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Understanding thermal-energy extraction prospects in wellbore fluid circulation

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***Abstract*—** The existing numerical and analytical models for fluid circulation in wellbores provide the necessary foundation for exploring geothermal energy prospects for generating power or hot water for various industrial usage. A steady-state fluid circulation rate in a closed-loop system provided insights into power generation's efficacy in previous studies. Lately, the introduction of analytical modeling paved the way for exploring realistic scenarios for the time-variant geothermal gradient at a well's proximity.

This article attempts to provide a roadmap for geothermal energy extraction by invoking the cyclical fluid circulation strategy for ensuring a stable surface fluid temperature or power. Both increasing and decreasing stepwise rate sequence provides the desired outcome. This rate-sequencing approach leads to assessing the value proposition of proposed thermal-energy extraction strategy in various North American basins. For a given depth, the overall thermal prospect depends on a well's geographic location. Given the abundance of abandoned wells in oil fields, this study explores retrofitting such wells and drilling designed wells in geothermal-friendly areas to compare their relative economic value propositions.

Keywords—Thermal-energy, fluid circulation, designed wells, repurposed wells, power generation.

I. INTRODUCTION

The current energy transition initiatives that are in play in most developed countries revolve around the minimization of carbon footprints. Renewable sources, such as wind, solar, geothermal, biomass, and hydrogen, have gained considerable traction. Although successful pilots abound, both scalability and the associated economic value proposition become a prime interest; for instance, offshore wind and biomass cost more than other sources, including geothermal and natural gas.

Given the preceding reality, both direct use of geothermal energy in various industries and indirect use for generating power provides an opportunity for energy transition with minimal carbon footprints. In this context, many studies in North American settings [1-6] have appeared in the literature. Specifically, Lund has chronicled the use of geothermal energy over four decades [5-7]. Some recent studies [8-9] have focused on exploring fluid circulation in abandoned wells in the deep shale play. The horizontal well configuration leads to the increased fluid residence time, which, in turn, ensures efficient thermal energy extraction, as shown recently with an analytical model [10]. However, these projects need reviewing with both engineering and economics lenses, as explored in [8-9].

Repurposing hydrocarbon wells for geothermal use when an oilfield is in late life has been recently studied in both the U.K. [11] and Italian [12] settings. Earlier, a plethora of studies [3, 13-25] promoted reusing abandoned wells. According to the environmental protection agency or E.P.A.'s 2020 estimates, the total number of abandoned wells is about 3.2 million in the U.S. While the concept of reuse of abandoned wells appears very attractive from the standpoint of capital investment, challenges remain. For example, the desired well depth and the geothermal gradient are the two key independent variables in the designed-well setting, as discussed in [10]. Besides, the well's age, vis-à-vis its mechanical integrity, may pose practical challenges. Nonetheless, we think that the use of abandoned wells presents an economic value proposition for a given setting to prove the concept of harnessing thermal energy by fluid circulation.

In this study, we investigated the use of both the abandoned and designed wells in various North American prospects to establish the economic value proposition in both systems. Exploring the technical feasibility for harnessing geothermal energy using the wellbore heat exchanger or WBHX became the focal point of this investigation to explore scalability. The designed wells can meet all the required metrics, including the physical location for either power generation or direct use in each industry. However, the abandoned wells present challenges in that they are suited for generating fluid temperature for direct use in various industries.

II. FLUID CIRCULATION MODELING APPROACH

The continuous fluid-circulation strategy has been investigated by many authors [2,15] in a closed-loop WBHX system for over a decade. Given the steep decline in the near-wellbore formation temperature with time, we [26] recently proposed a transient cyclical-circulation approach involving a circulation rate increase, followed by a rate decrease. Besides preserving the near-wellbore temperature, this strategy can deliver near-stable fluid temperature and power generation capability at the wellhead without well shut-in periods.

