Enhancing Flow Distribution in Utah FORGE EGS through Analytical Optimization of Fracture Zones and Well Orientation

Saugat Dotel[1,2], Robert Podgorney[1]

[1]Energy and Environment Science & Technology, Idaho National Laboratory, Idaho Falls, Idaho, USA
[2]Idaho State University, 921 S 8th Ave, Pocatello, Idaho 83209
saugatdotel@isu.edu

Keywords: FORGE, geothermal wells, reservoir utilization, circulation test, well orientation, fracture zones.

ABSTRACT

Enhanced Geothermal System (EGS) requires uniform fluid flow distribution through its engineered fracture zones for efficient heat extraction and balanced reservoir utilization. Data from the extended circulation test of August 2024 at Utah FORGE, revealed a highly localized flow with over 60% of the injected fluid recovered from the first three fracture zones. Such concentrated flow causes localized thermal stress and pressure spikes, which could result in degradation of fracture conductivity and performance over time. This study employs an analytical model, based on circuit analogies, to assess the effect on flow profile by modifying well orientation and fracture configuration. The base model is calibrated to match flow distribution, zone spacing, and well geometry of 16A (78)-32. Several scenarios for well spacing, with ten and fourteen fracture zones, in parallel and non-parallel (one angled and two angled) well orientations were simulated to identify strategies for improving flow uniformity at Utah FORGE. Fracture flow variation was observed to improve by over 20% with strategic addition of engineered fracture zones. Similarly, the change in well orientation led to increase in flow uniformity by 35%.

1. INTRODUCTION

Enhanced Geothermal System (EGS) depends fundamentally on effective fluid circulation through an engineered network of hydraulically stimulated fractured zones in the subsurface. The distribution of flow directly governs the heat extraction efficiency, reservoir longevity, and overall system performance. For effective EGS development, maximizing heat extraction from a given reservoir volume is critical, and hydraulic stimulation techniques are widely employed to enhance inter-well connectivity and improve heat recovery through fluid circulation (Zimmermann et al. 2010). Conversely, newly created and reactivated fractures can form preferential pathways that allow fluids to travel rapidly between wells and reduce residence time and limit heat exchange. Hence, while enhancing inter-well connectivity is important, it equally essential to promote a uniform flow distribution among multiple pathways to maximize thermal recovery (Zhang and Dahi Taleghani 2023).

When fluid flow occurs within a fracture network characterized by variable fracture permeability and heterogenous aperture distributions, preferential channelized flow pathways are likely to develop. Such channelized flow is unfavorable for geothermal heat extraction as it limits the contact area between the circulating fluid and surrounding rock, thereby reducing thermal exchange efficiency (Jia et al. 2022). Additionally, the presence of fractures with high hydraulic conductivity could develop early thermal breakthroughs and affect the efficiency of EGS. This can lead to the fluid flow to get localized into few conductive fractures and basically short-circuit the flow (Zhang and Dahi Taleghani 2023). To delay thermal breakthrough and achieve a uniform flow distribution in EGS wells, careful consideration must be given to the geometry, spacing, and hydraulic properties of the fracture zones, as well as to the well orientation that intersect them (Asai et al. 2022; Kumar and Ghassemi; Samin et al. 2019).

One of the prominent field-scale implementations of EGS is the Utah FORGE project. The FORGE (Frontier Observatory for Research in Geothermal Energy) site is located approximately 350 km south of Salt Lake City and 16 km northeast of Milford, Utah. Ongoing stimulation and circulation experiments at Utah FORGE provide critical insights into fracture flow behavior and offer a platform for developing strategies aimed at improving flow uniformity and long-term geothermal performance. The extended circulation test of August 2024 revealed significant challenges associated with non-uniform flow distribution at Utah FORGE. Based on the report of (England et al. 2024), a substantial portion, over 60%, of injected fluid can be observed to recover from the first three fracture zones revealing a highly localized flow. Such flow localization reduces fluid-rock interaction efficiency, increases the potential for thermal short-circuiting, and can accelerate deterioration of fracture conductivity overtime.

In this study, an analytical modelling framework is employed to investigate the fluid flow distribution in an Enhanced Geothermal System, with specific application to Utah FORGE site. It introduces several important advancements to the analytical model developed by (Asai et al. 2022; Asai et al. 2018). The presented model incorporates flow rate profiles observed during the August 2024 Extended Circulation Test at Utah FORGE site, enabling practical applications to actively simulated EGS reservoir. This study also extends the analysis of effect of well orientation on flow profile by introducing multi-segment (two-angle) well configurations, which have not been previously examined within a field-calibrated analytical framework. The combined effect of well-orientation, inter-well spacing, and fracture zone density on flow uniformity is quantitatively evaluated using objective performance metrics, enabling direct comparison of alternative design strategies.

