PROCEEDINGS, 49th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2024
SGP-TR-227

Downhole Flow Management to Enhance Efficiency of Fractured Geothermal Systems in Horizontal Wells

Qitao Zhang and Arash Dahi Taleghani

The Pennsylvania State University, University Park, PA 16801

Email: arash.dahi@psu.edu

Keywords: EGS; thermal short-circuiting; flow management; early thermal breakthrough.

ABSTRACT

Real-world geothermal systems often suffer from low system efficiency due to thermal short-circuiting, in which case fluid only circulates through just few dominant fractures. This issue is amplified in horizontal wells with numerous natural or induced fractures. Our study proposes a novel temperature-sensitive flow management system to address this challenge and unlock the full potential of horizontal wells in Enhanced Geothermal Systems (EGS). This downhole system features real-time temperature sensors and flow control devices, dynamically adjusting injection across the wellbore to prevent thermal shortcuts. We evaluate the performance of such systems over 50 years of operation by numerical analysis. Numerical simulations over 50 years demonstrate its effectiveness: with the proposed flow control system, the produced fluid temperature remains 40 K higher compared to the EGS with the uncontrolled flow, leading to an extra 1.18×10^{16} J of heat extraction at the 50th year. This innovative flow management approach paves the way for transforming horizontal wells into efficient EGS systems for future power generation and heat extraction.

1. INTRODUCTION

Thermal short-circuiting, where fluid flow and heat extraction concentrate in specific channels (Zhang and Dahi Taleghani., 2023), poses a major threat to geothermal systems. This localized flow neglects untapped areas, rapidly depleting preferred paths and leading to early thermal breakthroughs, where cold water returns directly to the surface (Fu et al., 2016). This significantly reduces heat extraction, jeopardizing both electricity generation and project economics (Al Balushi et al., 2023). Hydraulic stimulation, while enhancing fluid movement, can create "shortcuts" in fractures, further exacerbating the issue (McLean and Espinoza, 2023). For horizontal wells in EGS, preventing thermal short-circuiting at each stage and maintaining high fluid temperature are crucial for sustainable and efficient energy extraction(Zhang and Dahi Taleghani., 2024).

The goal of this research is to avoid thermal short-circuiting between horizontal wells to postpone or prevent thermal breakthroughs in EGSs. However, making the thermal flow between two wells uniform would not be a trivial job, because (1) the geometry of the induced fractures cannot be easily engineered or controlled in the subsurface, and (2) the inherent heterogeneity of the geological systems makes it almost impossible to adjust fluid flow in the subsurface in such a way to achieve uniform heat harvesting from the reservoir rock. Rather than changing anything inside the reservoir, we are pursuing adjusting the heat harvesting process by controlling flow injection based on the real-time temperature of fluid along the production well. In the oil and gas industry, inflow and injection control devices (ICDs) are developed technology used to uniform the flow across the length of the laterals (Banerjee et al., 2013). ICDs are quite flexible in terms of application in the field and can be even installed in open-hole completions. In high-permeability and high-pressure zones, the higher fluid velocity causes the ICD to exert higher backpressure than in less productive zones (Birchenko et al., 2010). Consequently, this would minimize the risk of bypassing reserves and increase fluid recovery. Such systems can also be used for controlling geothermal systems and could work independently from the stimulated fracture network or the geology of the formation. Since the proposed technology will be placed inside the borehole, it has the advantage of being independent of the geology or the completion methods pursued in these wells. On the other hand, distributed temperature sensors (DTS) are also a developed technology using fiber optics to reliably provide temperature along the wellbore at different depths (Williams et al., 2000). It is notable that the authors are not promoting special products here, but are trying to anticipate potential improvements that can be achieved by adopting such systems into the geothermal world.

