOLA was also used to compare the results with the model, as well as actual temperature and pressure logs from flowing wells (dynamic).

6.3.1 Spreadsheet model

A spreadsheet model was made as a part of this report to simulate temperature and pressure profiles to assess whether the well will flow or not, depending on the inflow parameters of the well (in this case assumed to be for the bottom conditions). The model then calculates flowing profiles from bottom to top. The input parameters should be for the main inflow but in this exercise: the bottom depth, the pressure at the bottom, the average enthalpy of the well discharge, and assumed pressure loss due to two-phase friction. After inputting the parameters, the spreadsheet model will give the pressure vs. depth up to the surface, the temperature vs. depth, the quality of steam, and density vs. depth based on the pressure and enthalpy. The pressure vs. depth is calculated by using Equation 3. A pressure drop with units of bar per kilometre factoring in friction losses is also incorporated in the model, and this value will be subtracted from the calculated pressure vs. depth. The results are displayed on a graph with the simulated pressure vs. depth inside the wellbore superimposed with the measured downhole data. It will also show if the well has a positive wellhead pressure and flow to the surface. The minimum pressure criterion to obtain sustainable flow at the surface ranges from 2 to 4 bar-a.

6.3.2 HOLA

HOLA is a software program, a wellbore simulator, which simulates a well temperature and pressure profile from the top to the bottom of the well. The input parameters are wellhead conditions (wellhead pressure, flow and enthalpy), casing geometry, and location of feedzones. After inputting the parameters, the program will give the downhole profile down to the bottom.

The user is first asked to enter the input parameters and they are:

- *Textlines.*
- *Wellhead parameters* - wellhead pressure (bar-a), wellhead enthalpy (kJ/kg), and wellhead flow (kg/s).
- *Heat loss parameters* (usually entered with default/assumed values) - rock thermal conductivity (2 W/m/°C), rock density (2800 kg/m^3), rock heat capacity (1000 J/kg/°C), and time passed (0.8640 10^5 s).

- *Wellbore geometry* - depth of well (m), number of well sections, length of each sections (m), well inner radius (m), well roughness (default/assumed value of 0.05 mm), and distance between nodal points (m).
- *Feedzone properties* (flow and enthalpy).

The user then has the option to select phase velocity method: Armand, Orkiszewski, Chisholm, or Björnsson (9-5/8" wells) but the default method is Orkiszewski (1967). Finally, the user can choose to calculate the wellbore conditions (temperature and pressure), write the results to a file, and then plot the results.

7. EXAMPLES

7.1 Air-lift pumping

As an example, a hypothetical well was made and its properties were entered into the air-lift spreadsheet model. The conditions are like for a cold well as the initial conditions for air-lift pumping. Only after first successfully unloading the cold water will the effects of flash-steam kick in as the well heats up. The effects of flashing are not a part of this model, only the air-lift pumping part to initiate the flow. The following are the input parameters:

- *Air volume flow:* 500 scfm.
- *Air line setting depth*: 400m.
- *Pressure at the air line setting depth*: 20 bar-a.
- *Temperature at the air line setting depth*: 20°C.
- *Expected water flow out the wellbore*: 25 L/s.
- *Air pipe inside diameter*: 50 mm.

Figure 10 shows the snapshot of the spreadsheet model while Figure 11 shows the results.