2. METHODOLOGY

2.1 Hydraulic-electrical analogy for flow distribution modeling

According to Kirchhoff's laws for closed electric circuits, the distribution of current within a loop depends on the resistance of each branch. The branches having lower resistance will carry higher magnitude of current and the potential difference developed across it is governed by the current flowing through it. This law can be applied directly to hydraulic networks through a circuit analogy, in which flow rate is analogous to electrical current, pressure drop corresponds to electrical potential difference, and hydraulic fracture resistance is treated as electrical resistance. Based on this framework, (Asai et al. 2018) developed an analytical model to calculate flow and pressure drop in a multifracture doublet system. This study employs the developed model to analyze the fluid flow distribution within the engineered fracture network at Utah FORGE. (Asai et al. 2022) illustrated the analytical modeling framework used to evaluate fluid flow distribution in a doublet EGS system and is referenced in Figure 1.
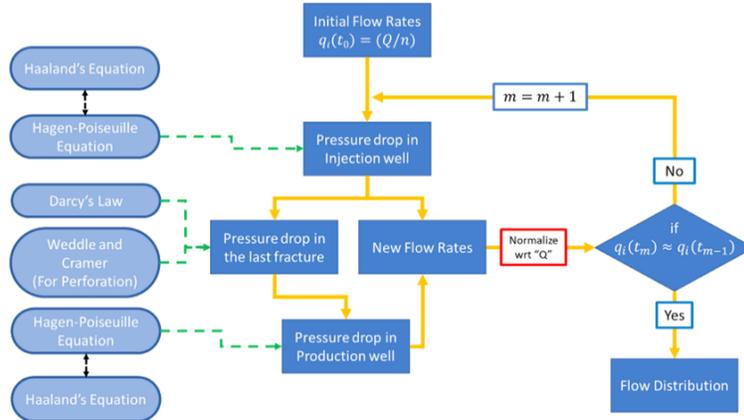

Figure 1: Working of the analytical model developed by (Asai et al. 2022).

### 2.2 Model calibration and case study configuration

The analytical model was modified to incorporate flow rate profiles observed during the August 2024 Extended Circulation Test at Utah FORGE. Table 1 represents the findings of (England et al. 2024) from the PLT/PTS survey run in well 16A(78)-32.

Table 1: Flow in well 16A (78)-32 from extended circulation test, August 2024

Stage	Perforations		Water (Injection is negative)	Water
			(bpd)	(%)
10	9270	9276	-3728.4	25.8%
9	9320	9323	-201.5	1.4%
	9345	9348	-362.8	2.5%
	9370	9373	-644.9	4.5%
	9395	9398	-725.5	5.0%
	9420	9423	-151.2	1.0%
	9445	9448	-90.7	0.6%
	9470	9473	-100.8	0.7%
	9490	9493	-262.0	1.8%
8	9545	9548	-100.8	0.7%

Stage	Perforations		Water (Injection is negative) (bpd)	Water (%)
	9570	9573	-100.8	0.7%
	9595	9598	-80.6	0.6%
	9620	9623	-201.5	1.4%
	9645	9648	-1410.7	9.8%
	9670	9673	-1007.7	7.0%
	9695	9698	-443.4	3.1%
	9720	9723	-423.2	2.9%
7	9798	9801	0.0	0.0%
	9850	9853	0.0	0.0%
	9898	9901	0.0	0.0%
6	9959	9962	0.0	0.0%
	9970	9976	0.0	0.0%
5	10020	10026	-604.2	4.2%
4-3R	below 10026		-3825.7	26.4
Totals			-14466.4	100.0%

The model calibration was achieved by adjusting fracture permeability values to match the measured flow distribution while preserving the fracture zone spacing and well geometry corresponding 16A (78)-32 well. Through this calibration, the base-case model accurately reproduces the flow localization observed at Utah FORGE and establishes a robust reference framework for parametric analysis of fracture configuration and well orientation. The flow distribution of base-case model is shown in Figure 2.
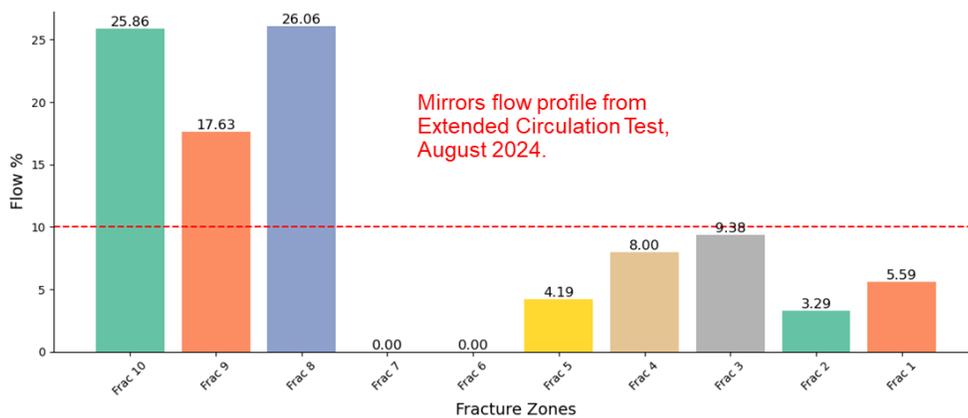
**Figure 2: Flow distribution in base model**