In this research, we aim to assess the feasibility of the proposed subsurface flow management system to increase heat extraction from an EGS and explore a reasonable and feasible strategy for fluid flow control throughout the system. This study is organized as follows: First, the concept of the subsurface flow management system is introduced in section 2, and we elaborate on how it removes thermal short-circuits during the operation. Then, in section 2, we establish a numerical model for the simulation of EGS operation with horizontal wells that can integrate the flow management system into it. After that, in section 3, we incorporate the flow management system into the EGS in the simulation model to numerically explore its advantages in an EGS operation. Finally, in section 3.3, the authors investigate the effect of heterogeneity in fracture hydraulic conductivity on the performance of the proposed flow control system. This research tackles the longstanding challenge of thermal short-circuiting in geothermal systems with a novel approach: a subsurface flow management system. By strategically directing fluid flow between wells, this system offers the potential for significant heat extraction improvements, unlocking a more efficient and sustainable future for geothermal energy.

2. REAL-TIME FLOW MANAGEMENT SYSTEM

To avoid the formation of thermal short-circuiting between horizontal wells and increase the heat extraction efficiency of the EGS, we propose a real-time flow management system to reasonably distribute the fluid flow in the geothermal system. The presented flow management system for EGSs consists of two parts.

The first part is the temperature sensors installed in the production well to provide real-time downhole temperature. Such downhole monitoring sensors, e.g., the fiber optics distributed temperature sensor (DTS), have been widely used in the oil & gas industry for the past 20 years (Ashry et al., 2022). Given the experience achieved in oil & gas wells, DTS also has great potential to be directly applied to the downhole temperature monitoring of a geothermal well. In recent years, DTSs have been gradually applied to several geothermal projects around the world (Kasahara et al., 2023). In the Brady geothermal field in Nevada (Patterson et al., 2017), operators recorded the real-time borehole temperature data to monitor the change of the steam-water interface, identify the warm/cool area, and visualize the temperature recovery after the shut-in of the fluid injection as shown in Fig. 2. However, in the previous geothermal projects, DTS was applied only in vertical wells for monitoring purposes with no further implications. The application of DTS in the horizontal well has not been tested yet in geothermal practice because the implementation of horizontal drilling in EGS projects has not yet been tried much in the field as well till recent practices in Utah FORGE. Regarding the EGS with multi-staged fractured horizontal wells, DTS also has a great potential for the detection of thermal short-circuiting between wells. Since the DTS nowadays can send real-time (update interval < 60 s) and high-resolution (< 1 m) temperature data during production, operators may notice locations of developing short-circuiting along the wellbore in the production well.

The second part of the flow management system is the flow control device to be installed in the injection well. Installing DTS in the injection well can pinpoint fractures or stages producing cold water. Knowing this information, operators may take action to control the fluid flow through these fracture pathways to adjust the injection rates in the counterparts of the injection wells. Therefore, installing flow control devices in the injection well may effectively limit the production of cold water in the production well. Such flow control devices, i.e., inflow and injection control devices (ICDs) have been used in the oil and gas industry, to address problems like coning, premature water/gas breakthrough, or heel-toe effect (Li et al., 2011; Medina, 2015; Javaheri et al., 2021). With extensive practices in oil and gas production, such flow control devices can be directly used in geothermal wells with few adjustments.

Geothermal systems can be plagued by "thermal short-circuiting," where water exploits a single, highly conductive fracture, bypassing untapped heat and leading to early "thermal breakthroughs", i.e., **Figure 1 (a)**. Fortunately, our proposed flow management system offers a solution. Distributed temperature sensors (DTS) act as our eyes downhole, identifying the culprit fracture with its abnormally low temperature i.e., **Figure 1 (b)**. Downhole inflow control devices (ICDs) then spring into action, strategically shutting down flow through this "shortcut" i.e., **Figure 1 (c)**. This results in a more uniform thermal gradient across the reservoir, allowing for proportional heat extraction from each zone i.e., **Figure 1 (d)**. By eliminating the thermal shortcut and ensuring even flow distribution, our system significantly improves heat extraction efficiency, unlocking the full potential of the geothermal system.