As shown in [26], the governing second-order differential equation is given by the following expression:

$$AB\frac{d^2T_t}{dz^2} - B\frac{dT_t}{dz} - T_t + T_{es} + zg_G = 0 \qquad (1)$$

The solution of Equation (1) leads to the temperature expressions for both the tubing (T_t) and annulus (T_a), as follows:

$$T_t = \alpha_1 e^{z\lambda_1} + \beta e^{z\lambda_2} + Bg_G + T_{es} + zg_G \qquad (2)$$

$$T_a = (1 - B\lambda_1)\alpha_1 e^{z\lambda_1} + (1 - B\lambda_2)\beta e^{z\lambda_2} + T_{es} + zg_G \qquad (3)$$

Using the superposition of the sequential flow rates with the exponential-integral or Ei-function, one can obtain the final form of the equation as follows [26]:

$$\frac{T_{ei} - T_{wb}}{Q_n} = \left(\frac{-1}{4\pi hk_e}\right) \times \sum_{i=1}^{n}\left[\frac{(Q_i - Q_{i-1})}{Q_n} \times E_i\left(\frac{-r_{wb}^2}{4\alpha(t - t_{i-1})}\right)\right] + \left(\frac{-1}{4\pi hk_e}\right) \times E_i\left(\frac{-r_{wb}^2}{4\alpha}\right) \qquad (4)$$

The left side of Equation 4 when plotted against the summation term on the right side allows one to obtain a straight-line fit for each flow period. Then, each regressed line allows one to compare the calculated initial-formation temperature with that measured to gauge the solution efficacy and assess the range of solutions over a time span of interest.

III. EVALUATING WELL PROSPECTS

We used our [26] recently developed transient analytical model to preserve the near-wellbore geothermal gradient. In this modeling approach, a stepwise increase and subsequent decrease of flow rates ensure minimal alteration of the geothermal gradient. This circulation strategy leads to significant improvement in the extraction efficiency of geothermal energy. In this approach, we used water as the circulating fluid for safe use.

A. *Power Generation Potential for Various System Variables with Design of Experiments*

We assumed a geothermal gradient of 0.11 ^{o}C/m for a designed well, given considerable thermal energy potential in the Western part of the U.S., as Fig. 1 suggests. In contrast, an abandoned well in a typical Texas setting is about 0.05 ^{o}C/m in a 4000 m well.

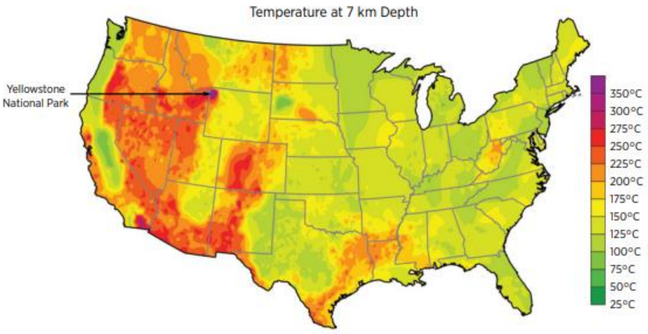

Fig. 1. Favorable formation temperature at 7 km depth shows the potential for harnessing energy in the U.S.

We learned earlier that both the geothermal gradient and well depth are the two most influential variables in generating the wellhead's high-fluid temperature. This reality prompted us to explore the efficacy of tubular ID's and fluid injection temperature, along with an operational variable, circulation rate. For a well depth of 4500 m and a P-50 geothermal gradient of 0.11 ^{o}C/m, we chose a range of independent variables to assess the value-added proposition in the transient fluid-circulation strategy. Table-1 presents the relevant data used in the statistical design of experiments or DoE. Both the outlet fluid temperature and power generation constituted the dependent variables of interest.

Table-1: Variables used in DoE runs.

DoE independent variables	**P10**	**P50**	**P90**
Tubing ID, cm	5.240	7.201	8.890
Annulus ID, cm	16.828	20.363	26.888
Injection Temp (^{o}C)	25	50	75
Circulation rate, min (m3/h)	3.180	6.359	9.539
Circulation rate, max (m3/h)	12.718	15.898	19.077

The Pareto chart in Fig. 2 shows the relative importance of the wellhead fluid temperature's independent variables. Although tubing ID's contribution is evident, casing ID and the injection-fluid temperature also provide a statistically significant value proposition in a relative sense.