The injection and production wells in the base-case model were assigned to be at a constant inter-well spacing of 100 m. Both wells replicate the fracture zone configuration of Utah FORGE well 16A (78)-32 and comprise of ten fractures zones from Zone 10 to 1. Building on this reference model, a non-parallel well orientation with same fracture zone arrangement was investigated. A range of heel-to-toe well spacing combinations were simulated to assess their influence on flow distribution. Among them, a spacing of 225 m at the heel and 60

m at the toe resulted in the most uniform flow distribution and was therefore selected as the representative non-parallel configuration. The parameters and corresponding values for the simulated cases are listed in Table 2.

Table 2: Simulation parameters

| Parameters	Values
Total well distance (heel to toe)	1375 meters
Number of existing fracture zones	10 nos.
Spacing between fracture zones within well	Mirrors well 16A
Number of perforations	10 nos.
Size of perforations	0.0254 meters
Permeability	Calibrated from extended circulation test, Aug 2024
Mass flow rate	10 barrels per minute
Additional fracture zones	4 nos. @ 225 m spacing near heel

Additional simulations were conducted with introduction of four new engineered fractures zones, Zones D to A, from the heel at a spacing of 225 m. These added fracture zones were assigned to have the same hydraulic permeability as the nearest fracture zone, Zone 10. These cases were analyzed for both parallel and non-parallel orientation. Furthermore, extending the selected non-parallel orientation, additional scenarios incorporating two angled well segments were simulated. In this two-angled well orientation, well spacing was varied at the heel, the fracture zone 10, and the toe. Heel spacing values of 200 m and 225 m were combined with intermediate and toe spacings of 150 m and 60 m, respectively. Across all simulation, the fracture zone spacing within each well, the number and size of perforations, and the mass flow rate were maintained constant, with only the well orientation and well spacing were varied to isolate their effects on flow distribution. The schematic diagram for different analyzed orientation is shown in Figure 3.

(a)