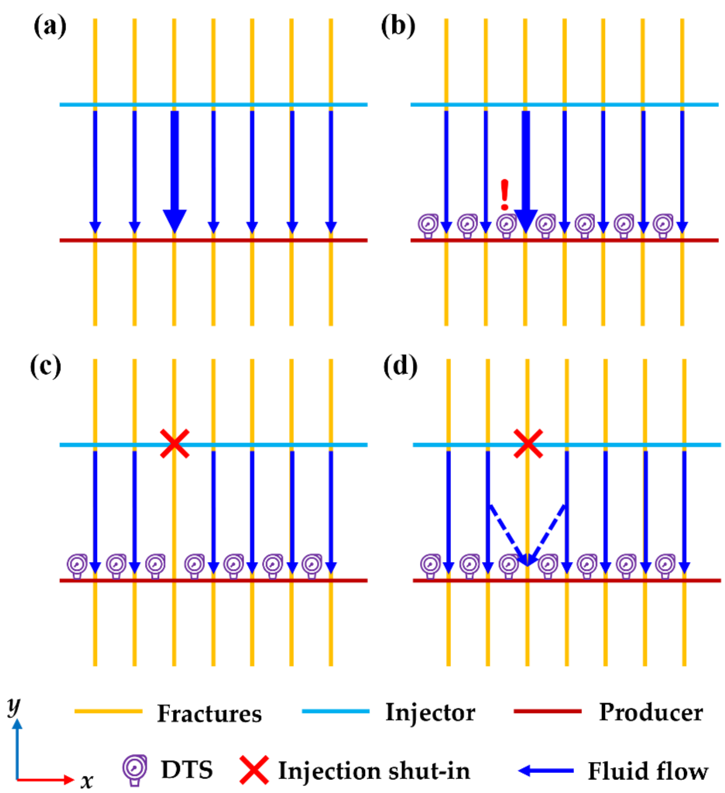

Figure 1: An illustration of how the flow management system may improve the heat extraction in an EGS formed by two horizontal wells: (a) the appearance of thermal short-circuiting between the wells; (b) real-time detection of thermal short-circuiting using DTS; (c) injection flow control using flow management system (ICD); (d) achieving uniform thermal gradient between wells.

3. MODEL DESCRIPTION

The model geometry in the 2-D horizontal view is presented in **Figure 2 (a)**. Two horizontal wells are drilled in this reservoir for injection and production purposes and the well spacing is 300 m. Seven fractures are created for each well and the fracture half-length is 300 m, which means the fractures from the injection and production wells can be connected directly. The fracture spacing is 100 m and the fracture height is 100 m, which fully penetrates the formation. In this work, we applied the unstructured tetrahedron elements for mesh generation given their high flexibility in dealing with complicated geometries like wells and cracks. **Figure 2 (b)** shows the grid element after the mesh generation. The highlighted reservoir area in the figure represents the geothermal formation which is shown in **Figure 2 (a)**. an underburden and an overburden layer are added to the model to consider the possible impact from other layers.