Air flow	scfm	L/s	n/s	kg/s	m3/min
	500	235.97	10.53	0.29	14.16

Depth	Press	Temp	Air volume	Water flow	Total volume	Total mass flow	Density (water)	Density (2 phase fluid)	Air volume flow	Pipe length	Air pipe (inside diameter)
(m)	(bar-a)	(°C)	(L/s)	(L/s)	(L/s)	(kg/s)	(kg/L)	(kg/m3)	m3/min	m	mm
0	2.11	20	121.59	25	146.59	25.25	1.00	172.24	14.16	400	50
20	2.50	20	102.71	25	127.71	25.25	1.00	197.70			
40	2.94	20	87.30	25	112.30	25.25	1.00	224.84			
60	3.44	20	74.67	25	99.67	25.25	1.00	253.32	Initial abs	dP	dP
80	3.99	20	64.29	25	89.29	25.25	1.00	282.77	pressure (kg/cm2)	(kg/cm2)	(bar)
100	4.60	20	55.72	25	80.72	25.25	1.00	312.78	20.41	0.64	0.63
120	5.28	20	48.62	25	73.62	25.25	1.00	342.97			
140	6.01	20	42.70	25	67.70	25.25	1.00	372.96	Press air line	Depth (m)	
160	6.80	20	37.74	25	62.74	25.25	1.00	402.44	20.63	0	
180	7.64	20	33.56	25	58.56	25.25	1.00	431.13	20	400	
200	8.55	20	30.03	25	55.03	25.25	1.00	458.83			
220	9.50	20	27.02	25	52.02	25.25	1.00	485.39			
240	10.50	20	24.44	25	49.44	25.25	1.00	510.71			
260	11.55	20	22.22	25	47.22	25.25	1.00	534.72			
280	12.64	20	20.30	25	45.30	25.25	1.00	557.41			
300	13.78	20	18.62	25	43.62	25.25	1.00	578.79			
320	14.95	20	17.16	25	42.16	25.25	1.00	598.88			
340	16.16	20	15.87	25	40.87	25.25	1.00	617.73			
360	17.41	20	14.74	25	39.74	25.25	1.00	635.40	Submergence	Water	Submergence
380	18.69	20	13.73	25	38.73	25.25	1.00	651.94	depth (m)	level (m)	%
400	20	20	12.83	25	37.83	25.25	1.00	667.43	195.75	204.25	48.94

FIGURE 10: Snapshot of the air-lift pumping spreadsheet model

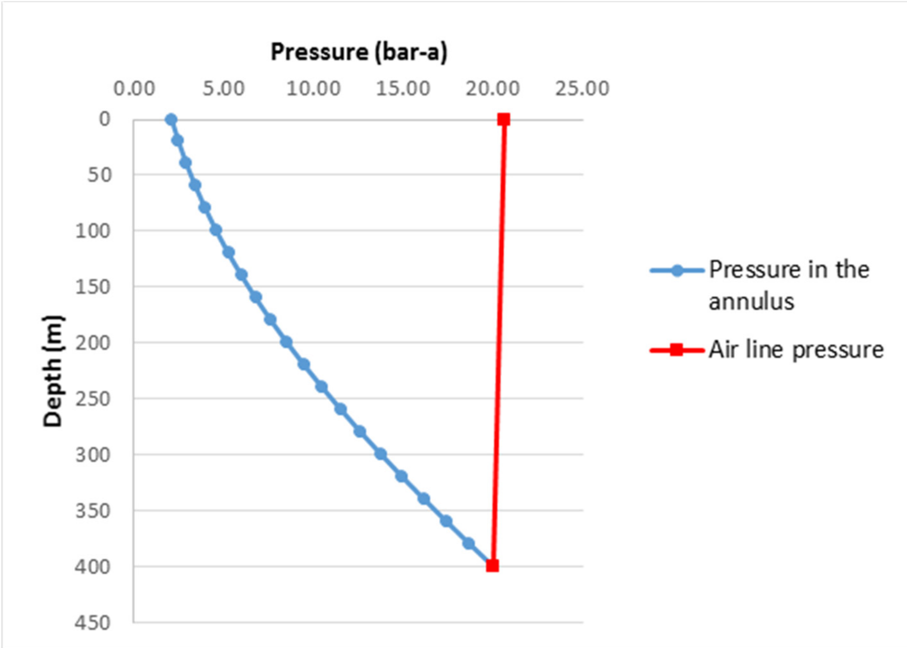

FIGURE 11: The spreadsheet model graph tells us that with the given air-lift pumping design parameters, the well will flow at the surface at 2.1 bar-a wellhead pressure, and the pressure at the air line will drop from 20.64 bar-a at the surface to 20 bar-a at the end of the air line at 400 m depth

7.2 Air compression (for planning)

Energy Development Corporation (EDC) uses an air package for air compression operations. An air package is a combination of an air compressor and an air booster. This equipment is important in reviving some of the production wells for augmenting the supply of steam. See Table 2 below for the compressor specifications.

