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DESIGN OF A CO-PRODUCTION SYSTEM FOR STEAM AND FRESHWATER IN FRACTURED POROUS MEDIA GEOTHERMAL RESERVOIRS

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ABSTRACT

Permeable fractures and fault zones mostly control the flow of water in volcanic systems. The need for freshwater for geothermal drilling operations and the attendant challenges in meeting its demand cannot be overemphasized. This paper proposes a one-stop shop solution for combined abstraction of geothermal fluids and groundwater from fractured reservoirs. Conventional well designs concentrate on the wellbore and the products therein which are basically geothermal fluids (steam and brine). This innovative co-production design attempts to increase the pay zones in a drilled well by allowing for the abstraction of freshwater for drilling, injection tests , cooling of geothermal power plants, dust suppression, cleaning, maintenance and direct use activities such as crop irrigation. This improves on geothermal well cost-benefits per drilled depth. The intermediate casing in a typical well is modified to accommodate a freshwater annular suction conduit that draws water from upper section to approximately 500m depth in the formation of a drilled geothermal well using a jet pump or multistage pump mounted on the surface. With further research the innovative technology can be employed in simultaneous abstraction of oil and gas in oil and/or gas reservoirs or a combination of both.

1. INTRODUCTION

Water consumption occurs at various stages along the development of geothermal power resources. Water is required for drilling operations of production and make-up wells (2,000 l/m for one GDC drilling rig on average), injection tests, cooling of geothermal power plants, dust suppression, cleaning, maintenance and direct use activities such as crop irrigation. In enhanced geothermal systems (EGS), water is required for stimulation and flow testing of engineered reservoirs.

The freshwater demand (present and future) for various scenarios versus availability is already a concern in many geothermal fields.

1.1 Hydrogeological conditions at 100m-400m depth

The hydrogeological condition is a combination of two main aspects: the solid and the fluid. The solid aspect comprises the material and the geometry of an aquifer and the hydraulic properties of the aquifer; the fluid aspect involves the hydraulic behavior of the groundwater.

Fractures in a geologic medium can greatly influence its hydrogeological characteristics. They can increase the hydraulic conductivity of an otherwise impermeable rock or soil by orders of magnitude in the dominant fracture directions.

The fundamental characteristic of fractured rock aquifers is extreme spatial variability in hydraulic conductivity, and hence groundwater flow rate. Hydraulic properties can also be highly anisotropic, so that hydraulic properties must be defined in conjunction with directional information. Water velocities through individual fractures can be extremely high, but the fractures usually occupy only a very small fraction of the aquifer. In *fractured porous media* water is also stored in the aquifer matrix between the conduits. Models of groundwater flow, however, usually assume either homogeneous porous media or purely fractured media. Furthermore, models of groundwater flow in purely fractured systems usually assume that fractures are planar and parallel and many also assume that the fractures are identical. While these assumptions are unlikely to be true in reality, they provide a useful starting point for our understanding of groundwater behavior in fractured rocks.

The figure 1 below illustrates a typical water rest level in a fractured reservoir:

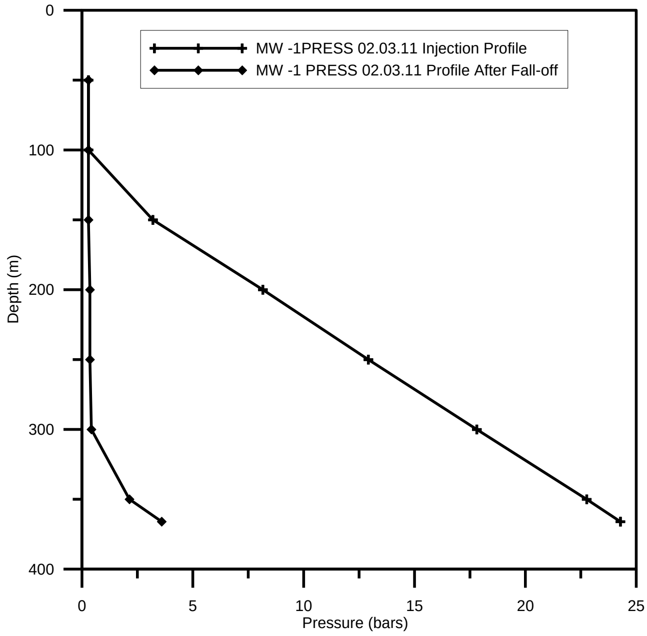

Figure 1: Hydrology test at Menengai well MW-01:Pressure profile (Source: GDC, 2011).

