The Impact of Autonomous Inflow Control Valve on Enhanced Oil Recovery in SAGD Application

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Abstract
The demand for non-conventional oil has increased globally. Non-conventional oil is categorized as extra heavy oil and bitumen. In reservoirs with extra heavy oil and bitumen, thermal methods are used to reduce the oil viscosity. Steam assisted gravity drainage (SAGD) is a thermal recovery method to enhance the bitumen recovery. In this method, steam is injected to bitumen and heavy oil to reduce the viscosity and make the oil mobile and extractable. To obtain an efficient SAGD process, the residence time for steam in the reservoir must be long enough for the steam to condense and release the latent energy to be transferred to the cold bitumen. Early breakthrough of steam in some parts of the well will eventually limit the oil production and must be avoided. Autonomous inflow control valve (AICV) can prevent the steam breakthrough and restrict the excessive production of steam. The objective of this paper is to investigate the performance of AICV and its impacts on increased oil production in a SAGD production well. This is achieved by focusing on the implementation, and performance evaluation of inflow control devices (ICDs) and AICVs compared with standard well perforations. CMG STARS, a multi-phase, multi-component thermal reservoir simulator, is used to perform numerical simulation studies. The simulation results demonstrate the significant benefit of AICV in steam reduction compared to ICD and well perforations. The simulation results demonstrate that utilizing AICV in a SAGD reservoir will lead to higher oil production, less steam production, and a more uniform temperature distribution, and steam chamber conformance. Reduction in steam production, will improve the overall SAGD operation performance. This will also result in more cost-effective oil production, as less steam is needed to be generated for production of each barrel of oil.

1. Introduction

The demand for non-conventional oil has increased globally. Non-conventional oil is categorized as extra heavy oil and bitumen. The mobility of bitumen is quite poor since the viscosity can be as high as 10^6 cP (Ghahfarokhi et al., 2012). In reservoirs with extra heavy oil and bitumen, thermal methods such as steam assisted gravity drainage (SAGD) are used to reduce the oil viscosity and make the bitumen mobile and extractable. More than 80 percent of the world's annual output of heavy oil is accomplished through the utilization of this technique (Xu et al., 2020).

The SAGD well configuration typically consists of a pair of horizontally aligned wells that are between 500 and 1000 meters in length (Shen, 2013). The top wellbore is utilized for steam injection which is located about 4-6m above the production well, and the lower wellbore is utilized for oil production. When horizontal wellbores are used in SAGD, reservoir contact, and the overall well productivity are both significantly improved (Shen, 2013). Steam is injected into the reservoir from the injection well. This creates steam chambers at the interfaces as shown in Figure 1. These steam chambers expand both vertically and laterally (Shen, 2013). Latent heat from the steam is transferred to the bitumen at the interface, making it less viscous and more mobile. Due to the action of gravitational forces, the steam condensate, and the mobile bitumen flow downwards into the producer well. SAGD has been shown to be a successful and cost-effective way to get bitumen out of heavy oil reservoirs.

Several technologies have been created to optimize the performance of the SAGD process. Advanced well completion devices such as inflow control devices (ICDs) and autonomous inflow control valves (AICVs) can be used for improving bitumen recovery in SAGD operations. ICDs are intended to control fluid flow within a wellbore and assuring uniform distribution of steam. AICVs, on the other hand, are adjustable valves that regulate the openings automatically based on the fluid viscosities. The AICVs are thereby preserving balanced production rates and are controlling the inflow profiles.

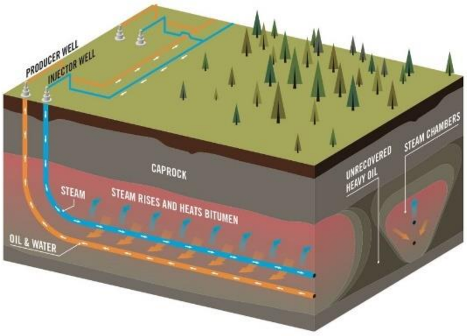


Figure 1: Principles of SAGD operation (staff, 2016)

The use of ICDs and AICVs in SAGD operations has the potential to solve several issues associated with steam injection and bitumen recovery. These issues include steam chamber conformance, early steam breakthrough, irregular fluid distribution, water and gas coning, and excessive production of undesirable fluids. By strategically employing ICDs and AICVs, operators can optimize thermal performance, maximize bitumen recovery, and reduce operating expenses.