TABLE 2: Air package specification

Equipment	Compressor	Booster
Discharge pressure	24.13 bar (350 psi)	149.96 bar (2175 psi)
Capacity	1350 scfm	1800 scfm @ two stage
Fuel consumption	200 litres/4 hours	250 litres/4 hours

As an example, actual field data from a well in the Philippines is used in the air compression spreadsheet model. Here are the input parameters for well 1:

- *Casing size:* 9-5/8”
- *Initial water level:* 1000m
- *Final water level:* 1700m
- *Initial pressure:* 1 bar-a
- *Final pressure:* 58 bar-a
- *Pumping time:* 2 h
- *Initial temperature:* 158°C
- *Final temperature:* 240°C

Model output – Air capacity: 707 scfm

This tells us that the primary air compressor alone will not be able to carry out the job, even though the volume capacity is sufficient. The maximum pressure requirements of 58 bar-a cannot be met without adding a booster. A combination of the compressor and booster is more than sufficient, and that is the set-up that is usually used in the Philippines.

In order to achieve a wellhead pressure of 58 bar-a in two hours, an air flow of 707 scfm is required. If we take the reverse and enter an air capacity of 350 scfm as input, the time will be 4.1 hours. This means that to reach the target pressure while using a small capacity compressor, it will take about twice as long to finish the job and build up the target wellhead pressure. Figure 12 shows the snapshot of the air compression spreadsheet model.

	Diameter (in)	Fraction	Radius (m)
Casing size (in)	9	5/8	0.122
Water level (m)	1000		
Target depth (m)	1700		
Initial casing vol (m^3)	46.97	**Initial P (bar-a)**	1
Final casing vol (m^3)	79.84	**Final P (bar-a)**	58
Initial casing vol (liters)	46965.74	**Initial temp (°C)**	158
Final casing vol (liters)	79841.76	**Final temp (°C)**	240
Initial moles (n)	1310.22	**Pumping time (hr)**	2
Final moles (n)	108543.48	**(seconds)**	7200
Δ (n/s)	14.89		
L/s	333.82		
SCFM	**707.34**		
Reverse:			
SCFM	350	**Time (seconds)**	14812.45
L/s	162.26	**Hours**	**4.11**
n/s	7.24		

FIGURE 12: Snapshot of the air compression spreadsheet model (for planning)

7.3 Air compression (for predicting success)

Well 1 described above was also used as an example for this model. The input parameters are the following: Bottom depth of 2100m, static temperature and pressure profiles, and target wellhead pressure of 58 bar-a, which is the pressure at the production casing shoe.

The pressure at the bottom, which is 80 bar-a, will be subtracted from the pressure to be injected, which is 58 bar-a. The difference is equal to 22 bar, which is at a depth of 1400 m, based on the flowing pressure per depth. The user will then use the second table to enter the second set of parameters which are the depth of 1400 m, the static pressure at this depth which is 33.3 bar-a and shift the enthalpy from the bottom of the well to this depth which is 991 kJ/kg. The other enthalpy figures are likewise shifted upwards as to simulate the effects of the air being released and the heated water moving up the well. Projecting these parameters to the surface tells us that this well will not discharge because the value at the surface is less than 2 bar-a. Figure 13 shows the snapshot of this spreadsheet model while Figure 14 shows the downhole profiles before compressing and after releasing the compressed air. This agrees with the field results, the well could not self-flow.

As a second example for testing this model, well 2 was used. The initial wellhead pressure is at 1 bar-a, and the water level is at 600 m. The target wellhead pressure is 66 bar-a, because this is the pressure at the production casing shoe, which is located around 1500 m. The input parameters are the following: bottom depth of 2400m, static temperature and pressure profile, and target wellhead pressure by air compression of 66 bar-a.