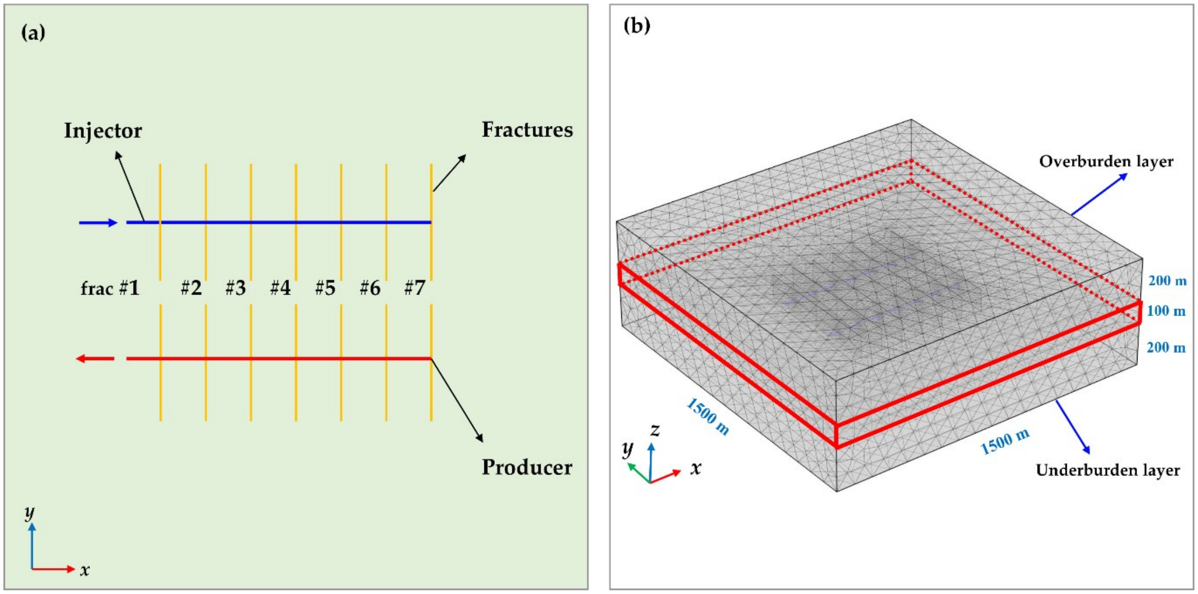

Figure 2: The diagram of (a) the geometry model of an EGS consisting of horizontal wells in the 2-D plane view and (b) the mesh generation of the simulation model in the 3-D view.

The parameters needed for the EGS simulation can be found in **Table 1**.

Table 1: Parameters for the simulation of EGS with horizontal wells.

Parameters	Value	Unit
Overall reservoir size	1500×1500×450	m^3
Thickness of geothermal formation	100	m
Thickness of overburden and underburden layers	200	m
Rock permeability	1	10^{-3} μm^2
Permeability of other layers	0.05	10^{-3} μm^2
Rock density	2700	kg/m^3
Rock thermal conductivity	2.8	W/(m·K)
Rock specific heat capacity	1000	J/(kg·K)
Injection rate	50	kg/s
Production rate	50	kg/s

Initial pore pressure of geothermal formation	3.0×10^{7}	Pa
Initial temperature of geothermal formation	473.15	K
Injection temperature	313.15	K
Simulation time	50	Year

To show the capability of the proposed flow control system, we presented two different simulation cases:

Case #1: we assume that the flow management system is not installed.

Case #2: the autonomous flow management system is applied during the development of the EGS.

In Case #2, the Inflow Control Devices (ICDs) remain inactive for the initial 20 years of operation, allowing unimpeded fluid flow into the wellbore. This strategy is based on the inherent heat retention of Enhanced Geothermal Systems (EGS) in their early stages. The naturally high temperatures of extracted fluids during this period negate the need for additional management measures. Upon reaching the 21st year, however, the flow control system is engaged, introducing a more selective approach to fluid management. If a particular stage yields fluid with a temperature lower than that of its neighboring stages, injection from that stage is promptly halted. This optimization strategy aligns with real-world practices, where operators exercise fluid flow control with greater flexibility based on continuous temperature monitoring of produced fluids.

To develop a thermal short-circuiting in 20 years of EGS operation, we assume that the fracture conductivity in each fracture stage are as shown in **Figure 3.**

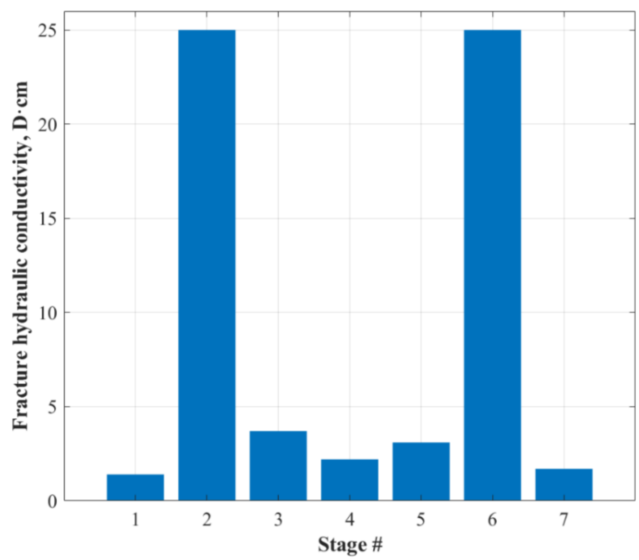

Figure 3: Fracture hydraulic conductivity in different fracture stages.

