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An Introduction to Flow Control Devices and the Potential Benefits to Geothermal Applications

Brandon Curkan, Jami DePencier, and Wayne Klaczek

C-FER Technologies (1999) Inc.

Keywords

Flow Control Devices, FCDs, Outflow Control Devices, OCDs, Inflow Control Devices, ICDs, Thermal Enhanced Oil Recovery, Steam Assisted Gravity Drainage, SAGD, Enhanced Geothermal Systems, EGS, Full-Scale Flow Loop, Production Optimization, Reservoir Conformance, Short-Circuiting, Flow Channeling

ABSTRACT

Geothermal operators face several significant challenges in creating and maintaining optimal production from their wells. One of these challenges is the uniform distribution of both injected and produced fluid to and from the reservoir. Preferential production of fluid from one zone of a reservoir can result in thermal drawdown, reducing the temperature of the produced fluid. Additionally, the formation of direct pathways between injection and production wells, commonly referred to as "short-circuits", can heavily impact downhole heat transfer efficiency, particularly in Enhanced Geothermal System (EGS) operations. Thermal heavy oil producers, particularly those who use Steam Assisted Gravity Drainage (SAGD), face a very similar challenge (though reversed in terms of heat transfer). In SAGD operations, the injected steam needs to be uniformly distributed in the target oil reservoir, or the operators risk abating the area effectively heated by the steam. Additionally, there is a risk that some of the injected steam may flow directly to the production well, resulting in an inefficient reservoir heating process and similar short-circuiting.

To help address this problem, SAGD operators have begun to employ Flow Control Devices (FCDs) to provide an effective means of well control. Though the concept of FCDs is not new, having been utilized in conventional Oil and Gas for many years, the widespread adoption of this technology in SAGD wells is relatively recent. The first commercial deployment of FCDs in a SAGD well was completed in 2009 by ConocoPhillips Corporation at their Surmont SAGD Project; however, in the last 10 years FCDs have since become more widely adopted.

Several SAGD operators have reported significant process improvements since the introduction of FCDs, including: better reservoir conformance, more efficient production of oil (i.e. less water and energy use, and lower GHG emissions) and increased total production. Given the similarities between the challenges faced by SAGD and Geothermal operators, FCDs may be a viable technology to help mitigate imbalanced reservoir flow in Geothermal operations. In order to evaluate the potential of FCD technology for Geothermal applications, there are key differences between the operations of a SAGD well and a Geothermal well that need to be assessed.

This paper will summarize the current state of commercially available FCDs and their operation, how FCDs are typically used in the Oil and Gas industry, and the potential benefits and limitations if operators used FCDs in the Geothermal industry.

1. Introduction

The need for economic and environmentally sustainable production in the Oil and Gas industry has advanced the development and optimization of horizontal and multilateral wells. These well configurations have become a standard design consideration when developing reservoirs; predominantly in unconventional resources. However, increased wellbore lengths have led to various production-related problems (Dikken 1990; Ihara et al. 1995), some of which have prompted the development and installation of Flow Control Devices (FCDs). Since the early 1990s, FCDs have been commonplace in many conventional applications; providing an effective means of well control (Al-Khelaiwi and Davies 2007; Mikkelsen et al. 2005). In recent years, FCDs have also demonstrated significant potential for implementation in Enhanced Oil Recovery (EOR) methods; predominantly in Steam Assisted Gravity Drainage (SAGD), where steam breakthrough may present similar issues as water/gas breakthrough in non-thermal applications (Noroozi et al. 2014; Stalder 2012; Vachon et al. 2015). By adopting advanced methods and novel technologies found in the Oil and Gas industry, Geothermal operations would likely improve (Denninger et al. 2015); leading to more efficient and cost-effective processes.

2. Overview of Flow Control Devices

The utilization of FCDs in SAGD operations are essentially aimed at promoting an even liquid level around the production well and improving the uniformity of steam chamber in the reservoir (known as “reservoir conformance”). ICDs are useful in this regard, where the pressure drop they impart on the produced fluid can effectively produce a "steam blocking effect". The theory indicates that the throttling process within a production well of a SAGD environment is likely adiabatic; therefore, if the fluid begins at zero quality, the differential pressure across the ICD may result in a phase change (Vachon et al. 2015).

In this manner, a relatively small liquid flowrate may result in a large flowrate of steam by volume; which in turn, may further increase the level of differential pressure across the ICD and effectively "block" additional steam (Vachon et al. 2015; Lastiwka et al. 2017). This effect is due to the pressure drop of a steam phase being much higher than that of a liquid phase through a restriction for a given mass flowrate.

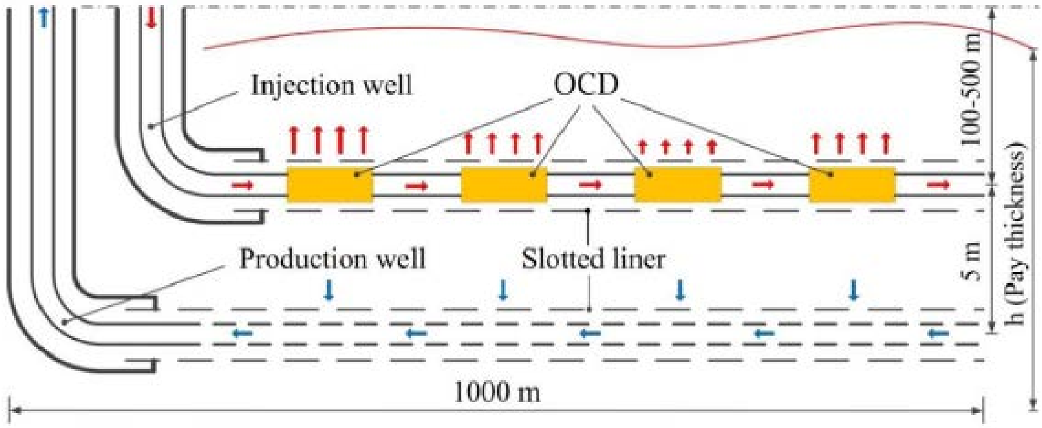


Figure 1: SAGD Well Completion with OCDs Deployed (Li et al. 2017)

2.1 Types of Flow Control Devices

FCDs are often referred to as either Inflow Control Devices (ICDs) or Outflow Control Devices (OCDs) depending on the flow direction (from the perspective of the wellhead at surface). For example, in a SAGD process (a "typical" SAGD well is shown in Figure 1 as reference) OCDs would be used on the steam injection well to control the outflow of steam from the wellhead out into the reservoir, while ICDs would be placed on the production well to control the inflow of steam, oil, and other fluids from the reservoir in towards the wellhead.