The pressure of the bottom, which is 135 bar-a, will be subtracted from the pressure to be injected, which is 66 bar-a. The difference is equal to 69 bar, which is at depth 1300 m based on the flowing pressure per depth. The user will then use the second table to enter the second set of parameters which are the depth of 1300 m, the static pressure at this depth which is 60 bar-a and the shifted enthalpy from the bottom of the well to this depth which is 1341 kJ/kg. All other enthalpy vs. depth figures are likewise shifted upwards. Projecting these parameters to the surface tells us that this well will discharge, since the pressure at the wellhead (surface) will be 33 bar-a. Figure 15 shows the downhole profiles before compressing and after releasing the compressed air.

Static Press (bar-a)	Depth (m)	Flowing Press (bar-a)	Static Temp (°C)	Enthalpy (kJ/kg)	Quality X	Dens (kg/m³)
1	0	#VALUE!	36.02	150.91	#VALUE!	#VALUE!
1	100	#VALUE!	36.02	150.91	#VALUE!	#VALUE!
1	200	#VALUE!	36.02	150.91	#VALUE!	#VALUE!
1	300	#VALUE!	36.02	150.91	#VALUE!	#VALUE!
1	400	-8.97	57.47	240.58	#VALUE!	#VALUE!
1	500	0.55	82.27	344.47	0	970.36
1	600	0.68	105.03	440.34	0.029	14.10
1	700	0.79	116.90	490.64	0.044	10.56
1	800	0.94	116.97	490.91	0.036	15.30
1	900	1.43	118.15	495.93	0.016	50.44
8	1000	1.52	161.12	680.44	0.095	9.12
13.06	1100	10.25	177.58	752.53	0	889.61
20.13	1200	14.54	200.48	854.55	0.01	437.26
26.52	1300	19.61	214.52	918.39	0.01	516.52
33.27	1400	23.36	227.11	976.69	0.02	382.65
40.34	1500	31.40	235.25	1014.94	0	820.08
46.67	1600	39.44	236.82	1022.40	0	818.67
54.42	1700	47.44	239.64	1035.82	0	815.43
57.53	1800	55.52	234.13	1009.66	0	824.18
63.70	1900	63.74	224.88	966.29	0	837.67
73.88	2000	71.92	228.03	980.99	0	834.24
80.08	2100	80.08	230.33	991.75	0	831.93

Depth (m)	Press (bar-a)	Temp (°C)	Enthalpy (kJ/kg)	Quality X	Dens (kg/m³)
0	0.74	91.47	490.64	0.05	9.38
100	0.87	95.70	490.91	0.04	12.87
200	1.52	111.73	495.93	0.01	66.36
300	1.62	113.62	680.44	0.09	9.99
400	10.34	177.60	752.53	0.00	889.62
500	12.13	188.44	854.55	0.03	181.72
600	13.27	192.57	918.39	0.05	116.68
700	14.13	195.49	976.69	0.07	87.97
800	14.91	198.00	1014.94	0.09	78.58
900	15.73	200.55	1022.40	0.09	83.79
1000	16.57	203.08	1035.82	0.09	86.40
1100	17.71	206.33	1009.66	0.07	116.00
1200	20.10	212.64	966.29	0.03	243.58
1300	25.16	224.29	980.99	0.01	515.37
1400	33.27	230.29	991.75	0.00	827.23

FIGURE 13: Snapshot of the air compression spreadsheet model (for predicting success)

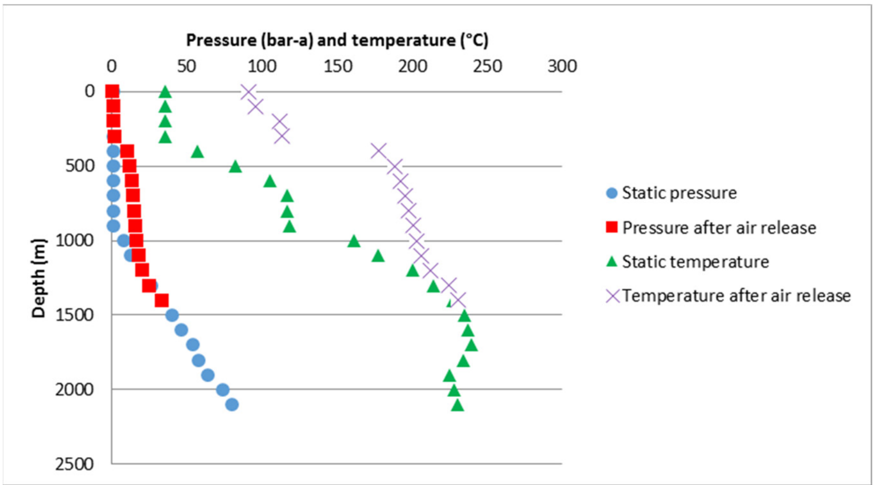

FIGURE 14: Downhole profiles of well 1 before air compression and after releasing compressed air