4. RESULTS AND DISCUSSION

Figure 4 (a) illustrates the temperature distribution within the fracture system after 50 years in Case #1, where no flow management was implemented. The figure reveals the detrimental impact of thermal short-circuiting, evident in stages #2 and #6, on the overall heat extraction efficiency. Conversely, **Figure 4 (b)** depicts the temperature profile in Case #2 after 50 years with the flow management system in place. The figure convincingly demonstrates the system's effectiveness in preventing thermal shortcuts, leading to a more uniform and balanced heat extraction across all stages.

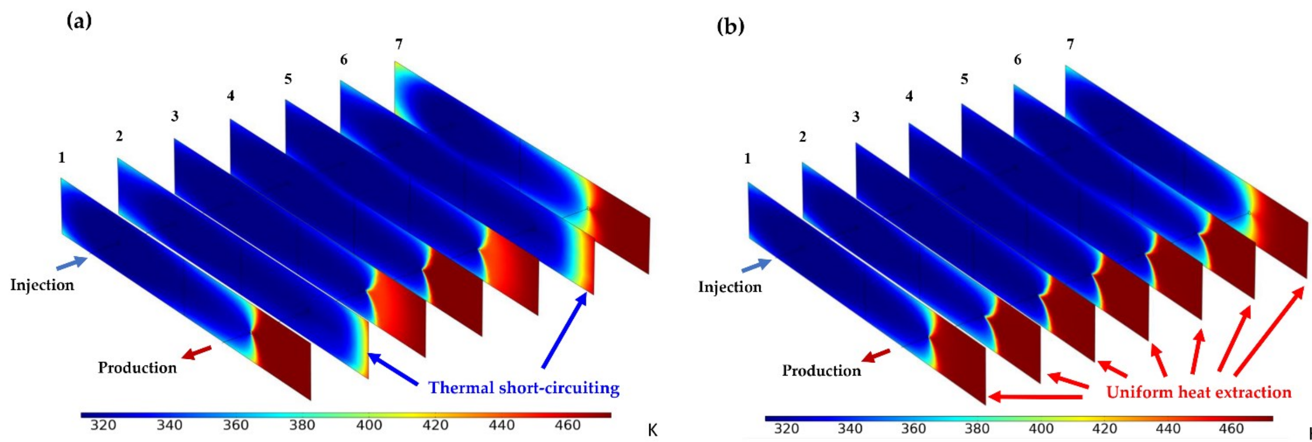

Figure 4: Temperature distribution in the fracture system according to Cases #1 and #2 after 50 years of operation. The cold fluid accumulation near the production wellbore in stages #2 and #6 in (a) indicates that when the fluid management systems is not installed, thermal shortcuts will be developed after long-term operation.

While the previous analyses offered valuable qualitative insights, a quantitative comparison is necessary to fully grasp the impact of the flow management system. **Figure 5** depicts the overall temperature of the produced fluid in both Case #1 (without ICDs) and Case #2 (with ICDs) over a 50-year period. Initially, both cases exhibit identical temperatures due to inactive control devices in Case #2 for the first 20 years. However, the lack of flow control in Case #1 leads to an alarming decline in fluid temperature throughout the operation, dropping from 473.15 K to a mere 352.76 K by year 50, almost reaching the injection temperature. Conversely, Case #2 demonstrates the effectiveness of the flow management system. After activating the control devices at year 21, a slight temperature increase occurs due to the cessation of excessive cold-water injection through specific stages. Crucially, after 50 years, the production temperature in Case #2 stabilizes at 392.19 K, a significant 40 K higher than Case #1. This concrete evidence reinforces the flow management system's ability to maintain optimal fluid temperature and enhance long-term geothermal energy extraction.