From figure 1 above, the water level begins at 100m.

1.2 Thermogeological conditions at 300-400m in borehole drilled in fractured geothermal zone

a). Geological conditions at 400m

Geothermal fields occur in a wide variety of geological environments and rock types. The one common denominator in all these fields is the highly permeable, fractured and faulted nature of the formations in which the reservoir resides. This high permeability is one of the fundamental and requisite components of any geothermal system to exist.

Typically, the permeable nature of the formations is not limited to the geothermal reservoir structure alone, but occurs in much of the shallower and overlying material as well.

b). Geochemical properties of geofluids at 300m-400m

At greater depths beyond 400m, geothermal fluids contain varying concentrations of dissolved solid and gases. The dissolved solids and gases often provide highly acidic and corrosive fluids and may induce scaling during well operations. Dissolved gases are normally dominated by CO_2 but can also contain significant quantities of H_2S, both which can provide a high risk to personnel and induce failure in drilling tools, casings and wellhead equipment.

The presence of these dissolved solids and gases in the formation and reservoir fluids imposes specific design constraints on casing materials, wellhead equipment and casing slurry designs.

There is very little information on the geochemistry of the fractured reservoirs at 300m-400m because of the least importance attached to the fluids in this region. However, between 0-400m, normal groundwater is expected. Water boreholes are in the range of 0-400m and thus normal borehole water chemistry is what can be expected unless where we have relatively shallow level thermal reservoirs (not locally researched)!

c). Thermal properties of rocks at 400m

The temperature of the earth's crust increases gradually with depth with a thermal gradient that usually ranges from 5º to 70º per kilometre. In anomalous regions, the local heat flux and geothermal gradients may be significantly high than these average figures. Such anomalous zones are typically associated with the edges of the continental plates where weakness in the earth's crust allow magma to approach the surface, and are associated with geologically recent volcanism and earthquakes. It is in such settings that the majority of geothermal resources are found and that the majority of geothermal wells have been drilled.

The well, the well downhole components and the near-well formations are subject to large temperature changes both during the drilling process and at the completion of drilling. These large temperature differentials require special precautions to be taken:

- to avoid entrapment of liquid between the casings strings which can exert extreme pressure that can result in collapse of casings.
- to ensure casing grade and weight , and connection type is adequate for the extreme compressive forces caused by thermal expansion.

1.3 Justifications for the co-production system:

1. Avails freshwater for geothermal development. Freshwater is required for drilling production wells and make-up wells.

2. Provides a one-stop-shop solution for drilling of freshwater and steam to minimize disturbance on hydrologic flow regimes

3. Management of geothermal reservoirs through induced drawdown. Abstraction of water from a depth of 300m -400m allows for drawdown that results in localized boiling thus minimizing cold inflows at upper aquifers (≤1500m). The technology when fully developed can be used to control scaling in the formation to enhance steam quantity and abstraction of gases for industrial uses (CO_2, H_2S and other noble gases).

4. Improves on the well economics (Cost/depth improves). More products obtained from the well as the depth advances in addition to commercial temperatures and pressures.

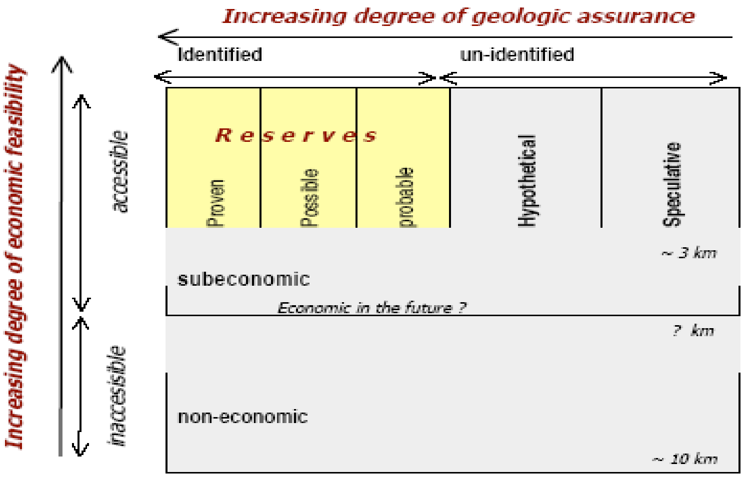

Figure 2: *The Mac Kelvey Mineral Resource Classification Diagram [adapted by Mufler and Cataldi, 1978]*