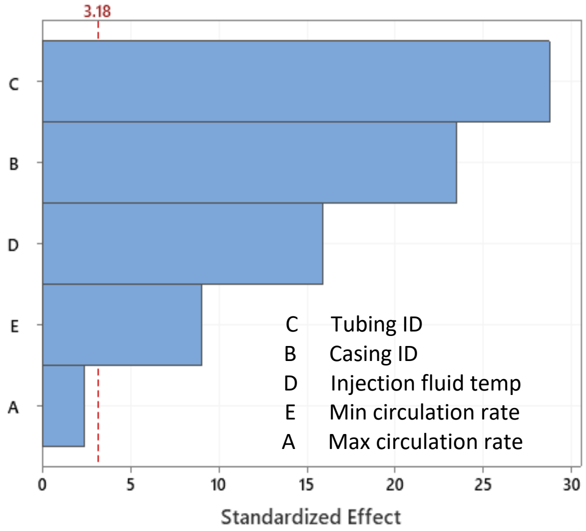

Fig. 2. The Pareto chart for the wellhead-fluid temperature.

Then, we generated Fig. 3 to learn the overall picture with the cumulative-distribution function or CDF plot. The p-50 outcome suggests that this fluid temperature can be fed into a binary plant to generate power.

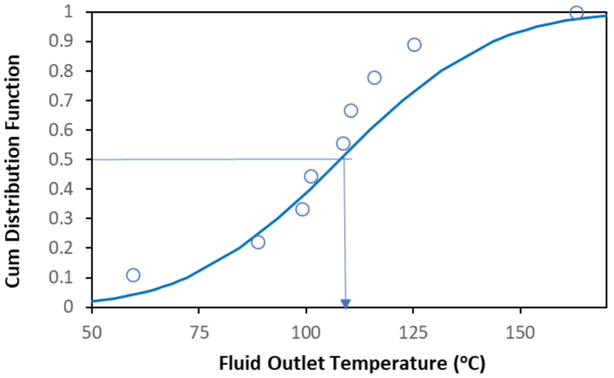

Fig. 3. The CDF plot suggests a promising P-50 output for the wellhead-fluid temperature.

When these data are viewed through the lenses of power generation capability, we observed that handling the larger fluid volume through increased casing ID has considerable merit for the overall value proposition. The Pareto chart in Fig. 4 makes this point. The fluid injection temperature becomes the second most important variable, followed by the tubing ID.

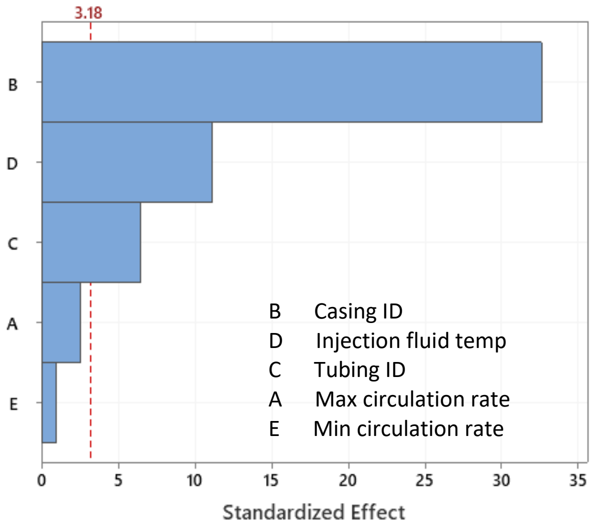

Fig. 4. The Pareto chart for power generation.

Fig. 5, showing the CDF plot for power generation, displays the range of possibilities. The dominance of casing ID suggests that handling larger fluid volume during circulation leads to a higher power generation capability. We think that this finding makes a significant value proposition while pursuing a designed well's output potential.

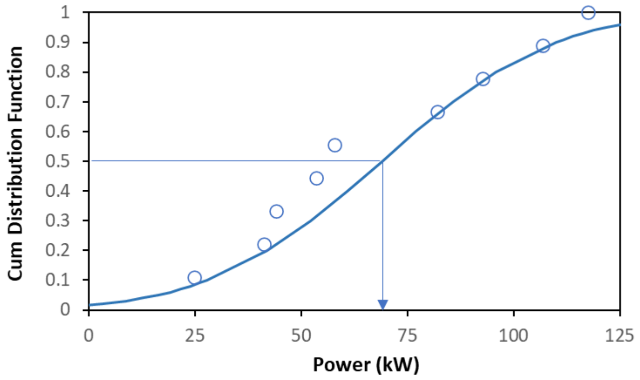

Fig. 5. The CDF plot presents the range of power output.