In many sources, including literature and commercially available documents, both ICDs and OCDs are termed FCDs, and these acronyms are sometimes used interchangeably. However, the flow conditions, key objectives and internal design architecture for an ICD are significantly different than that of an OCD; as such, this paper will refer to ICDs and OCDs separately where applicable.

2.1.1. Inflow Control Devices

In production wells, the type of FCDs used are referred to as ICDs. In SAGD wells, ICDs are designed to restrict steam flashing and subsequent high-rate fluid entry into the production liner. In a production well where steam is encountered, the localized pressure increases in the reservoir and consequently forces the inflow to lower pressure entry points. This occurs laterally through the reservoir and into the well through adjacent ICDs; effectively promoting lateral inflow conformance which, in turn, improves steam efficiency and recovery (Burke et al. 2018).

The geometry of an ICD may include a combination of various elements (i.e. as further discussed in Section 2.2), including restriction-style elements, channel-style elements or a combination of both. ICD geometries are typically complex because they are expected to operate effectively under multiphase flow conditions that include steam, various produced fluids, and solids from the reservoir. Understanding the performance and reliability of various ICD geometries under thermal production conditions is of significant interest to SAGD operators (Vachon et al. 2015), while also understanding the influence of the sand control system is important within unconventional production (Burke et al. 2018).

2.1.2. Outflow Control Devices

OCDs are predominately used in SAGD injection wells to create a uniform distribution of steam along the wellbore. By adding steam injection segments between the heel and toe of an injection well, OCDs contribute to creating an even distribution of steam, enabling improved conformance of the steam injection profile. This ultimately results in better steam chamber growth and more efficient production with a reduced Steam Oil Ratio (SOR) (Medina 2015).

Steam injection control is an important method for unconventional well performance. In unconventional wells, OCDs are often deployed in conjunction with slotted liners or screens into an injection well to control the steam injected into the system and optimize steam distribution (Cavender et al. 2011).

Theoretically, when coupled together, ICDs and OCDs have the potential to generate an effective injection and drawdown of the entire lateral section of the wellbore; accelerating production and improving cumulative SOR. (Burke et al. 2018)

2.2 Geometries of Flow Control Devices

Many types of FCD geometries have been commercialized; however, they are all based on the same underlying operating principle: restrict flow by inducing a pressure drop. The mechanism by which this pressure drop is created varies greatly between geometries, resulting in unique long-term injection and production behaviors as reservoir and operational conditions change (Denney 2015). Knowing the optimal geometry (including the level of restriction and sizing), and the optimal spacing or placement of the FCD are key considerations when attempting to optimize the use of this technology.

There are typically three primary mechanisms by which FCDs may be sorted (Banerjee 2016; Garcia et al. 2009):

- Channel-style FCDs, which direct flow through helical channels or long tortuous pathways;

- Restriction-style FCDs, which are typically an orifice or nozzle-based design and use changes in flow area to create instantaneous pressure drops in the device; and

- Autonomous FCDs, which are hybrid designs that use a combination of restriction and frictional pressure drop mechanisms.

These mechanisms are further summarized in Table 1.

Table 1: Summary of Commercially Available FCD Designs (Banerjee 2016)

Geometry	Mechanism of Action	Strengths for SAGD Applications	Weaknesses for SAGD Applications
Channel-style FCD	Frictional Drag	• Low risk of plugging or erosion • May control steam flashing • No moving parts	• Sensitive to flowing fluid viscosity
Restriction-style FCD	Bernoulli Principle	• Inexpensive • No moving parts	• Significant risk of plugging or erosion • May cause steam flashing
Autonomous FCD	Varied	• Additional steam trap control	• Varied

Autonomous FCDs are not a homogenous group; as such, Table 2 expands upon sub-types of these mechanisms.

Table 2: Comparison of Commercially Available Autonomous FCDs (Banerjee 2016)

Autonomous FCD Type	Mechanism(s) of Action	Strengths for SAGD Applications	Weaknesses for SAGD Applications
Hybrid	Frictional Drag, Bernoulli Principle, Momentum Effects	• Low risk of plugging or erosion • May control steam flashing • Insensitive to fluid viscosity • No moving parts	• Smallest autonomous response
Fluidic Diode	Momentum Effects	• No moving parts	• Risk of plugging or erosion • May cause steam flashing
Rate Control Valve	Variable-Size Restriction	• Additional steam trap control • Strongest autonomous response	• Risk of plugging or erosion • Moving parts • Limited throughput • May cause steam flashing

The following subsections further discuss each primary mechanism.

2.2.1. Channel-style Flow Control Devices

Channel-style FCDs are considered one of the earliest geometries of FCDs used downhole in the Oil and Gas industry and were the first FCD to be used in unconventional production. Channel-style FCDs use surface friction to generate a pressure drop through one (or more) flow channels that are wrapped around the base pipe of a screen. Alternatively, labyrinth-style mechanisms use a tortuous pathway to create a pressure drop, making the fluid change directions multiple times while traversing through the device (Banerjee and Hascakir 2017; Garcia et al. 2009). These mechanisms are particularly useful when distributing pressure drop over a relatively long-range wellbore, compared to instantaneous loss using an orifice-based design, and are typically recognized as more erosion resistant than restriction-style devices.