5. Minimize competition for fresh water with host communities and water activists.

6. With further thinking, conceptualization, research and design, a technology can be obtained for simultaneous abstraction of oil and gas. Maybe abstraction of geothermal steam, gases and oil/acids from one or different fractured reservoirs within one field- possible in fields like Lake Albert Basin in Uganda and the Hawaii island and on other islands in the Hawaiian archipelago.

2. DESIGN OF THE CO-PRODUCTION SYSTEM

2.1 Typical/conventional well design

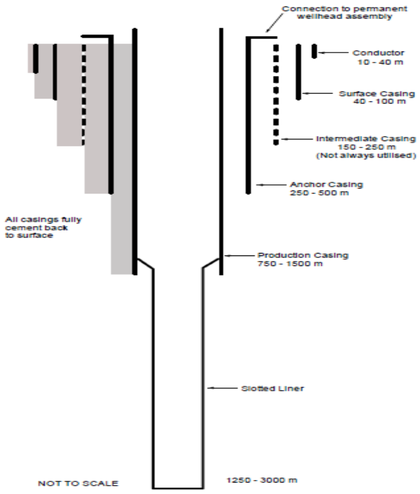

Figure 3: Casing strings and liners for a typical geothermal well

2.1.2 Modified well casing design and flow (Hydromechanics)

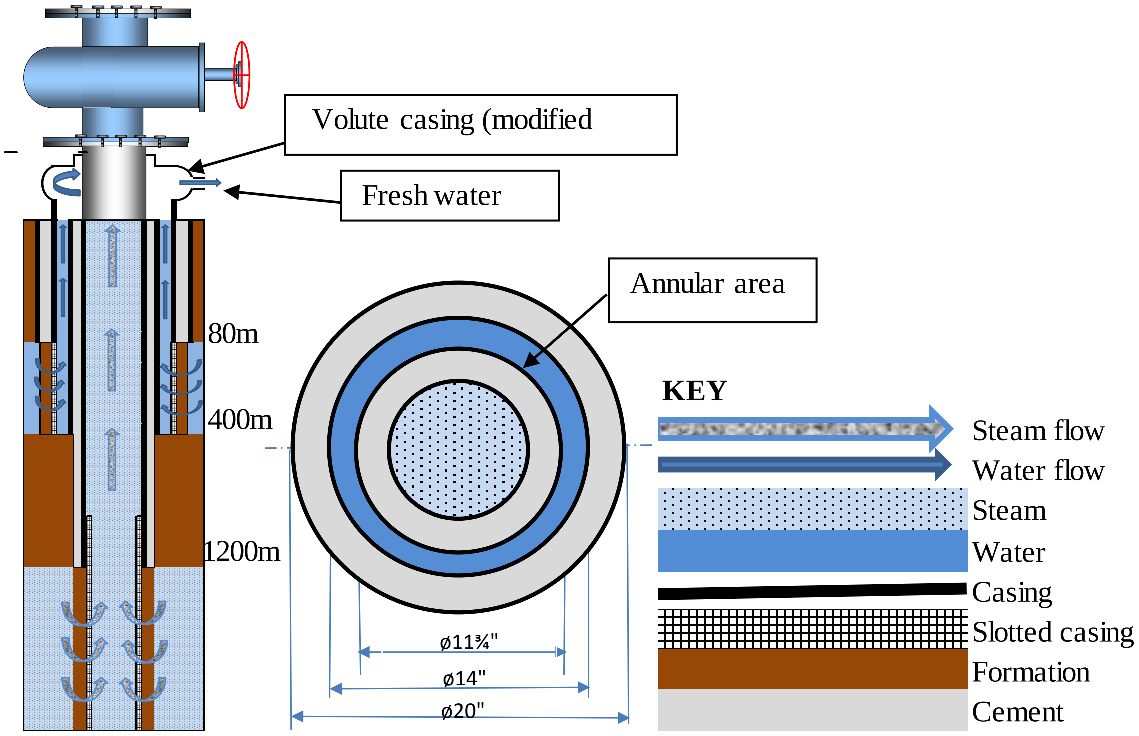

Figure 4: Simplified co-production system

The intermediate casing in a conventional geothermal well casing system is modified by longitudinally welding two concentric pipes of external diameters 14.00’’ and 11.75’’ (small diameter wells) and creating slots in the last five (5) intermediate casing pipes. Freshwater flows through the created slots into the created annulus. The freshwater can be lifted via the annulus using multi-stage pumps.