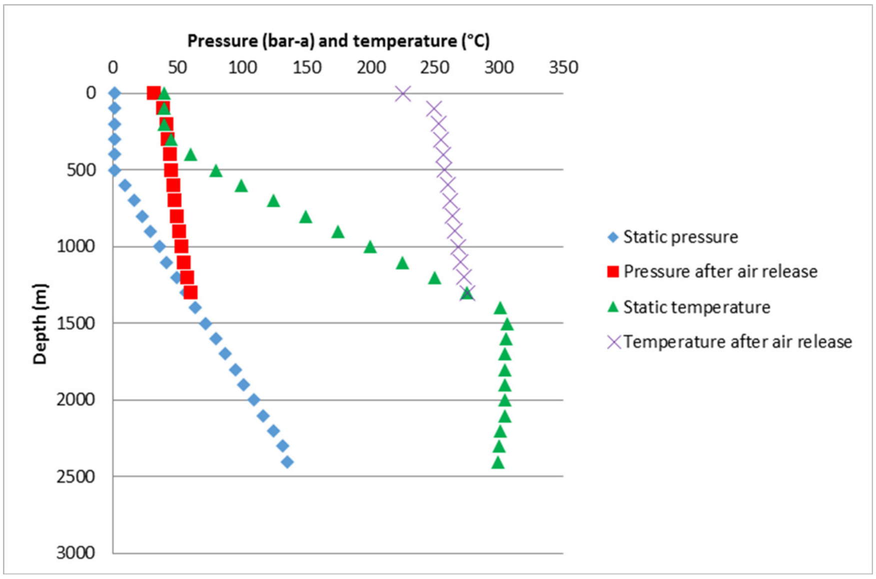

FIGURE 15: Downhole profiles of well 2 before air compression and after releasing compressed air

7.4 Flowing wells

Down-hole measurements from flowing wells (dynamic logs) are used as actual examples to validate predictions by the spreadsheet model and the HOLA program.

Input parameters are used from a number of wells in the two-phase spreadsheet model. The assumed two-phase pressure drop (assumed) in the well was varied from values 4 to 7 (bar/km). After a number of runs and testing a number of wells, a value within the range 4-7 produced good predictions.

The input parameters for well 3 in the spreadsheet model are the following:

- *Bottom depth*: 2700 m
- *Pressure at bottom depth*: 69.9 bar-a
- *Pressure drop*: 5.35 bar/km
- *Enthalpy*: 1228 kJ/kg

Figure 16 shows the snapshot of the two-phase simulator model.

The input parameters for well 3 in the HOLA program are the following:

- *Wellhead pressure*: 12.2 bar-a
- *Wellhead enthalpy*: 1228 kJ/kg
- *Wellhead flow*: 29 kg/s
- *Rock thermal conductivity*: 2 W/m/°C
- *Rock density*: 2800 kg/m^3
- *Rock heat capacity*: 1000 J/kg/°C
- *Time passed*: 0.8640 E^5 s
- *Depth of well*: 2500 m (vertical depth)
- *Number of well sections*: 2 (production casing and slotted liner)
- *Length of section 1 (production casing):* 1600 m (vertical depth)
- *Well inner radius*: 0.120 m
- *Well roughness*: 0.05 mm
- *Distance between nodal points*: 2 m
- *Length of section 2 (slotted liner)*: 900 m (vertical depth)
- *Well inner radius*: 0.089 m
- *Well roughness*: 0.05 mm
- *Distance between nodal points*: 2 m
- *Number of feed-zones*: 1