4
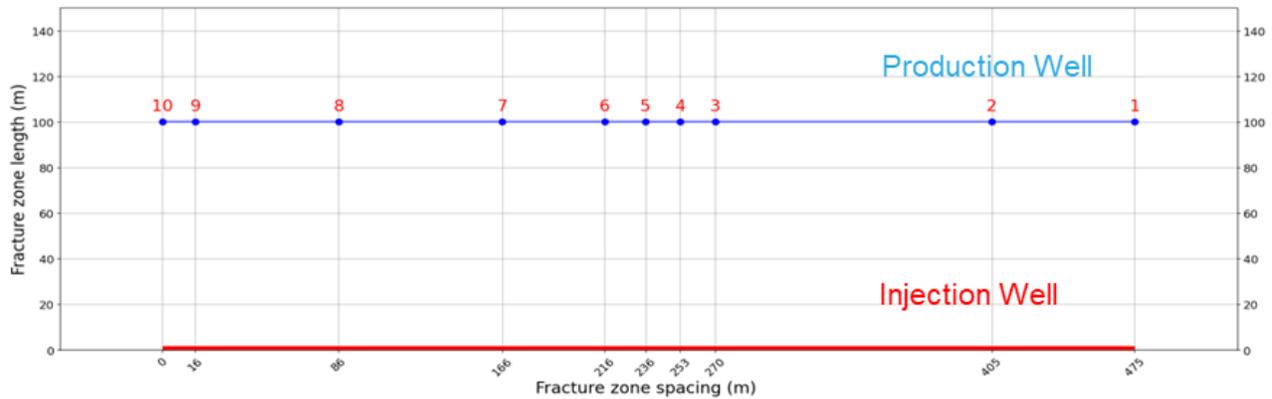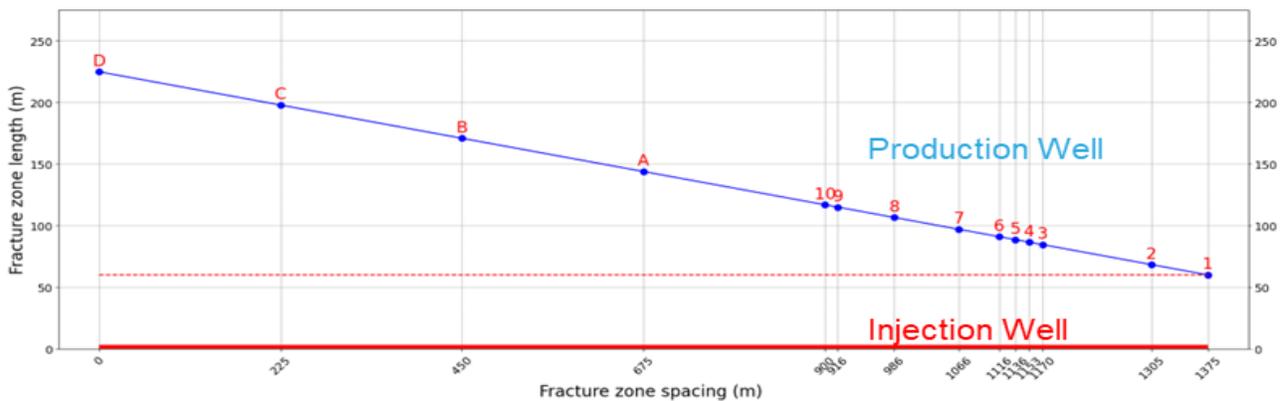
(b)
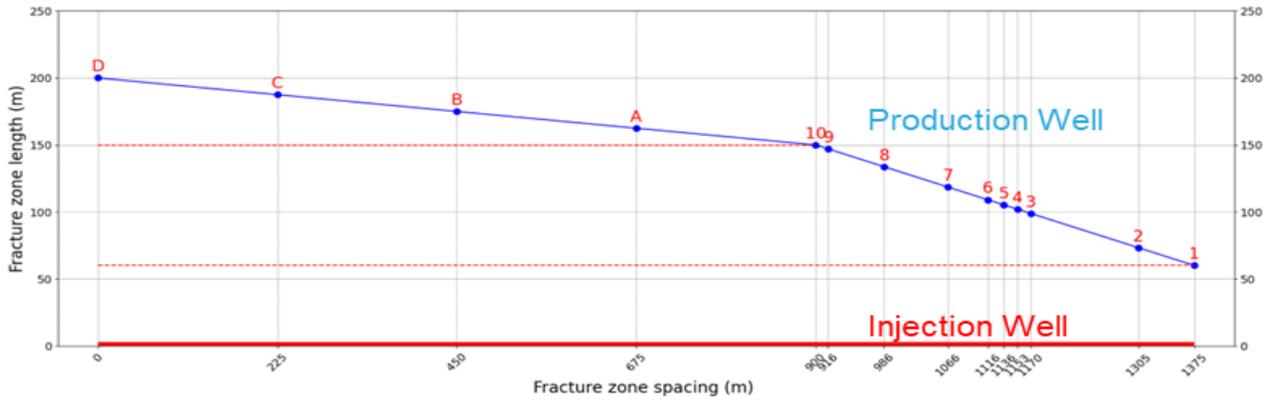
(c)

Figure 3: Schematic representation of analyzed well orientation of doublet system with fracture zones numbered, including (a) Parallel, (b) Single-angled non-parallel, (c) Two-angled non-parallel.

The well orientation represented in Figure 3 form the basis for six simulation cases with varying number of fracture zones and well spacing, which are listed in Table 3.

Table 3: Summary of evaluated modeling cases

Cases	Well orientation	Number of fracture zones	Spacing between injection and production well at the fracture zone
A	Parallel	10	(Zone 10, Toe) = (100, 100) meters, Base model
B	Non-Parallel (Single angled)	10	(Heel, Toe) = (225, 60) meters
C	Parallel	14	(Heel, Toe) = (100, 100) meters
D	Non-Parallel (Single angled)	14	(Heel, Toe) = (225, 60) meters
E	Non-Parallel (Two angled)	14	(Heel, Zone 10, Toe) = (200,150,60) meters
F	Non-Parallel (Two angled)	14	(Heel, Zone 10, Toe) = (225,150,60) meters

2.3 Flow uniformity assessment metric

Flow uniformity is quantified for each of the design strategies by coefficient of variation (CV) of fracture zone flow rates. It was calculated as the ratio of standard deviation to the mean, shown in Equation 1.