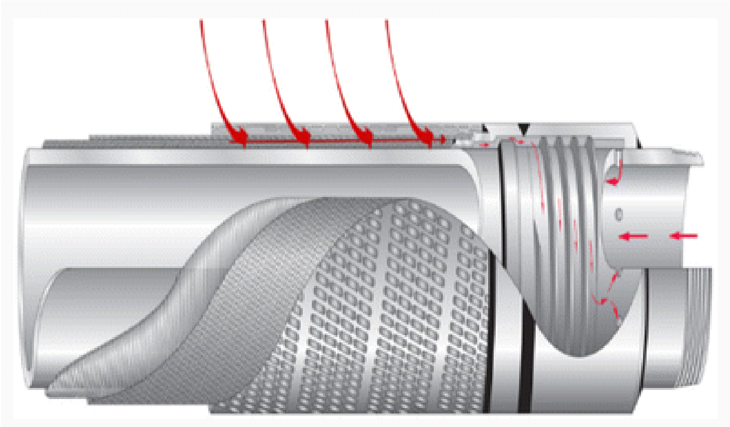


Figure 2: Channel-style FCD. Adapted from Bitto (2005) (Banerjee 2016)

2.2.2. Restriction-style Flow Control Devices

Generally, restricted-style FCDs use an instantaneous fluid constriction to produce a differential pressure across a device. This method forces the fluid from a larger area down through a small-diameter port or ports, creating flow resistance (Banerjee and Hascakir 2017; Garcia et al. 2009). In the Oil and Gas industry, restricted-style FCDs are heavily used as wellhead chokes to control production from conventional wells. In unconventional reservoirs, restricted-style FCDs have been deployed in injection wells as "steam splitters" to mechanically divert steam down the wellbore, add additional steam points of steam injection, and control the rate of injection into targeted zonal areas of the reservoir to equalize steam delivery along the lateral length (Ghesmat and Zhao 2015; Medina 2015).

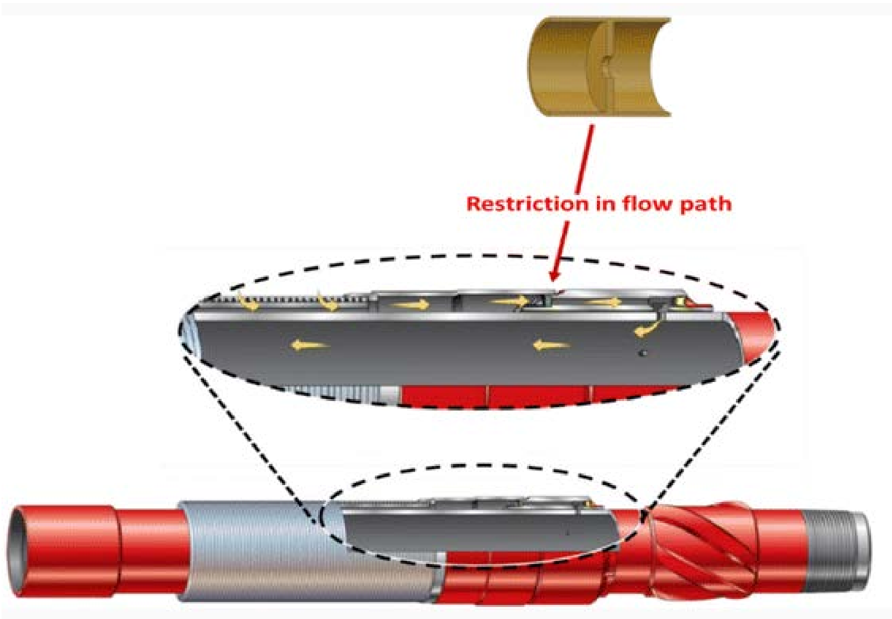


Figure 3: Restriction-style FCD. Adapted from Oyeka et al. (2014) (Banerjee 2016)

2.2.3. Autonomous Hybrid Flow Control Devices

Autonomous hybrid FCDs consist of a series of flow passages in a maze arrangement. The primary pressure drop mechanism is restrictive; although, in a distributive configuration. Having one or more slots, a series of bulkheads are incorporated into a hybrid design FCD. Additionally, new adjustable hybrid FCDs also incorporate a simple adjustment feature which can alter the FCDs flow resistance immediately before running in a well, should real-time data collected during drilling indicate the need to adjust flow resistance (Banerjee and Hascakir 2017; Garcia et al. 2009).

Adjustable autonomous hybrid FCDs have multiple onboard discrete chambers, each with a different number of stages, which allow an operator to select the desired setting; with more stages for a higher resistance or fewer stages for lower resistance. Without the need to generate the pressure drop instantaneously, as with an orifice-based FCD, the flow through the slots is relatively large in an autonomous FCD, dramatically increasing erosion and plugging resistance (Banerjee and Hascakir 2017; Garcia et al. 2009).

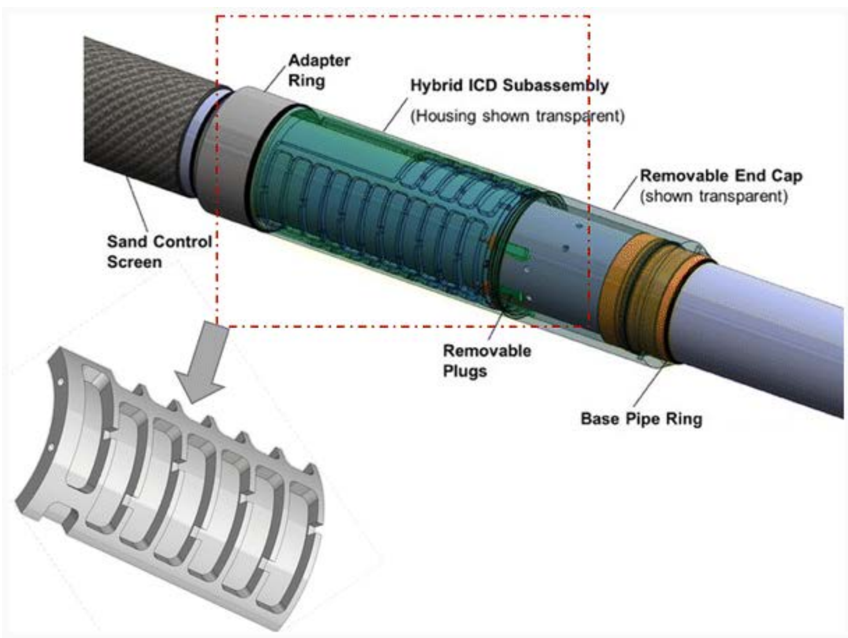


Figure 4: Autonomous Hybrid FCD. View of Hybrid Assembly with Transparent Housing Subassembly (Banerjee et al. 2013)