Depth (m)	Press (bar-a)	dP bar/km	Temp (°C)	Enthalpy (kJ/kg)	Quality X	Dens (kg/m^3)
0	12.22	5.35	**188.80**	1228	0.21	28.29
67.5	12.78	5.35	**190.84**	1228	0.21	30.01
135	13.35	5.35	**192.85**	1228	0.21	31.80
202.5	13.94	5.35	**194.84**	1228	0.20	33.69
270	14.54	5.35	**196.81**	1228	0.20	35.66
337.5	15.15	5.35	**198.76**	1228	0.20	37.73
405	15.77	5.35	**200.69**	1228	0.19	39.90
472.5	16.41	5.35	**202.60**	1228	0.19	42.18
540	17.07	5.35	**204.51**	1228	0.18	44.58
607.5	17.74	5.35	**206.41**	1228	0.18	47.12
675	18.43	5.35	**208.29**	1228	0.18	49.79
742.5	19.14	5.35	**210.18**	1228	0.17	52.62
810	19.87	5.35	**212.06**	1228	0.17	55.62
877.5	20.62	5.35	**213.94**	1228	0.17	58.80
945	21.39	5.35	**215.82**	1228	0.16	62.17
1012.5	22.19	5.35	**217.70**	1228	0.16	65.77
1080	23.01	5.35	**219.59**	1228	0.15	69.62
1147.5	23.86	5.35	**221.49**	1228	0.15	73.73
1215	24.74	5.35	**223.40**	1228	0.15	78.14
1282.5	25.65	5.35	**225.33**	1228	0.14	82.89
1350	26.60	5.35	**227.27**	1228	0.14	88.02
1417.5	27.58	5.35	**229.23**	1228	0.13	93.58
1485	28.60	5.35	**231.22**	1228	0.13	99.63
1552.5	29.66	5.35	**233.23**	1228	0.12	106.23
1620	30.77	5.35	**235.28**	1228	0.12	113.48
1687.5	31.94	5.35	**237.36**	1228	0.11	121.48
1755	33.16	5.35	**239.48**	1228	0.11	130.37
1822.5	34.45	5.35	**241.66**	1228	0.10	140.31
1890	35.82	5.35	**243.89**	1228	0.10	151.52
1957.5	37.27	5.35	**246.20**	1228	0.09	164.28
2025	38.81	5.35	**248.58**	1228	0.09	178.97
2092.5	40.47	5.35	**251.06**	1228	0.08	196.13
2160	42.27	5.35	**253.65**	1228	0.07	216.49
2227.5	44.23	5.35	**256.38**	1228	0.07	241.17
2295	46.39	5.35	**259.30**	1228	0.06	271.95
2362.5	48.81	5.35	**262.45**	1228	0.05	311.78
2430	51.60	5.35	**265.92**	1228	0.04	366.21
2497.5	54.92	5.35	**269.88**	1228	0.03	447.39
2565	59.19	5.35	**274.70**	1228	0.01	590.31
2632.5	64.54	5.35	**278.35**	1228	0	753.51
2700	**69.9**	**5.35**	**278.40**	**1228**	0	754.28

FIGURE 16: Snapshot of the two-phase simulator spreadsheet model

It is important to note that the feedzone is assumed to be one and the depths entered should be the vertical depths and not the measured depths of a deviated well. If there are discrepancies or errors with the values, it could be attributed to these factors. Figure 17 shows the measured data and the simulated data from the spreadsheet model and HOLA program. The model results agree well on the wellhead pressure (WHP) but show a slightly lower pressure deep in the hole as compared to HOLA and the measured values. The figure includes a sample well profile from another well (blue X) that will not self-flow by inputting a low value for enthalpy (temperature profile of the well) in the model.