The Casing Head Flange (CHF) in conventional wellhead design is modified to accommodate a volute casing which is connected to the annulus (suction side) and the pumps for delivery of freshwater to the surface storage facilities.

The transient flow of high temperature fluid in the wellbore can result in artesian flows (buoyancy-driven flow) within the freshwater annulus. This will lower the pumping energy requirements thus cost savings.

During power generation period, a micro-steam turbine can be used as a power source for the pump to improve on the abstraction economics.

Re-perforation with explosive charges can be employed to make holes that allow fluid (freshwater) entry in the annulus of the modified intermediate casing.

2.1.3 Flow in annulus

Following the studies of Gunn and Darling and Caetano et al, the expression for turbulent flow in a concentric annulus is as follows:

$$\frac{1}{\left\{f_{CA}\left(\frac{F_P}{f_{CA}}\right)^{0.45exp\left[-\left(\frac{Re-3000}{10^6}\right)\right]}\right\}^{0.5}} = 4log\left[Re\left\{f_{CA}\left(\frac{F_P}{F_{CA}}\right)^{0.45exp\left\{-\left(\frac{Re-3000}{10^6}\right)\right\}}\right\}^{0.5}\right] - 0.4 \quad (1)$$

Where:

f_{CA}= Moody friction factor for laminar flow in concentric annulus.

$$f_{CA} = \frac{64}{Re} \frac{(1-K)^2}{\left\{ \frac{1-K^4}{1-K^2} - \frac{1-K^2}{ln\left(\frac{1}{K}\right)} \right\}} \tag{2}$$

f_p= Laminar flow friction factor geometry parameter.

$$F_P = \frac{(1-K)^2}{\left\{ \frac{1-K^4}{1-K^2} - \frac{1-K^2}{ln\left(\frac{1}{K}\right)} \right\}} \tag{3}$$

K= Diameter ratio d_t/d_c of the annulus pipes (figure 5 below): 0.82

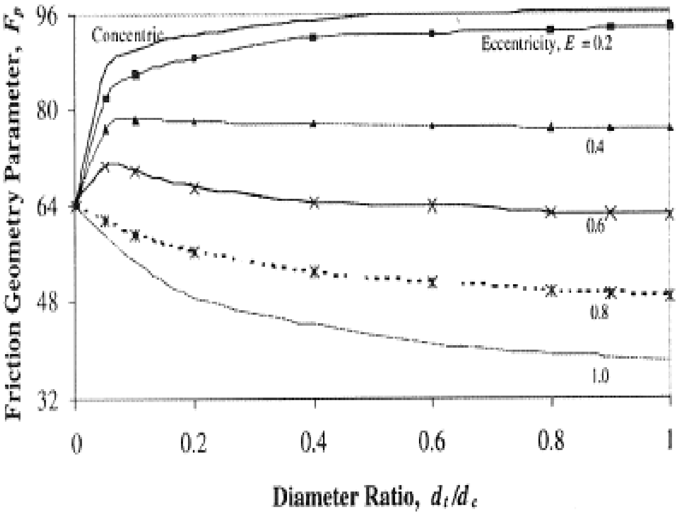

Figure 5: Friction geometry parameter for concentric and eccentric annuli.

2.1.4 Heat transfer mechanism between freshwater in the annulus and the wellbore fluids

The heat transfer mechanism takes in account the radial concentric geometry of the wellbore (high temperature geothermal fluids conduit) and the annulus (freshwater flow conduit). In addition the heat transfer mechanism takes in account the cement insulation between the production casing and the freshwater abstraction annulus. The heat transfer is by conduction.