Coefficient of Variation (CV) = Standard deviation / Mean   (1)

As a dimensionless indicator of relative variability, CV facilitates consistent comparison of flow distributions across different well orientation and fracture configurations. Lower CV values correspond to higher uniformity in flow distribution among fracture zones, while higher values indicate increased flow localization. Notably, CV is used in this study as a comparative metric rather an absolute design criterion.

3. RESULTS AND DISCUSSION

3.1 Calibrated fracture permeability distribution

The fracture zone permeability values were calculated by calibrating the analytical model to field flow data and are provided in Table 4. The results show substantial variation in base permeability across the fracture zone. Zones 10, 9 and 8 exhibit the highest permeability values ranging from 1.25 to 1.85 x 10^{-13} m^2, indicating strong hydraulic connectivity near the heel of the well. The permeability for Fracture Zones 7 and 6 were assigned to be zero to represent their negligible contribution to fluid flow during the Extended Circulation Test. PLT/PTS survey results indicate no detectable flow from these zones, suggesting limited or ineffective simulation, potential

mechanical isolation, or poor hydraulic connectivity. Accordingly, zero permeability therefore represents hydraulically inactive fracture zones rather than an arbitrary modeling assumption. For the remaining fracture zones, the permeability was found to be generally decreasing away from the heel. This heterogenous flow distribution explains the observed flow localization at Utah FORGE and highlights the dominance of fracture-scale hydraulic variability on overall flow distribution.

Table 4: Calibrated permeability values

Fracture zones	Base permeability (x10^-13 m^2)
10	1.83
9	1.25
8	1.85
7	0 (No flow)
6	0 (No flow)
5	0.30
4	0.57
3	0.67
2	0.23
1	0.40

3.2 Effect of well orientation and fracture zone density on flow distribution

The influence of well orientation on flow distribution was analyzed by comparative evaluation of parallel, single-angled non-parallel, and two-angled well configuration for fracture networks comprising of ten and fourteen fracture zones. Flow profile was plotted for each case and coefficient of variation in distribution was calculated. The results are presented in Figure 4. The parallel well configuration demonstrated flow localization near the heel, with substantial fraction of injected flow concentrated in the early fracture zones. In contrast, a non-parallel well configuration resulted in better flow circulation with redistribution toward the mid and toe located fractured zone. For ten fracture zones, the flow distribution improved by about 15% when transitioned to non-parallel orientation. The flow profile is shown in Figure 4(a, b). This enhancement in flow uniformity in non-parallel well configuration is observed for both the ten and fourteen fracture cases.
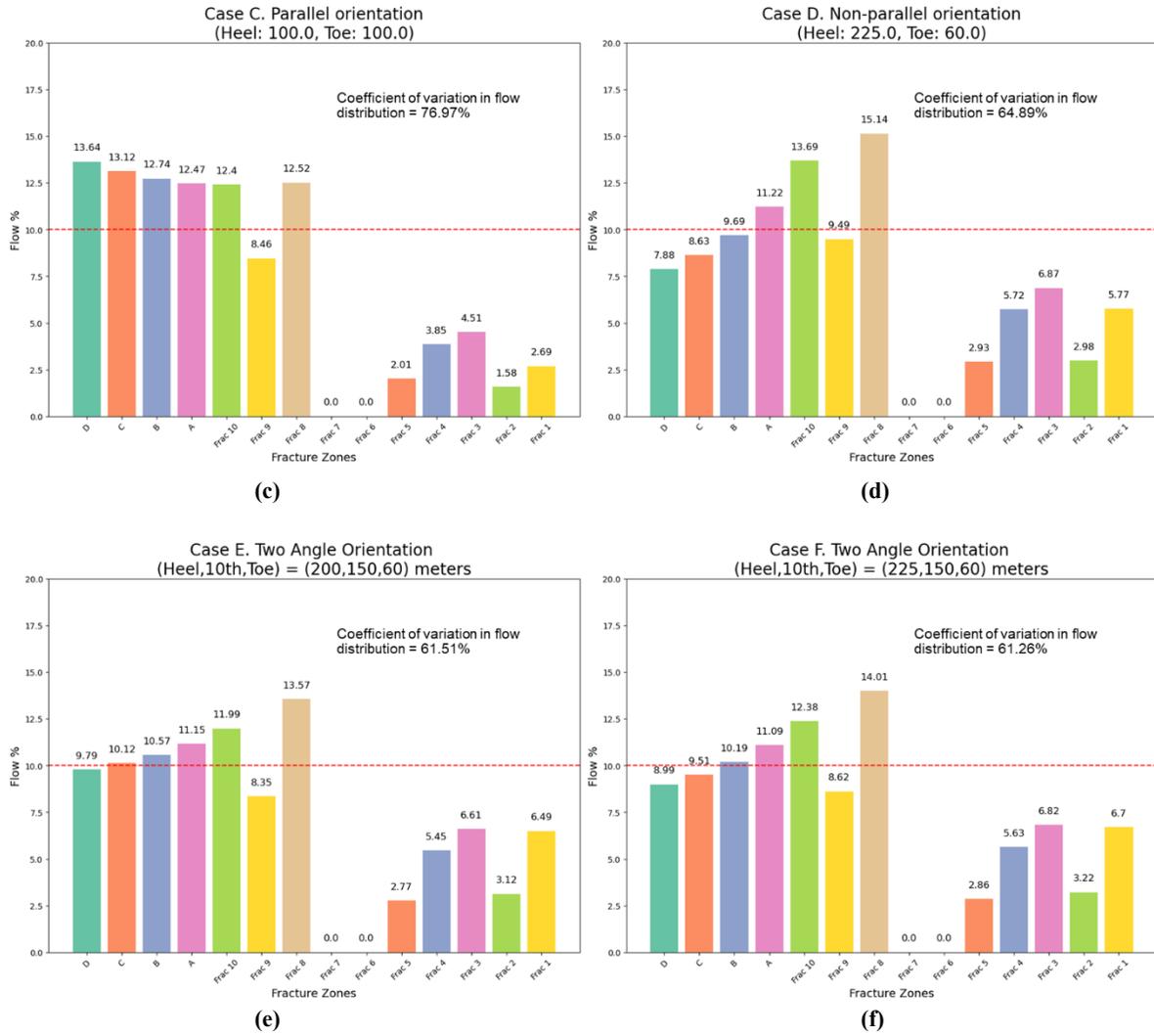