3. Flow Control Devices in the Oil and Gas Industry

ICDs have been utilized in conventional oil resources since the early 1990's to delay water or gas breakthrough in horizontal wells (Banerjee 2016). In conventional resources, oil may be located with a gas cap above and/or aquifer below the target reservoir. A high rate of production in a localized zone along the horizontal well may draw the gas cap or aquifer interface closer to the production well (this process is referred to as "drawdown"). If this drawdown is significant enough, gas and/or water may breakthrough, reducing the amount of oil produced. Typically, this happens at the heel of the well, as frictional pressure drop reduces draw from the toe of the well. However, reservoir characteristics and other factors may cause this localized breakthrough to occur anywhere along the horizontal well (Li et al. 2011).

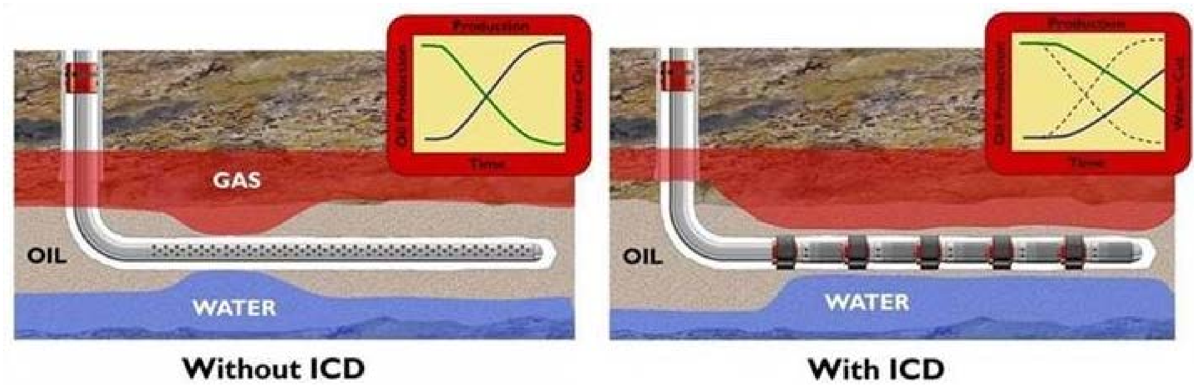


Figure 5. Localized Gas/Water Drawdown in Conventional Horizontal Wells (Halliburton 2019)

To prevent this localized breakthrough of water and/or gas, ICDs were developed and employed to provide a more balanced production rate along the length of the horizontal well, as illustrated in Figure 5. This way, production rate could be optimized without the risk of increased gas or water production.

Despite the widespread use of FCD technology in conventional applications, it has only been applied to thermal oil production scenarios (like SAGD) in recent years. The first field pilot of ICDs in a SAGD well was conducted by ConocoPhillips Corporation ("ConocoPhillips") at their Surmont asset in Alberta in 2009 (Stalder 2012). Given the similarities between operating thermal oil production wells and Geothermal wells the use of FCDs in SAGD is more relevant, and thus explored further in this paper.

3.1 Use of Flow Control Devices in Steam Assisted Gravity Drainage Operations

In SAGD, two wells are drilled in parallel and ran horizontally through the target reservoir, with the injection well typically positioned approximately five meters above the production well. The upper (injection) well delivers high temperature saturated steam into the reservoir. This steam forms a "steam chamber" within the reservoir, which heats the bitumen, reducing its viscosity and "mobilizing" it, as illustrated below in Figure 6.

This heated bitumen flows by gravity drainage to the lower (production) well, where an artificial lift system pumps it to the surface. A key step in the SAGD method is the formation of the steam chamber, as uniformly distributed steam is important for optimizing production and maximizing thermal efficiency of the system. FCDs have been utilized in SAGD operations to better control the steam distribution throughout the target reservoir, and thus improve reservoir conformance.