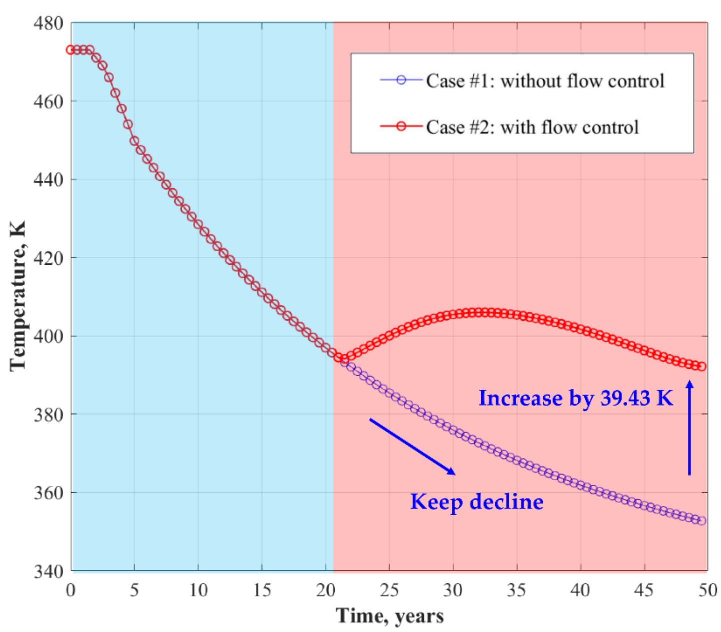

Figure 5: Temperature of the produced fluid in Case #1 and Case #2.

Figure 6 showcases a compelling comparison of cumulative heat extraction over 50 years between Case #1 and Case #2. The data reveal a remarkable 21.61% (or 1.18×10^{16} J) increase in heat extraction achievable with the flow control system. This translates to a total extracted heat of 6.64×10^{16} J in Case #2 compared to 5.46×10^{16} J in Case #1. This significant improvement demonstrates the flow control system's crucial role in optimizing geothermal energy extraction.

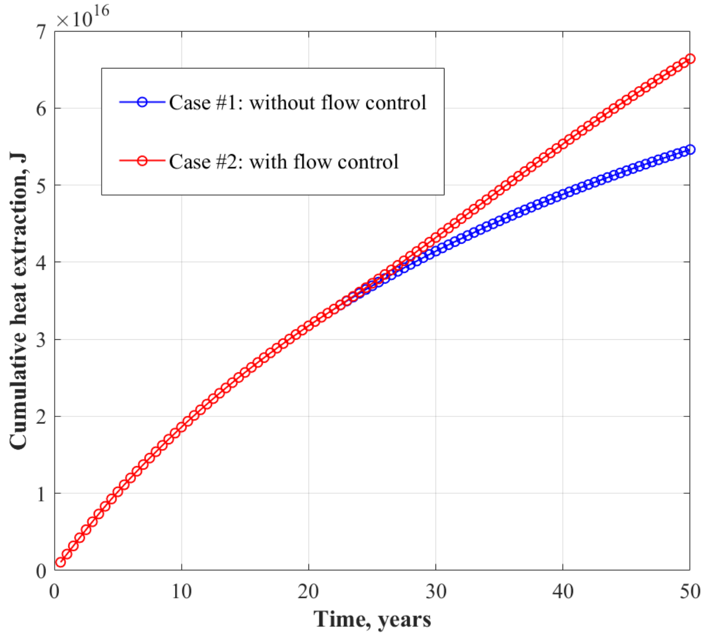

Figure 6: Cumulative heat extraction after 50 years of EGS operation in Case #1 and Case #2.

5. CONCLUSIONS

In this paper, we introduced a new concept: the downhole flow management system with horizontal geothermal wells to boost heat extraction. These temperature-sensitive devices, installed downhole, adjust injection rates in different sections based on the hotness of the produced fluid. This targeted approach combats thermal short-circuiting, where heat gets stolen by specific pathways, leaving vast areas untapped. We assessed the effectiveness of such systems to remove or at least mitigate the negative impacts of thermal short-circuiting. By the real-time function of these flow control devices, thermal shortcuts can be managed along the wellbore autonomously and then concurrently limit the injection of cold water into the corresponding zones. Our numerical analyses show that the proposed flow management system can significantly improve heat extraction from the reservoir. When the EGS circulates fluids at constant pressure, the produced fluid temperature could be about 40 K higher than that without any ICDs. Meanwhile, the cumulative heat extraction will also benefit from the proposed system and may achieve an improvement of 1.18×10^{16} J after 50 years of development. which means the heat extraction at the later life of the well can be almost doubled by using the flow management system. The proposed system can further benefit the EGS when the problem of heterogeneity in fracture conductivity is more serious. This paper provides insights into the efficient management of the fluid circulation within horizontal well EGS systems to substantially increase heat extraction.