(a)

(b)

6

(c)

(d)

(e)

(f)
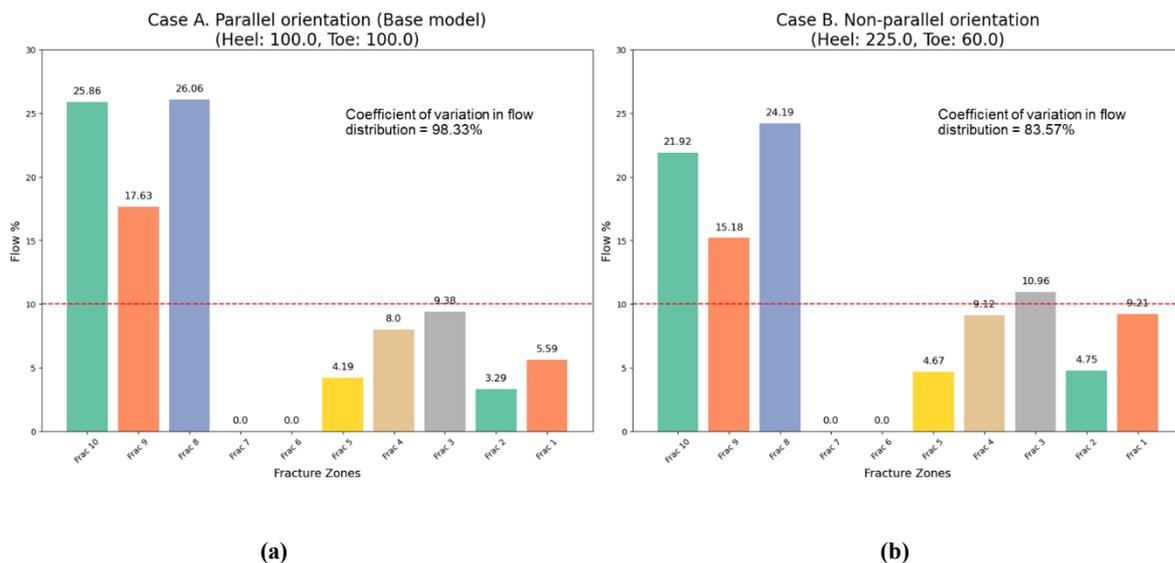
Figure 4: Flow profile for simulated cases (summarized in Table 5).

**Table 5: Summary of flow uniformity metrics for all simulation cases.**

Cases	Well orientation	Number of fracture zones	Coefficient of variation
A	Parallel	10	98.33
B	Non-Parallel (Single angled)	10	83.57
C	Parallel	14	76.97
D	Non-Parallel (Single angled)	14	64.89
E, F	Non-Parallel (Two angled)	14	61.51, 61.26

Similarly, the addition of engineered fracture zones improved the flow profile of the doublet system. From flow profile illustrated in Figure 4 (a, b, c, d), uniformity in distribution is observed to be improved by more than 20% on strategic addition of four fractured zones in both cases of parallel and single-angled non-parallel doublet well configuration. Further uniformity in flow distribution was achieved with two-angled well orientations evaluated for fourteen fractures as shown in Figure 4 (e, f). This orientation reduced peak flow concentration near the heel, while increasing the contribution form mid and toe fracture zones. The coefficient of variation in flow distribution was obtained to be about 62%. For comparison, the field calibrated base model had variation of about 98%. These results

highlight the importance of well orientation and fracture density as key design parameters for controlling uneven flow distribution and improving reservoir utilization in EGS system. Table 5 provides the flow variability for the simulated cases.