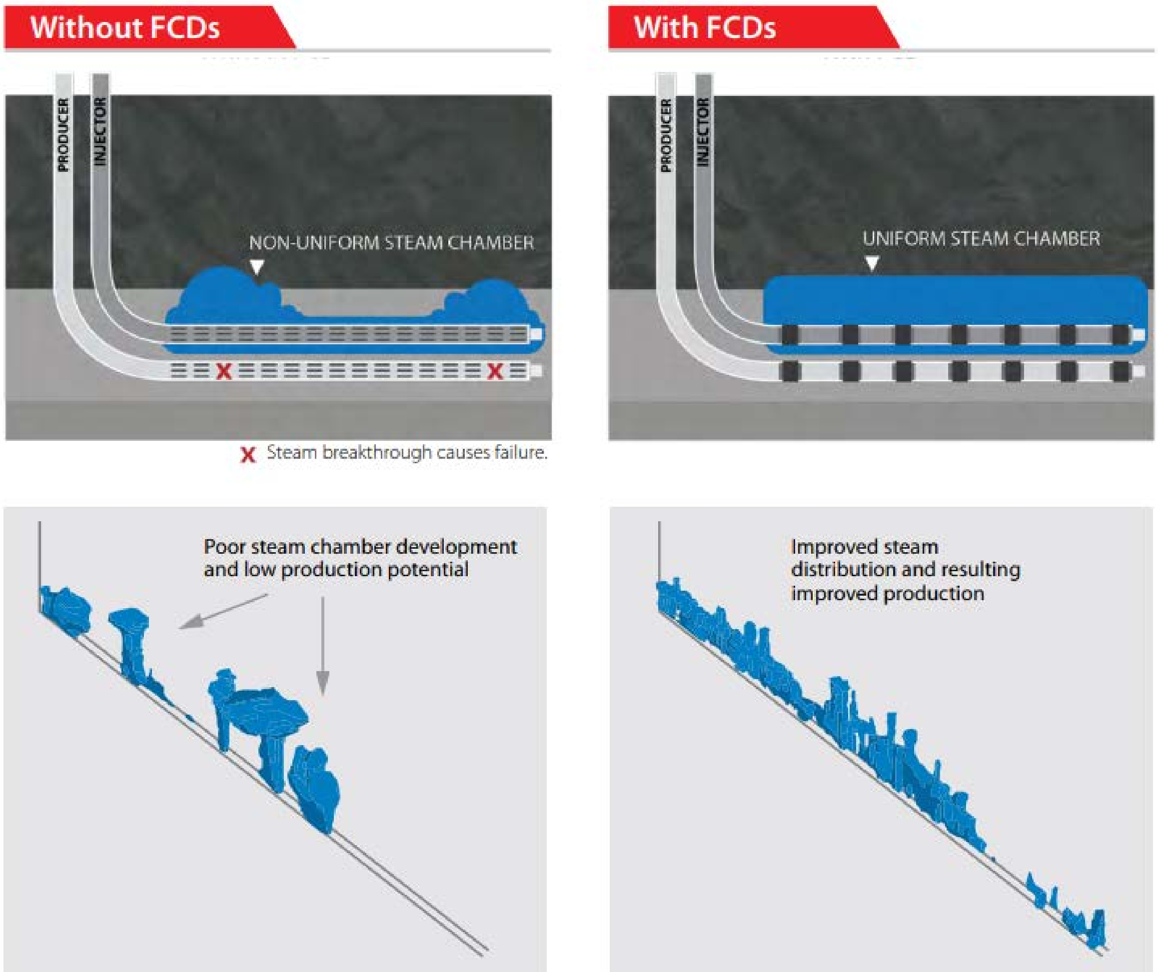


Figure 6: Steam Chamber Development Graphical Representation (ConocoPhillips 2016)

There are many factors that may cause uneven steam chamber formation and/or localized breakthrough, where some common causes of irregular production and injection include (but are not limited to) the following (Banerjee 2016):

- Horizontal and/or vertical permeability distribution;
- Variations in porosity;
- Water saturation heterogeneity/characteristics;
- Variations in the distance between the wellbore(s) and fluid contacts;
- Variations in localized reservoir pressure;
- Changes in capillary pressure and relative permeability along the wellbore,
- Localized skin damage or fractures;
- Changes in mineralogy or wettability;
- Changes in temperature;
- Changes in fluid density, viscosity, or both; and
- The presence or absence of in-situ emulsifiers that blend reservoir and/or introduce fluids into something novel.

Uneven formation of the steam chamber can result in significant thermal inefficiencies in the SAGD process (i.e. higher SORs and reduced production rates). Another crucial factor in SAGD operations is the control of the liquid level around the production well. This liquid level must remain above the production well; otherwise steam will directly flow into the production well from the injection well (known as localized breakthrough or “short-circuiting”). This reduces the economics of the operation, as steam is produced rather than transferring heat into the reservoir to mobilize the bitumen. When the steam chamber forms unevenly, the liquid level above the production well varies. As such, productions rates must remain low enough such that the lowest liquid level point remains above the production well.

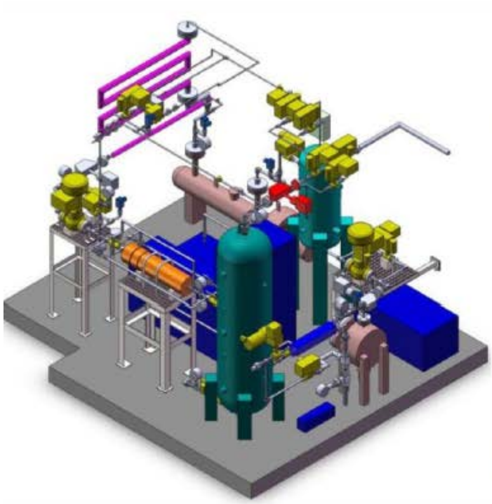
Similarly, production of the mobilized bitumen must also be evenly distributed throughout the length of the horizontal production well. Even with a well-formed steam chamber, production rates can vary throughout the horizontal well length. If production is greater in a localized area, the fluid drawdown may again cause an uneven liquid level and potentially localized breakthrough (Banerjee and Hascakir 2017). Meanwhile OCDs on injection wells also promote the uniform growth of the SAGD steam chamber by ensuring even injection of steam across the horizontal length of the injection well. This helps to create an even liquid level at the production well, which allows the SAGD operator to produce at higher rates without causing localized breakthrough.

3.3 Current Challenges when using Flow Control Devices in Steam Assisted Gravity Drainage Operations

Identifying the optimal ICD geometry for maximizing performance in a SAGD production well (i.e. one that effectively blocks the steam but still preferentially allow viscous fluids to enter the production string) can still be a significant challenge for operators, as there are relatively few commercial options for ICDs that were specifically designed for SAGD applications. Ideally, the ICD's thermal hydraulic performance would be well known to allow SAGD operators to select and size the most appropriate ICD technology for their wells. Unfortunately, modelling the complex multiphase flow conditions within a SAGD production well is challenging, and most ICD vendors have limited experimental capabilities constrained to multiphase fluid mixtures that are not representative of an in-situ SAGD environment.