ACKNOWLEDGMENT

The authors are grateful for financial support from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Geothermal Technologies Office, Award Number DE-EE0009787.

REFERENCES

Al Balushi, F., Zhang, Q., Dahi Taleghani, A.: Autonomous Fracture Conductivity Using Expandable Proppants in Enhanced Geothermal Systems. SPE Journal, 2023, 1-15.

Ashry, I., Mao, Y., Wang, B., Hveding, F., Bukhamsin, A.Y., Ng, T.K., Ooi, B.S.: A review of distributed fiber–optic sensing in the oil and gas industry. Journal of Lightwave Technology, 40(5), (2022), 1407-1431.

Banerjee, S., Abdelfattah, T., Nguyen, H.: Benefits of passive inflow control devices in a SAGD completion. Proceedings, SPE Canada Heavy Oil Conference, Calgary, Alberta, Canada (2013)

Birchenko, V.M., Muradov, K.M., Davies. D.R.: Reduction of the horizontal well's heel–toe effect with inflow control devices. Journal of Petroleum Science and Engineering, 75(1-2), (2010), 244-250.

Fu, P., Hao, Y., Walsh, S.D., Carrigan, C.R.: Thermal drawdown-induced flow channeling in fractured geothermal reservoirs. Rock Mechanics and Rock Engineering, 49 (3), (2016), 1001–1024

Javaheri, M., Tran, M., Buell, R.S., Gorham, T., Munoz, J.D., Sims, J., Rivas, S.: Flow profiling using fiber optics in a horizontal steam injector with liner-deployed flow control devices. SPE Journal, 26(05), (2021), 3136-3150.

Kasahara, J., Hasada, Y., Mikada, H., Kuzume, H., Ohnuma, H., Fujise, Y.: Seismic Study at the Mori Geothermal Power Plant, Japan using DAS and DTS in a geothermal well. Proceedings, 48th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2023)

Li, Z., Fernandes, P., Zhu, D.: Understanding the roles of inflow-control devices in optimizing horizontal-well performance. SPE Drilling & Completion. 26(03), (2011), 376-385.

McLean, M.L., Espinoza, D.N.: Thermal destressing: Implications for short-circuiting in enhanced geothermal systems. Renewable Energy, 202, (2023), 736-755.

Medina, M.: Design and field evaluation of tubing-deployed passive outflow-control devices in steam-assisted-gravity-drainage injection wells. SPE Production & Operations, 30(04), (2015), 283-292.

Patterson, J.R., Cardiff, M., Coleman, T., Wang, H., Feigl, K.L. ., Akerley, J., Spielman, P.: Geothermal reservoir characterization using distributed temperature sensing at Brady Geothermal Field, Nevada. The Leading Edge, 36(12), (2017), 1024a1-1024a7.

Verma, A., and Pruess, K.: Enhancement of Steam Phase Relative Permeability Due to Phase Transformation Effects in Porous Media, Proceedings, 11th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (1986).

Wang, C.T., and Horne, R.N.: Boiling Flow in a Horizontal Fracture, Geothermics, 29, (1999), 759-772.

Williams, G.R., Brown, G., Hawthorne, W., Hartog, A.H., Waite, P.C.: Distributed temperature sensing (DTS) to characterize the performance of producing oil wells. Proceedings, Environmental and Industrial Sensing, Boston, MA (2000)

Zhang, Q., and Dahi Taleghani, A.: Autonomous fracture flow tunning to enhance the efficiency of fractured geothermal systems. Energy, 281, (2023), 128163.

Zhang, Q., and Dahi Taleghani, A.: Intelligent fluid flow management for enhanced geothermal system in fractured horizontal wells. Applied Thermal Engineering, 239, (2024), 122191.