B. *Understanding Influence of Certain Variables on Fluid Temperature Output and Power Generation*

The lessons learned from the statistical DoE runs provide the foundation for an overall understanding of various independent variables' relative importance. We compared some of those solutions by generating time-dependent outputs for three different injection fluid temperatures to gain further insights. Fig. 6a presents three such cases for generating the wellhead fluid temperature profiles, and the corresponding power generation appears in Fig. 6b.

The short plateau periods reflect the constant circulation periods in both increasing and decreasing rate sequence in each cycle. The rates increased from 20 to 80 m^3/h with an increment of 2 m^3/h spanning every two days in the increasing-rate sequence. We followed the same protocol in the decreasing-rate sequence.

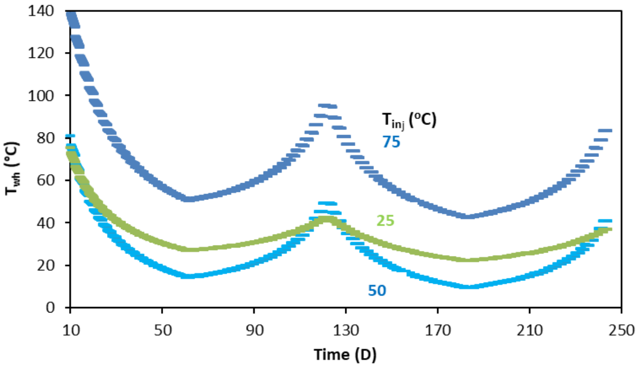

Fig. 6a. Wellhead fluid temperature profiles in different settings.

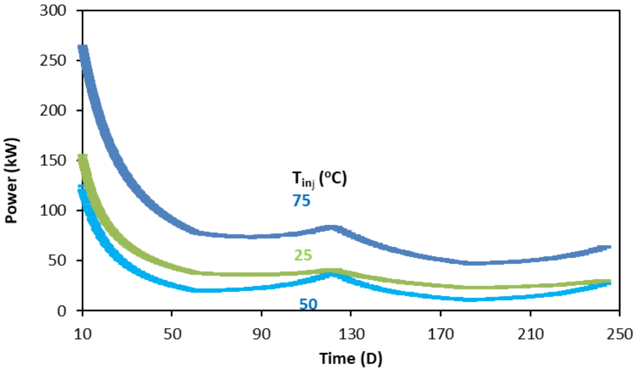

Fig. 6b. Power generation for the three corresponding cases.

The dominance of the highest injection fluid temperature of 75 ^{o}C comes through clearly in Fig. 6(a) and 6(b). However, the other two temperature and power profiles' difference relates to the increase in circulation rates that offset the injection inlet temperature deficiency. Specifically, the maximum and minimum flow rates of 15.9 and 3.2 m^{3}/h, respectively, are higher in the 25 ^{o}C fluid temperature situation than in the other. The maximum and minimum flow rates for the 50 ^{o}C case were 12.7 and 3.2 m^{3}/h, respectively. This example points to learning the nuances of different independent variables that are in play in each situation.

An increase in casing ID can significantly benefit both the output fluid temperature and the consequent power generation that occurs. For example, when the casing ID increased from 16.83 cm to 26.88 cm, a significant increase in the fluid output temperature occurred, as Fig. 7(a) illustrates. Consequently, the power output doubled, as Fig. 7 (b) shows.

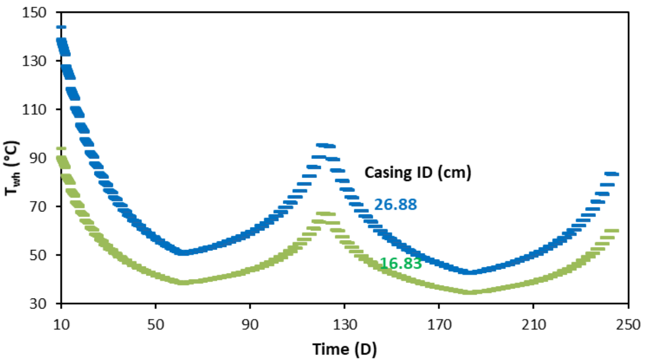

Fig. 7a. Increased casing ID significantly improves the wellhead fluid temperature.