Additionally, there are reservoir and well specific factors to consider, such as the number of FCDs per well and the optimal spacing. For example, some SAGD operators began by installing one FCD in every joint of casing, but improved reservoir and production models may provide an opportunity for optimization of this practice (Lastiwka et al. 2017). Another key consideration is evaluating the likelihood of erosion and wear, especially for ICDs in production wells that will likely be exposed to solid particle erosion (in addition to the potential cavitation erosion and liquid droplet erosion mechanisms that OCDs would likely see in a SAGD well). Many FCDs in SAGD operations are inserted on casing strings that are meant to remain downhole for the life of the SAGD well (i.e. which is typically 15 to 25 years).

To address these challenges, the Oil and Gas industry has invested significant effort into understanding and improving FCD technology. As an example, ConocoPhillips and C-FER Technologies (1999) Inc. ("C-FER") designed and built a unique high temperature multiphase flow loop in 2013 that could consistently and accurately test the performance of various ICDs under SAGD representative conditions. As a result of this work, a detailed protocol for characterizing the performance of various ICDs under SAGD representative conditions was developed (Vachon et al. 2015). An image of the High Temperature ICD Characterization Loop located at C-FER's facilities is shown in Figure 7, as reference.



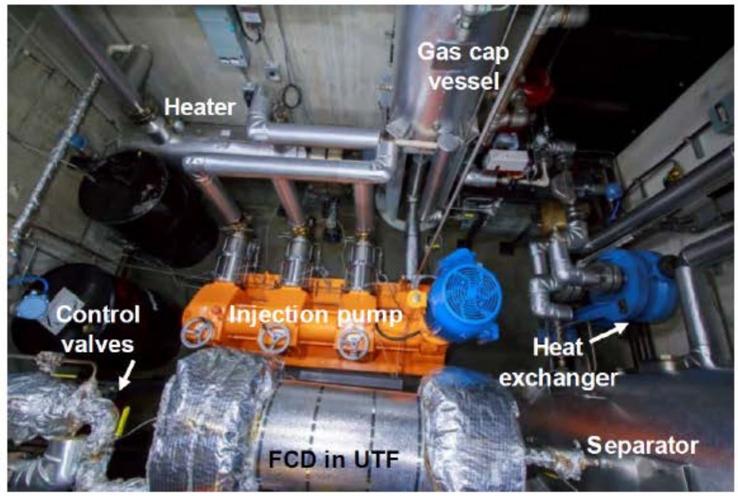


Figure 7: Images of C-FER's High Temperature ICD Characterization Loop

Following this initial work, C-FER also expanded on this offering by designing and building a specialized experimental ICD Erosion Apparatus, capable of replicating various erosive environments and key mechanisms encountered by an ICD in a SAGD well. High pressure gas is strategically injected with slurry before entering the ICD inlet to simulate the presence of steam and mimic the key parameters affecting the most important erosion mechanisms in thermal production; resulting in accelerated wear which replicates years of aggressive SAGD production well conditions within days of laboratory testing.

When used in conjunction with the High Temperature ICD Characterization Loop, the ICD Erosion Apparatus allows for the performance of an ICD to be determined as a function of the wear rate. The results from these two flow loops allows operators to input the expected performance profile of a casing-deployed ICD in a SAGD well (i.e. over 15 to 25 years) into their reservoir and production models; aiding in ICD selection and optimizing their field performance (C-FER 2019).

Research programs such as this can help to advance technology development and reduce field implementation risks to operators. This is a key step in widespread adaptation of novel ideas and could be used as a road map for new technology development in the Geothermal industry.

4. Applications to the Geothermal Industry

4.1 Imbalanced Reservoir Flow Challenges in the Geothermal Industry

Geothermal operations have many parallels with the conditions experienced in thermal oil recovery methods, such as SAGD operations. Though there are critical differences, many of the key challenges experienced in both processes share similar aspects, including imbalanced reservoir flow.

In the Geothermal industry, short-circuiting is a widespread issue associated with imbalanced reservoir flow. Short-circuiting (also known as "Flow Channeling") refers to the formation of a highly permeable path between injection and production wells. Fluid from the injection well follows these paths and flows directly to the production well, bypassing a significant amount of the reservoir. This results in sub-optimal heat transfer, as the injected fluid does not have adequate retention time or surface area contact in the reservoir to heat up. Short-circuiting can impact both hydrothermal and EGS operations and has been identified as a major issue for successful EGS development (Idaho National Laboratory 2006).

Reasons for the formation of short-circuits can vary; for example: initial stimulation may result in formation of highly permeable flow channels, thermal stresses caused by cold water injection and thermal drawdown can cause fractures to expand and, depending on the reservoir composition, mineral dissolution may result in increased pathway permeability. (DuTeau et al. 1994; Enhanced Geothermal Systems Reservoir Management and Operations Workshop 2007; Idaho National Laboratory 2006)

Once short-circuiting occurs, there are limited options available for remediation. A common method for addressing short-circuits is chemical precipitate injection. This method involves the injection of a chemical that precipitates in the short-circuit and plugs off the channel. Though this tactic has been used successfully, it is not always an infallible method. For example, high flow rates can wash out the chemical even if it was correctly delivered. To apply this method in the first place, the problem area also needs to be identified ahead of time, which is not always a simple task (Enhanced Geothermal Systems Reservoir Management and Operations Workshop 2007, Idaho National Laboratory 2006). Another common remediation technique for short-circuiting is simply to drill a new injection well. Though this method will almost certainly solve the immediate concern, drilling a new well is costly, and may not be an economically viable solution for EGS operations.

An additional issue resulting from imbalanced reservoir flow in the Geothermal industry is thermal drawdown (Enhanced Geothermal Systems Reservoir Management and Operations Workshop 2007; Pengcheng and Carrigan 2014). Thermal drawdown refers to a drop in reservoir temperature as fluid is produced. Thermal drawdown is detrimental to the produced heat capacity of the geothermal resource, as optimal surface area in the reservoir is not utilized, and the temperature of the produced fluid declines over time.