The objective of this paper is to investigate the performance of AICVs, and its impacts on increased oil production in a SAGD production well. This is achieved by focusing on the implementation, and performance evaluation of ICDs and AICVs compared with standard well perforations. The novelty of this work is to simulation of the AICV and ICD behavior in a dynamic reservoir simulator under SAGD conditions. The functionality of the AICV and ICD is simulated through tabulated data based on the experiments presented in previous author's work (Taghavi et al., 2022). CMG STARS, a multi-phase, multi-component thermal reservoir simulator, is used to perform numerical simulation studies.

2. Advanced Wells with Inflow Control Technologies; ICD and AICV

Inflow control technologies such as ICDs and AICVs were introduced to the oil industry to overcome the early water and gas breakthrough challenges associated with the heel-toe effect in horizontal wells. Drilling long horizontal wells can increase reservoir contact, resulting in improved oil recovery. The pressure difference between the toe and heel sections of the well becomes large in long horizontal wells due to the pressure drop induced by friction between the inner pipe surface and fluid flowing through the pipe. This pressure difference in the well generates a higher pressure drawdown between the wellbore and the reservoir at the heel than at the toe, resulting in a greater inflow of reservoir fluid in the heel rather than in other areas of the well as shown in Figure 2. This phenomenon is known as the heel-toe effect. Because of heel-toe effect, early breakthrough of water and/or gas occurs at the heel section of the well, decreasing oil recovery efficiency.

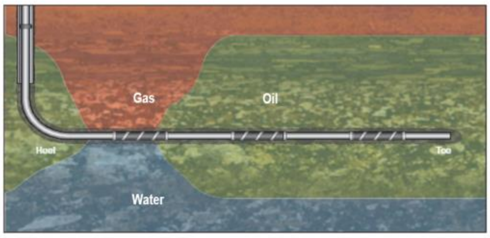


Figure 2: Gas and water breakthrough at the heel section of the well (Ellis et al., 2009).

2.1. ICDs in advanced wells

ICD is used to restrict the flow of fluid entering the base pipe from the annulus. It is a passive inflow control device, meaning it has no active components that can be regulated or altered to regulate the flow through it.

The governing equation of the nozzle-type ICD, as shown in Figure 3, is as follows (Lauritzen & Martiniussen, 2011):

$$\Delta P = \frac{8\rho Q^2}{d^4\pi^2 n^2 {C_D}^2} \tag{1}$$

Where ΔP is the pressure drop through the nozzle, ρ is the fluid density, Q is the volumetric flow rate of the fluid through the nozzle, d is the diameter of the nozzle, n is the number of tested nozzles, and C_D is the discharge coefficient. C_D is mostly a function of the Reynolds number (Re) (Lauritzen & Martiniussen, 2011).

The pressure drop through the nozzle is mainly dependent on the fluid density.

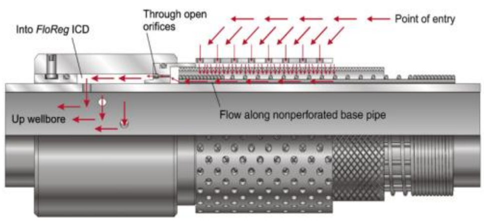
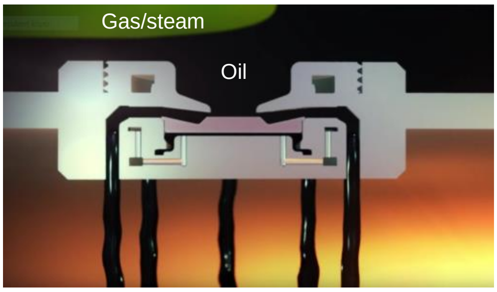


Figure 3 : Nozzle-type ICD (Birchenko et al., 2010).

2.2. AICVs in advanced wells

AICV is a novel inflow control system that combines the most advantageous characteristics of inflow controllers. AICVs are autonomous, meaning that they operate without the need of external control systems and constant human involvement. For oil production, AICV offers minimal flow restriction and the capability to close for water and gas/steam while simultaneously producing oil from other zones along the well. The valves in zones where gas/steam and water break through into the well, will close locally. Figure 4 shows AICV in closed and open position. Figure 4a shows that valve is open and producing oil as gas/steam is approaching the valve. Figure 4b illustrates that the gas/steam has reached the valve inlet, and valve is closed for gas/steam.