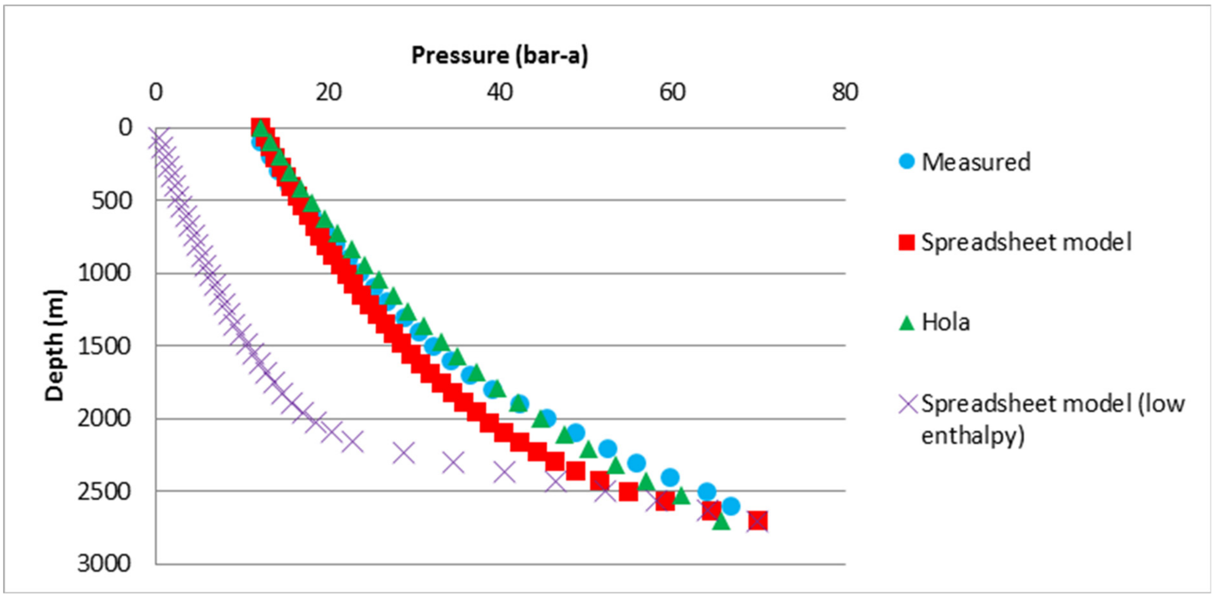

FIGURE 17: Results of the simulated data using the spreadsheet model and HOLA vs. the measured data of well 3

8. CONCLUSIONS

To conclude, let us go back to the main objective which was to answer the question: "What are the technical requirements for a successful discharge by air-lifting and compressing the well?"

For the air-lift pumping, what submergence of the coiled tubing or drill pipe and air-compressor rating (pressure and air flow) are required?

- Based on air-lift graphs, 50% of pumping submergence is required for efficient air-lift with wells about 60-150 m of total pumping lift. This percentage decreases as the pumping lift increases, such as 40% for 150-270 m. The minimum wellhead (or compressor) pressure requirement to initiate flow in the air line is calculated by getting the difference of the air line setting depth and static water level, then multiplying by the water density and g (9.8). For the air volume requirement, the total pumping lift, pumping submergence and the size of air pipe or line and casing are the factors needed to be considered. Practical guidelines from air lift pumping of water wells were applied.
- Based on the spreadsheet model, the success of an air-lift set up can be assessed based on the air volume and expected water flow (air/water ratio) and the submergence depth.

For air compression, what volume capacity of compressor is required for a certain job and how long does it take to compress a well from initial to final pressure? What air pressure is needed to discharge the well by compression alone?

- Based on the spreadsheet model results, the capacity of the compressor in terms of air volume flow rate can be computed by knowing the well conditions and downhole profile of the initial and desired state of air compression, well geometry, and duration of compression. The user can play around with the model, making the capacity the known variable and duration of pumping the unknown. This is good for planning the compression job, estimating capacity and time, even before going into the field.

- For a compression job, one should maximize the water level depression, whether at the first loss zone or at the production casing shoe, considering also the pressure rating of the wellhead and the pipes used at the surface. Because the water level is typically compressed down to the production casing shoe depth, the optimum wellhead pressure one can achieve by compressed air depends on the reservoir pressure at this depth. With this factored in, the next important factor is the temperature (enthalpy) of inflow. With sufficient temperature, the well should flow. Based on the spreadsheet model for predicting success of compression, the combination of downhole pressure and temperature and the casing shoe depth dictates whether a well will flow at the surface or not after rapidly releasing the compressed air.