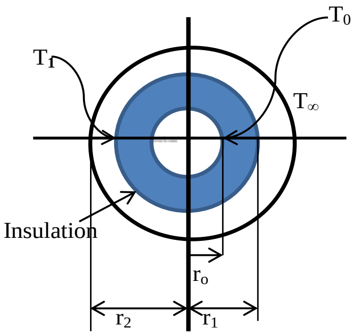

Figure 6: Temperature distribution in concentric circular pipes.

r_o, r_1, r_2, To and $T\infty$ are radius of production casing, radius of intermediate casing (inner annulus), radius of the external annulus, wellbore fluid temperature, temperature of the annulus fluid / formation temperature at 300-400m respectively.

Heat transfer, Q, to the annulus fluid is computed as follows:

$$Q = \frac{2\pi L \Delta T}{\left(\frac{1}{k1}\right)\ln\frac{r1}{r0} + \frac{1}{k2}\ln\frac{r2}{r1}} \tag{4}$$

Where:

L, ΔT, $k_1$and k2 are the length of annulus, change in temperatures between the insulation (cement) , thermal conductivity of insulator (cement) and pipe material (grade API K55 or N80) respectively.

Conductive cooling of the wellbore fluids is minimized by the cement insulation. The resident time of the flowing annulus fluid is small enough for it to cause a major cooling effect on the high temperature wellbore fluid.

2.1.6 Thermal expansion and casing collapse pressure

The permanent wellhead components include:

- Casing Head Flange (CHF) usually, and preferably, attached to the top of the Anchor casing – but in some instances is attached directly to the top of the production casing. The casing head flange may incorporate side outlets to which side valve are attached.
- Double flanged Expansion / Adaptor spool. Side outlets may be incorporated in the expansion spool (as an alternative to those on the CHF).
- Master Valve

A typical wellhead assembly for a 'Standard' well completed with an 8½" diameter production hole section, 95/8" production casing and 133/8" anchor casing is illustrated schematically in Figure 7 below:

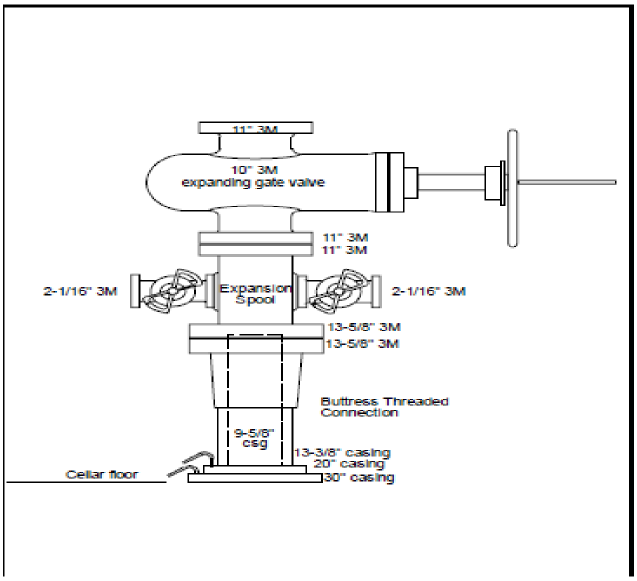

Figure 7: Typical Completion Wellhead

In spite of the best efforts made in cementing the casing strings, there is usually some residual relative axial thermal expansion between casings at the surface. If the wellhead is mounted on the anchor casing (which is typical), the production casing movements relative to the anchor casing is accommodated below the master valve, within a double flanged spool such that interference with the base of the master valve is prevented.

The intermediate casing through which the fresh water will flow trough will be set at the same depth as the anchor casing. 400m (1312ft) is the most frequent anchor casing depth in Menengai. We will therefore use this depth as the setting depth for the intermediate casing. The casing design will be for this depth and 13⅜ inch casing diameter. The design pressures for this casing will form the minimum requirements for the modified intermediate casing through which fresh water will flow. The design will be based on collapse, burst and tension.

The following minimum design factors will be used in this casing design.

Criteria	**Design factor**
Collapse	1.125
Burst	1.1
Tension	1.8

Collapse pressure

For a waste case scenario in casing collapse pressure, we assume the internal pressure is zero and the fluid in the annulus is cement slurry before it cures. This cement slurry weight is usually higher than mud weight at casing setting depth. In this case, we will use cement slurry whose weight is 14 ppg.