Thermal drawdown is more severe in channelized (or high permeability) fractures as the high flow rate of cooler fluid moving through the fracture causes the surrounding rock to cool. This in turn induces thermal stresses in the surrounding rock, potentially further increasing the permeability of the fracture. This cycle of thermal stress can lead to formation of short-circuits in the reservoir (Pengcheng and Carrigan 2014).

Though some thermal drawdown may be unavoidable, especially in EGS operations, it may be possible to optimize the well to maximize heat exchange area by utilizing different fracturing methods and controlling flow throughout the reservoir.

4.2 Potential Benefits of Installing Flow Control Devices in Geothermal Operations

Short-circuiting and thermal drawdown in the Geothermal industry share much in common with localized breakthrough and imbalanced steam chamber formation in SAGD processes (described in Section 3). In both cases, the injected fluid bypasses the ideal reservoir volume and is produced before the proper heat transfer can take place. Of course, the primary difference is that in SAGD, the purpose of the injected fluid is to heat the reservoir volume, where in Geothermal the injected fluid is to collect heat from the reservoir; however, the mechanisms are similar.

SAGD operators have successfully employed FCDs to promote uniform steam chamber formation by proactively installing ICDs and/or OCDs with well completions. This method has been shown to be effective in addressing the issues of localized breakthrough and imbalanced steam chamber formation and has often led to increased productivity in these wells (Burke et al. 2018). Considering the similarities between the mechanisms driving these issues in both Geothermal and SAGD operations, it is hypothesized that utilization of FCDs may similarly help to mitigate short-circuiting and thermal drawdown in Geothermal operations.

Installing OCDs in a Geothermal injection well could promote balanced distribution of injected fluid into the target reservoir. This would not only mitigate short-circuiting by preventing high flow in direct pathways but may also promote more surface area for heating as flow is forced through more of the reservoir, reducing the severity and localization of thermal drawdown. Similarly, installing ICDs in a production well would also mitigate short-circuiting by preventing high rate production from a preferred pathway, and may prevent thermal drawdown associated with producing fluid through localized zones in the reservoir.

Furthermore, installation of FCDs may provide increased confidence in the success rate of potential EGS projects. Short-circuiting has been identified as a critical remaining issue in the successful stimulation of EGS (Enhanced Geothermal Systems Reservoir Management and Operations Workshop 2007; Idaho National Laboratory 2006). Not only would FCDs potentially mitigate this issue, they may result in increased heat transfer of the system, increasing the economic attractiveness of EGS projects.

While the initial capital for installation of FCDs will be higher than typical open wells, the successful utilization of this technology has the potential to reduce overall costs in the long-term (Denninger et al. 2015). Successful utilization of FCDs would potentially result in operational cost savings such as:

- Reduction in well workovers: Prevention of short-circuiting would eliminate remediation efforts such as chemical precipitates. These efforts require costly troubleshooting time (to attempt to find problem area), and workover costs associated with the delivery of the chemical downhole.

- Fewer injection wells: A common solution to short-circuiting in conventional hydrothermal applications is to drill a new injection well. Prevention of short-circuiting could reduce the number of injections wells required, resulting in associated cost savings.

- Reduced downtime: Bringing production offline to deal with issues results in lost profits. Proactively dealing with these issues would reduce these downtime costs.

4.3 Limitations and Potential Issues with Flow Control Devices in Geothermal Operations

Though FCDs have been successfully used in the Oil and Gas industry, there exists very little information on the use of them in Geothermal operations. Differences between Oil and Gas and Geothermal operations may pose challenges to existing FCD designs. As such, this is an unproven technology for use in the Geothermal industry and will require development/refinement.

Examples of differences between Geothermal and Oil and Gas operations that may be of concern for FCD design include:

- Higher Flowrates: flowrates in SAGD operations are typically quite low compared to Geothermal operations. FCDs would likely require significant redesign work to create correct pressure drop and survive the erosion effects associated with these flow rates.

- Scaling/Plugging: Another potential issue for adaptation of FCDs to the Geothermal industry is plugging. As FCDs work by inducing pressure drop they would encourage flashing of the hot water, which would likely lead to increased scaling issues.

- Advanced Completions: Most Geothermal resources use open-hole wells to minimize capital costs; however, FCDs require advanced completions (such as liners or tubing) to deploy (CHOA 2015; Lastiwka et al. 2017). Initial costs would increase to add the components required for FCD installation to production and/or injection wells.
    - Note that for Geothermal applications, it is likely that only OCDs or ICDs would need to be installed, not both. This may limit the additional costs associated with installation of FCDs.

5. Conclusions

In conclusion, FCDs have provided the Oil and Gas Industry with improved reservoir conformance. Based on the similarities between the industries, the deployment of FCDs within Geothermal application could provide significant benefits to the industry.

Concluding points from this paper are as follows:

- FCDs are downhole equipment designed to promote uniform flow into or out of a well. These devices typically work by inducing a pressure drop either by channel flow, restrictions, or through autonomous processes.

- Reservoir conformance is important in both conventional and thermal EOR, as uniform inflow (and in the case of SAGD operations, outflow) along the horizontal well allows for higher production rates.
  - Uneven steam chamber formation or production rates in SAGD operations may result in localized breakthrough, in which steam flows into the production well.

- FCDs have been used in conventional Oil and Gas, and more recently, SAGD operations to help improve reservoir conformance.
  - In conventional Oil and Gas, FCDs prevent water/gas breakthrough by reducing localized drawdown around the production wells.
  - In SAGD operations, FCDs help maintain a uniform liquid level around the production well by promoting even steam chamber generation (by installing OCDs on the injection well) and by ensuring uniform production throughout the well length (by installing ICDs on the production well).

- In Geothermal operations, thermal drawdown can occur when highly permeable fractures form, and higher flow comes from a localized area of the reservoir. Short-circuiting can occur when these highly permeable fractures connect the injection and production wells, in which case, high rates of cool injection water flows directly to the injection well.