What other key factors are considered necessary for a well to attain successful discharge and maintain self-flow?

- Based on the developed two-phase simulator (simulating from bottom to top), attaining successful discharge and maintaining self-flow depends on the bottom pressure, well inflow enthalpy, and pressure loss due to friction up the hole. This model was compared to the HOLA wellbore simulator (simulating from top to bottom) and the results were also comparable with downhole logging data.

ACKNOWLEDGEMENTS

First I would like to thank the UNU-GTP director, Lúdvík S. Georgsson and staff, Ingimar G. Haraldsson, Markús A.G. Wilde, Málfrídur Ómarsdóttir, Thórhildur Ísberg, and María Gudjónsdóttir, thank you very much for the opportunity and for supporting each and every fellow. To my best advisers, Sverrir Thórhallsson and Benedikt Steingrímsson, I highly appreciate your eagerness to teach and guide me with this project. “Takk fyrir”!

To our (EDC) President, Mr. Richard B. Tantoco, our (GREG) Senior Vice-President, Mr. Manuel S. Ogena, our (GREG) Assistant Vice-President, Mr. Francis Xavier M. Sta. Ana, our Department Manager, Mr. David M. Yglopaz, and Section Supervisor, Mr. Edson B. Emoricha, thank you for the opportunity and for nominating me for this geothermal programme. To my colleagues back home, thank you for suggesting project ideas, and for providing me with much needed data, special thanks to Ms. Kristine Antonio, Ms. Selnalyn Marquez, Ms. Emma Rose Baula, Mr. Renan Jhon Guerra, Mr. Ramil Derecho, Mr. Joselito "Yam" Alcaraz II, Mr. Gualbert Gerona, and Mr. Bryan Cacho.

To the UNU Fellows, thank you for the time well spent together, hope our paths will cross someday.

To my family, thank you for always being there for me, especially my dad who even went to Iceland to visit me. To all our Filipino friends who are living in Iceland, thank you for making our stay warmer, happier, and much more exciting. Lastly, to my mom, who I know has always been my greatest fan, I dedicate this accomplishment to her.

Finally, I would like to thank God. With him, anything is possible.

REFERENCES

Australian Drilling Industry Training Committee, Ltd., 1997: *Drilling: The manual of methods, applications, and management.* Lewis Publishers, 624 pp.

Björnsson, G., Arason, P., Bödvarsson, G.S., 1993: *The wellbore simulator HOLA. Version 3.1. User´s guide*. Orkustofnun, Reykjavík, Iceland, 36 pp.

Buning, B.C., Gonzaga, L.D., Aqui, A.R., Salera, J.R.M., and Sarmiento Z.F., 1998: Discharge initiation by gas-lifting: PNOC-EDC experience in Philippine geothermal wells. *Proceedings of the 23rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, US,* 379-383 pp.

Colina, R.N., Omagbon, J.B., Austria, J.J.C., Sta. Ana, F.X.M., Malate, R.C.M., 2008: *Review of guidelines in predicting discharge stimulation success using selected air compressed wells from 1993 to 2008*. Energy Development Company (EDC), research paper, 10 pp.

Driscoll, F.G., 1986: *Groundwater and wells* (2nd ed.). Johnson Screens, St. Paul, MN, US, 1089 pp.

Orkiszewski, J., 1967: Predicting two-phase pressure drops in vertical pipes. *J. Petroleum Technology, 19,* 829-838.

Sarmiento, Z.F., 2011: Application of well testing in assessing geothermal resources. *Presented at "Short Course on Geothermal Drilling, Resource Development and Power Plants", organized by UNU-GTP and LaGeo, Santa Tecla, El Salvador*, 13 pp.

Steingrímsson, B., 2015: *Discharge measurement and injection* tests. UNU-GTP, Iceland, unpublished lecture notes, 64 pp.

The Engineering Toolbox, 2015: *Compressed air – Pressure drop in pipe lines – Online pressure drop calculator.* The Engineering Toolbox, website: *http://www.engineeringtoolbox.com/pressure-drop-compressed-air-pipes-d_852.html*