3.3 Effect of heel-toe inter-well spacing on flow uniformity for non-parallel configuration

A comprehensive parametric analysis was conducted to evaluate the effect on flow distribution for both single-angled and two-angled non-parallel configuration by systematically varying the inter-well spacing at the heel and toe. The spacing combinations were selected to avoid excessively narrow well separations, ensuring practical applicability for the results. For each configuration, flow distributions were quantified using the coefficient of variation (CV). Figures 5(a) and 5(b) present the heatmaps of the coefficient of variation for single-angle non-parallel cases with ten and fourteen fracture zones. In both cases, the results show a consistent reduction in CV as the spacing at the heel increases and the spacing at the toe decreases. Additionally, the fourteen-fracture configuration consistently yields lower CV values due to increased availability of flow pathways, while maintaining a consistent sensitivity to heel-toe inter-well spacing as observed in ten-fracture case.

(a)

(b)

(c)
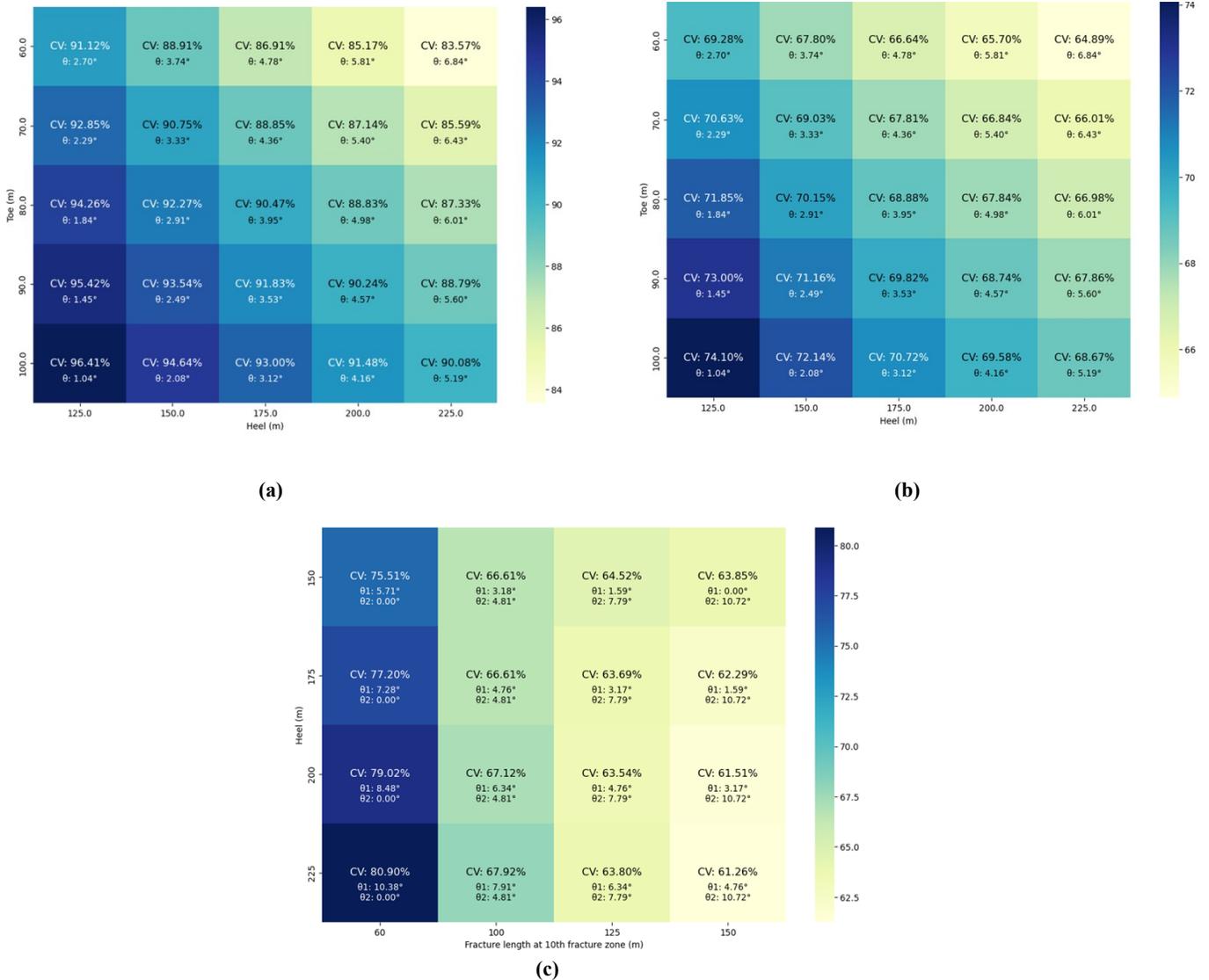
Figure 5: Heat maps of coefficient of variation in flow distribution in (a) Single-angled 10 fracture zones, (b) Single-angled 14 fracture zones, (c) Two-angled 14 fracture zones. Note: θ = angle between heel and toe in degrees, θ1 = angle between heel and Fracture Zone 10, θ2 = angle between Fracture Zone 10 and toe.