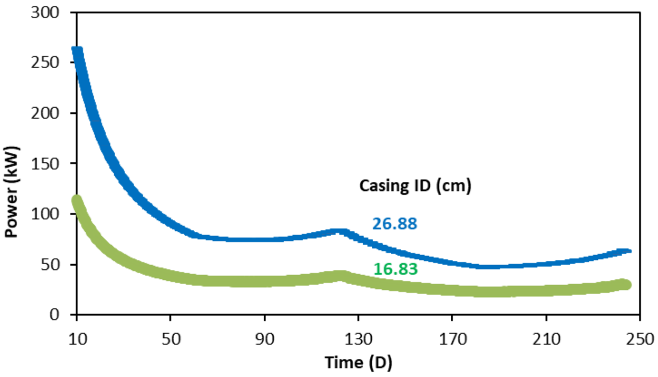

Fig. 7b. Doubling of power output occurs with the increased casing size.

V. DISCUSSION

This study focused on the designed wells, given that the abandoned wells pose challenges on many fronts. As indicated in this study and others, for existing wells, the probability of generating power will be low, given that they may not meet the requirements of geothermal gradient, well-depth, and the ID of tubulars. Given this reality, the direct usage of hot water in various industries appears to be the logical solution. However, those wells need to be in reasonable physical proximity to the sector of interest.

Given the potential issues with abandoned wells, targeting the 'drilled but uncompleted' (DUC) wells present a better opportunity in terms of the well's age, ability to choose tubing ID, and provide tubular insulation. Many plays in the Permian, Eagle Ford, Anadarko, Bakken, and Appalachia offer over 7,100 DUCs, according to the U.S. Energy Information Administration (EIA).

Let us share some of the other lessons learned with designed wells. Although not shown here in an explicit form, we observed that the high geothermal-gradient (g_T) wells markedly outperform those in low-g_T environments; this advantage exists even in adverse fluid-circulation timestep situations. Hence, if this type of energy harnessing measure leads to power generation, the abundance of prospects in the Western states provide industrial-scale field development opportunity, as Fig. 1 illustrates.

Although outside the scope of this investigation, project economics of designed wells need probing with care, given the current low-power-generation cost associated with natural gas. Such research also needs to explore the excellent value proposition that this green energy offers toward carbon emission minimization. Given that most countries are poised to meet the Paris climate accord goals, a green energy source deserves due attention.

V1. CONCLUSIONS

The statistical design of experiments showed that for a given well depth and geothermal gradient system, both the casing ID and inlet-fluid temperature have significant impacts on the output wellhead temperature and power generation capability. Specifically, we reached the following conclusions:

1. Fluids with higher injection temperatures produce higher fluid temperature output, leading to a higher power generation.

2. The larger casing ID, which allows handling larger fluid volume in a designed well, can provide increased power output with all the other variables being the same.

Nomenclature

T_a	temperature of annulus fluid, ˚C
T_{ei}	formation temperature, ˚C
T_{es}	surface temperature of earth, ^{o}C
T_t	temperature of tubing fluid, ˚C
T_{wb}	temperature at wellbore/formation interface, ^{o}C
g_G	geothermal gradient, ˚C/m
k_e	conductivity of the formation, J/s-m- ˚C
r_w	wellbore radius, m
α_1	differential equation solution constant, ˚C
λ_1	parameter defined by Eq. A-3, m^{-1}
λ_2	parameter defined by Eq. A-4, m^{-1}
h	perforation interval length, m
β	differential equation solution constant, ˚C
A	parameter defined by Eq. A-1, m
B	parameter defined by Eq. A-2, m
Q	heat flow rate, W
z	any depth of vertical section of well, m
α	heat diffusivity of formation (= k_e/ c_e ρ_e), m^{2}/sec

L total depth, m

Appendix-A

Let us define the four parameters of interest as they relate to Equations 1 through 4.

$$\boldsymbol{A} = \frac{wC_f T_D T_D}{2\pi}\left[\frac{(k_e + r_w U_a)}{r_w U_a k_e}\right] \qquad \text{(A-1)}$$

$$\boldsymbol{B} = \frac{wC_f T_D T_D}{2\pi r_t U_t} \qquad \text{(A-2)}$$

$$\boldsymbol{\lambda_1} = \frac{-1+\sqrt{1+\left(\frac{4A}{B}\right)}}{2A} \qquad \text{(A-3)}$$

$$\boldsymbol{\lambda_2} = \frac{-1-\sqrt{1+\left(\frac{4A}{B}\right)}}{2A} \qquad \text{(A-4)}$$

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