The equation for collapse pressure is given by:

$$P_c = (0.052)(MW)(Depth) \tag{5}$$

Where:

P_c = Collapse pressure, psi

MW = Mud weight, ppg

Depth is in feet.

$P_{c,} = (0.052)(MW)(Depth)$ = (0.052)(14)(1312) = 956 psi

Rated collapse pressure = calculated collapse pressure × design factor (6)

$P_{c,}$ = 956 × 1.125 = 1076 psi

Choose least expensive and lowest grade of casing (but readily available) with a collapse pressure resistance more than 1076 psi.

According to API tables, we choose 13⅜" casing grade 54.5 lb/ft, BTC with a collapse pressure resistance of 1130 psi.

Burst

Calculation of pressure at the casing shoe. The fracture gradient at 1312 feet is 1.0 psi/ft

$$P_b = (Fracture\ gradient)(Depth) \tag{7}$$

P_b = 1.0 × 1312 = 1312 psi

Since pressure is low, we assume gas gradient is = 0. Therefore, pressure at the surface is 1312 psi.

Rated burst pressure = calculated collapse pressure × design factor (8)

P_b = 1312 × 1.1 = 1444 psi

To confirm if the K55 casing will be sufficient to be run to the surface, we look at API tables to check burst pressure for BTC connection. This value is indicated as 1730 psi. Therefore, it is ok to run K55 casing to the surface.

Tension

When using mud weight of 10 ppg for geothermal well, we take into consideration the effect of buoyancy on tension.

$$B = 1 - (0.0153)(MW) \tag{9}$$

Where:

B = Buoyancy

B = $1 - (0.0153)(10)$ = 0.85

The buoyancy factor will be used to calculate the axial neutral point in the casing

$$Axial\ neutral\ point = (B)(Depth) \tag{10}$$

Axial neutral point = 0.85× 1312 = 1116 ft.

However, for a worst case scenario, we assume buoyancy = 0.

Tension will then be due to the entire casing length = 1312 ft.

$$T = weight\ per\ foot\ \times length \tag{11}$$

T = 54.5 × 1312 = 71,504 lb.

Now we check design factor (DF) for tension

$$DF_t = \frac{joint\ strength}{T} \tag{12}$$

Where:

DF_t = Design factor in tension

From API tables, joint strength for 54.5 lb/ft K55 BTC casing is 547,000 lb. The design factor in tension is then equal to

$DF_t = \frac{547,000}{71,504}$ = 7.65

Since $DF_t > 1.8$ then 54.5 lb/ft K55 BTC casing is acceptable and meets tension requirements.

Calculating design factor for collapse,

$$DF_c = \frac{collapse\ resistance}{P_c} \tag{13}$$

Where:

DF_c = Design factor in collapse

$$DF_c = \frac{1130}{956} = 1.183$$

Similarly, calculating design factor for burst,

$$DF_b = \frac{burst\ restance}{P_b} \tag{14}$$

Where:

DF_b = Design factor in burst

$$DF_b = \frac{2741.213}{1312} = 2.09$$

Casing Design Summary					
Casing description: size, weight, grade, connection	**Bottom**	**Total weight**	**Design factors**		
			Collapse	**Tension**	**Burst**
13⅜, 54.5lb/ft, K55, BTC	1312 ft	71,504 lb	1.183	7.65	2.089

The wellhead should be designed to comply with codes of practice for pressure vessels or boilers, and in accordance with API Spec. 6A – and most importantly, rated for the maximum pressure / temperature exposure possible at the surface under static or flowing conditions. The fluid at the wellhead may be water, saturated steam, superheated steam, cold gas, or mixtures of some of these fluids. Due to the column of fluid in the well, surface conditions cannot equate to downhole values, but in some circumstances can approach downhole conditions closely.

The pressure ratings are dera0ted as temperature increases in accordance with ANSI B16.5 and API 6A.

2.2 Determination of appropriate lift pump

Generally , total suction head of the positive displacement pumps is given by the equation below:

$$H_s = h_{ps} + h_s + h_{vs} - h_{fs} \tag{15}$$

Where H_s is total suction head, h_{ps} is suction reservoir pressure head, h_s is static suction head, h_{vs} is velocity head at the pump suction flange and h_{fs} is friction head in the suction line.