Figure 5c shows the results for the two-angle non-parallel configuration with fourteen fracture zones, which includes well divergence between the heel to Fracture Zone 10 and Fracture Zone 10 to toe. The two-angle well configuration results in lower CV values as compared to single-angle cases. This indicates that distributing the angular deviation along the well further balances hydraulic conductivity and enhances uniformity in fracture zone participation. Overall, the finding highlights that optimizing heel-toe inter-well spacing, fracture density and multi-segment well orientation, provides an effective approach on enhancing the flow uniformity in non-parallel EGS doublet wells.

8

4. CONCLUSION

Based on the findings of the study, the following conclusions are drawn:

- An analytical model based on hydraulic-electrical circuit analogy was successfully calibrated using flow profile from Extended Circulation Test, August 2024 and fracture parameters of Utah FORGE 16A (78)-32. Calibrated permeability indicates high flow localization behavior across fracture zones, which can impact the efficiency and sustainability of the system. This uneven flow distribution can be found to be strongly influenced by well geometry and fracture network configuration.

- Modification of well orientation from parallel to non-parallel configuration substantially enhanced flow uniformity by reducing flow concentration in early fracture zones. Two-angled well orientation further improved flow circulation as compared to single-angled parallel configuration, promoting balanced fracture participation. Such strategies can be effective for mitigating heel-dominated flow and promoting uniform fracture contribution in future FORGE wells.

- Strategic addition of fracture zones from ten to fourteen, further enhanced the flow uniformity by introducing additional flow pathways and reducing flow localization. Fracture density and placement should be considered in future stimulation programs.

- Overall, the proposed analytical framework developed in the study serves as an efficient and practical tool for assessing well and fracture design strategies. It supports improved reservoir utilization and long-term performance at Utah FORGE and comparable doublet geothermal system.

REFERENCES

Asai, P., Panja, P., Velasco, R., McLennan, J., and Moore, J.: Fluid Flow Distribution in Fractures for a Doublet System in Enhanced Geothermal Systems (EGS), Geothermics, 75, (2018), 171–179.

Asai, P., Podgorney, R., McLennan, J., Deo, M., and Moore, J.: Analytical Model for Fluid Flow Distribution in an Enhanced Geothermal System (EGS), Renewable Energy, 193, (2022), 821–831.

England, K., Swearingen, L., and McLennan, J.: Extended Circulation Test Report: Utah FORGE 16A(78)-32 and 16B(78)-32, Utah FORGE Technical Report, (2024).

Jia, Y., Tsang, C.-F., Hammar, A., and Niemi, A.: Hydraulic Stimulation Strategies in Enhanced Geothermal Systems (EGS): A Review, Geomechanics for Energy and the Environment / Geomechanics, Geophysics, Geo-energy, and Geo-resources, 8(6), (2022), 211.

Kumar, D., and Ghassemi, A.: Multistage Hydraulic Fracturing of EGS Wells with Application to FORGE, Proceedings, 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, (2018).

Samin, M.Y., Faramarzi, A., Jefferson, I., and Harireche, O.: A Hybrid Optimisation Approach to Improve Long-Term Performance of Enhanced Geothermal System (EGS) Reservoirs, Renewable Energy, 134, (2019), 379–389.

Zhang, Q., and Dahi Taleghani, A.: Autonomous Fracture Flow Tuning to Enhance Efficiency of Fractured Geothermal Systems, Energy, 281, (2023), 128163.

Zimmermann, G., Moeck, I., and Blöcher, G.: Cyclic Waterfrac Stimulation to Develop an Enhanced Geothermal System (EGS)—Conceptual Design and Experimental Results, Geothermics, 39(1), (2010), 59–69.