- Considering the similar challenge of imbalanced reservoir flow experienced by both thermal EOR and Geothermal operations, there exists opportunities for the Geothermal industry to benefit from innovative mitigation strategies employed by thermal EOR operators.
  - FCDs may promote more even flow throughout the target reservoir in Geothermal operations. This would help to optimize heat extraction from the target reservoir, and mitigate potential short-circuiting.

- Though the potential benefits of FCD use in Geothermal operations are significant, there remains a number of potential challenges with the implementation of this equipment. Development of these devices for the unique conditions of Geothermal operations would need to take place to adapt this technology for widespread use in the Geothermal industry.

REFERENCES

Alkhelaiwi, F.T., and Davies, D.R. "Inflow Control Devices: Application and Value Quantification of a Developing Technology." *Proceedings: 2nd International Oil Conference and Exhibition in Mexico 2007,* Society of Petroleum Engineers, Veracruz, Mexico (2007).

Banerjee, S. "Flow Control Devices in SAGD Completion Design: Enhanced Heavy Oil/Bitumen Recovery Through Improved Thermal Efficiencies." *Dissertation*, Texas A&M University, College Station, TX (2016).

Banerjee, S., and Hascakir, B. "Design of Flow Control Devices in Steam-Assisted Gravity Drainage (SAGD) Completion." *Journal of Petroleum Exploration and Production Technology*, 8(3), (2018) 785-797.

Burke, L., and Ghazar, C. "Flow Control Devices in SAGD – A System-Based Technology Solution." *Proceedings: SPE Thermal Well Integrity and Design Symposium*, Society of Petroleum Engineers, Banff, AB (2018)

Cavender, T.W., and Hunter, T. "Method of Minimizing Liner Expansion Issues in Horizontal Thermal Applications." *Proceedings: SPE Heavy Oil Conference and Exhibition*, Society of Petroleum Engineers, Kuwait City, Kuwait (2011).

C-FER Technologies (1999) Inc. High Temperature ICD Characterization Loop. Available from: https://www.cfertech.com/testing/experimental-flow-loops/high-temperature-icd-characterization-loop, (2019).

ConocoPhillips. "Flow Control Devices: An Industry Game Changer." *Spirit Magazine*, Fourth Quarter (2016), 25-26.

Denninger, K., Eustes, A., Visser, C., Baker, W., Bolton, D., Bell, J., Bell, S., Jacobs, A., Nagandran, U., Tilley, M., and Quick, R. "Optimizing Geothermal Drilling: Oil and Gas Technology Transfer." *GRC Transactions*, 39, (2015), 171-180.

Denney, D. "Analysis of Inflow Control Devices". *Journal of Petroleum Technology*, 62(05), (2010), 52-54.

Dikken, B. J., "Pressure Drop in Horizontal Wells and Its Effect on Production Performance." *Journal of Petroleum Technology*, November, (1990), 1426-1433.

DuTeau, R., Sprecker, T., and Swenson, D. "Preventing Short-Circuiting of Flow in Hot Dry Rock Reservoirs." *GRC Transactions*, 18, (1994), 415- 422.

Garcia, L.A., Coronado, M., Russell, R.D., Garcia, G.A., and Peterson, E.R. "The First Passive Inflow Control Device that Maximizes Productivity During Every Phase of a Well's Life." *Proceedings: International Petroleum Technology Conference*, Doha, Qatar (2009)

Ghesmat, K., and Zhao, L. "SAGD Well-Pair Completion Optimization Using Scab Liner and Steam Splitters." *Journal of Canadian Petroleum Technology*, 54(6), (2015), 387-393.

Halliburton. Inflow Control Devices: Extending the Life of Mature Field Wells. Available from: https://halliburtonblog.com/inflow-control-devices-extending-the-life-of-mature-field-wells/, (2019).

Idaho National Laboratory. "The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century". *Idaho National Laboratory Report*, INL/EXT-06-11746, Contract DE-AC07-05UD14517, November (2006).

Ihara, M., Yanai, K., and Takao, S. "Two-Phase Flow in Horizontal Wells." *SPE Production &* Facilities, November, (1995), 249-255.

Lastiwka, M., Bailey, C., James, B. and Zhu, D. "A Practical Approach to the Use and Design of Flow Control Devices in SAGD." *Proceedings: SPE Canada Heavy Oil Technical* Conference, Calgary, AB (2017).

Li, T., Shiozawa, S., and McClure, M. "Thermal Breakthrough Calculations to Optimize Design of a Multiple-Stage Enhanced Geothermal System." *GRC Transactions*, Vol. 38, (2014), 313-324.

Medina, M. "Design and Field Evaluation of Tubing-Deployed Passive Outflow-Control Devices in Steam-Assisted-Gravity-Drainage Injection Wells." *SPE Production Operations*, 30(4), (2015), 283-292.

Mikkelsen, J.K., Norheim, T., and Sagatun, S.I. "The Troll Story." *Proceedings: Offshore Technology Conference*, OTC, Houston, TX (2005).

Noroozi, M., Melo, M., Singbell, R.P., and Neil, B. "Investigation of Orifice Type Flow-Control Device Properties on the SAGD Process Using Coupled Wellbore Reservoir Modeling." *Proceedings: SPE Heavy and Extra Heavy Oil Conference – Latin America*, Society of Petroleum Engineers, Medellin, Colombia (2014).

Pengcheng, F., and Carrigan, R. "Exploring EGS Well Layouts that Mitigate Thermal Drawdown-Induced Flow Channeling." *Proceedings: 39th Workshop on Geothermal Reservoir Engineering, Stanford University,* Stanford, CA (2014).

Stalder, J. "Test of SAGD Flow Distribution Control Liner System, Surmont Field, Alberta, Canada." *Journal of Petroleum Technology*, Volume 52, Issue 2, (2012), 95-100.

Vachon, G.P., Klaczek, W., Erickson, P.J., Langer, D.C., Booy, D., and Baugh, A. "Use of Flow Control Devices (FCDs) to Enforce Conformance in Steam Assisted Gravity Drainage (SAGD) Completions." *Proceedings: SPE Canada Heavy Oil Technical* Conference, Calgary, AB (2015).