The total discharge head of the pump is given by the equation below:

$$H_d = h_{pd} + h_d + h_{vd} + h_{fd} \tag{16}$$

Where H_d is the total discharge head, h_{pd} is the discharge reservoir pressure head, h_d is static discharge head , h_{vd} is velocity head at pump discharge flange and h_{fd} is the total friction head in discharge line.

The total differential head (H_t) :

$H_t = H_d + H_s$ (with a suction lift)

$H_t = H_d - H_s$ (with a suction head)

The total cross-sectional area (approximate area for design purposes) of the annular concentric pipes is 337.5 cm^2 (using conventional casings).

Jet pumps and multistage pumps are best suited to create suction lift in annular concentric pipes and are commercially available.

3. RECOMMENDATIONS

1. Production and testing of a physical model. This involves conceptualization and construction of artificial reservoir and fabrication of appropriate size of the co-production components at an appropriate site to aid testing of the model.

2. Economic analysis of the real practical assembly from the prototype physical model developed.

3. Material selection for various parts of the conceptualized assembly.

4. Collaboration with global metallurgical ‘masters’. Collaborative advantage can be obtained from design and manufacturing entities like Weatherford. Such established companies will offer practical designs and manufacturing modified casings (concentric pipes) and wellheads for use in the field of co-production.

4. CONCLUSIONS

Depth is a key factor governing exploitation economics in geothermal reservoirs.

The cost of the downhole part has a high impact on economics of a geothermal project than the surface part (power plants and steam lines).

The co-production system discussed will serve to avail freshwater to the surface while abstracting steam for power generation

REFERENCES

Antics, M: Insight into wellbore mass and Heat Transfer, *World Geothermal Congress (SC)*, Bali Indonesia, (2010), 79-118.

Arora, C.P: Heat and Mass Transfer, Khanna Publishers, 2nd Edition (1983).

Banks, D: An Introduction to Thermogeology, Ground Source Heating and Cooling, 2nd Edition, Wiley Blackwell, (2012).

Bobo, J.: Fundamentals of casing design. Petroskills llc. Petroskills . Oklahoma, USA (2013).

Douglas, J.F., and Gasiorek, J.M., and Swaffield, J.A., Fluid Mechanics: Pearson Education Limited, 6th Revised Edition, (2011).

Gabolde, G., and Nguyen, J.: Drilling data handbook. Editions Technip. Paris, France, (2006).

Grace, D. R., Shorsen, L. J., and Carden, S. R.: Drilling practices. GSM training Inc. Petroskills LLC Oklahoma, USA (2012).

Harto, C., and Schroeder, J., and Horner, R., and Clark, C.: Geothermal Energy: The Energy-Water Nexus,*Proceedings*, 38th Workshop on Geothermal Engineering Stanford University ,Stanford, California, (2013) 86-87.

Hole, H: Geothermal Well Design- Casing and Wellhead, *World Geothermal Congress Short course (SC)*, Bali Indonesia, (2010), 119-161.

Huenges, E: Geothermal Energy Systems, Exploration, Development and Utilization, Wiley VCH Verlag GmbH & Co. KGaA (2012).

Ingebritsen, S and Sanford, W and Neuzil, C: Groundwater in Geologic Processes, Cambridge University Press, 2nd Edition (2006).

Irawan, D.E and Puradimaja, D.J: The hydrogeology of the volcanic spring belt, east slope of Gunung Ciremai, West Java, Indonesia, Geological Society of London (2006).

Louis, L.F, Louis, F.I and Grambas ,A: Geophysical Prospecting for shallow geothermal fluids in volcanic rock environments: the case of low enthalpy geothermal potential of Kimolos Island, Greece, Department of Geophysics & Geothermic, University of Athens, (2003).

Nakashima, C.Y., and Oliveira Jr, S., and Caetano, E.F.: Calculation of pressure drops in narrow rotating annular clearances, Mechanical Engineering Dept, University of São Paulo Polytechnic Brazil, Thermal Engineering Vol.7 No.02, (2008).

Suwai, J: The hydrology test report for well MW-01 Menengai geothermal field, GDC Internal Report, (2011).

Willoughby, L.: Underground water reserves found in Hawaii’s high country,

Eos, 96, doi: 10.1029/2015EO022539 (2015).