(a)



(b)

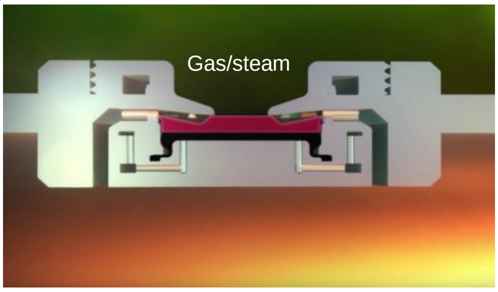


Figure 4: AICV in open (a) and closed (b) position (Aakre et al., 2018).

The mathematical model describing the performance of the AICV can be described as:

$$\Delta P_{Tot} = \left(\frac{\rho_{mix}^2}{\rho_{cal}}\right) \cdot \left(\frac{\mu_{cal}}{\mu_{mix}}\right)^y \cdot a_{AICD} \cdot Q^x \quad (2)$$

where ΔP_{Tot} is the differential pressure across the AICV, ρ_{cal} and μ_{cal} are the calibration fluid density and viscosity, and ρ_{mix} and μ_{mix} are the mixture fluid density and viscosity respectively. The parameter a_{AICD} is a valve characteristic given by the ICD strength, Q is the volumetric mixture flow rate, and x and y are constants (Taghavi & Ghaderi, 2021). It can be interpreted from equation (2) that the pressure drop through the AICV is much more viscosity dependent than density dependent. The concept and principle of AICV is described in detail in earlier scientific works (Aakre, 2017; Aakre et al., 2013).

3. Reservoir and Wellbore Model in CMG

CMG 2022.10 general release by Computer Modeling Group Ltd. is used for accomplishing the objectives of this paper. The software has thirteen modules, each for a specific purpose. Reservoir grid modeling, well modeling, creation of fluid models, rock fluid properties and importing previously created well, reservoir and component properties are done using the Builder module of the CMG software. CMG STARS is responsible for conducting thermal and steam additive simulations. Thermal oil recovery methods such as SAGD, can be simulated with the help of STARS.

3.1. Reservoir construction in CMG Builder

A cuboid shaped reservoir has been considered where gravitational force is acting along the k-direction (vertical). The reservoir grid building constraints have been shown in Table 1.

Table 1:The dimensions of the drainage area.

Direction	No. of Blocks	Block size distributions (No. of blocks*block length) [m]
I (x)	30	30*50
J (y)	15	2*20, 10, 8, 5, 4, 3, 1, 3, 4, 5, 8, 10, 2*20
K (z)	20	11*3.5, 1, 2*3, 1, 3*3, 2*5

The areas marked in blue in Figure 5 represent the location of the injector and producer wells. All the cells within the blue area are very small in dimensions.

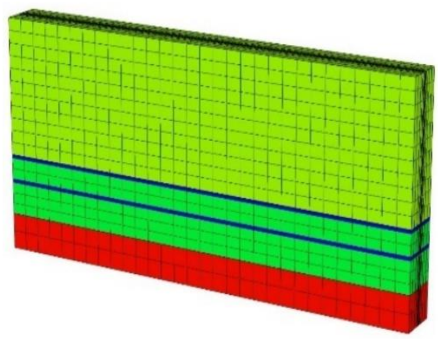


Figure 5: Reservoir 3D view

The details regarding the reservoir characteristics and parameters for initialization are presented in Table 2.

Table 2: Reservoir Characteristics initialization details.

Property	Value
Porosity	30 %
Rock wettability	Water wet
Reservoir top depth	400 m
Initial pressure at top of the reservoir	1500 kPa
Initial temperature	12°C
Initial water saturation	0.10
Reference depth	430 m
Water-oil contact depth	455.5 m
Oil mole fraction (dead oil)	0.80
Oil mole fraction (solution gas)	0.20

3.1.1. Reservoir rock and fluid properties

The reservoir rock and fluid thermal properties are given in Table 3.

Table 3: Reservoir rock and fluid thermal properties.

Property	Value
Formation compressibility	2.90×10^{-6} 1/kPa
Rock volumetric heat capacity	2.35×10^{6} J/(m^3·C)
Rock thermal conductivity	6.60×10^{5} J/(m·day.C)
Oil thermal conductivity	1.25×10^{4} J/(m.day.C)
Water thermal conductivity	5.35×10^{4} J/(m.day.C)
Gas thermal conductivity	3.20×10^{3} J/(m.day.C)
Over/Under-burden volumetric heat capacity	2.35×10^{6} J/ (m^3.C)
Over/Under-burden thermal conductivity	1.496×10^{5} J/(m.day.C)

The viscosity changes of bitumen as a function of temperature is taken from the experimental work of (Ghahfarokhi et al., 2012) and is shown in Figure 6. The oil viscosity at standard pressure decreases radically with the increase in temperature.

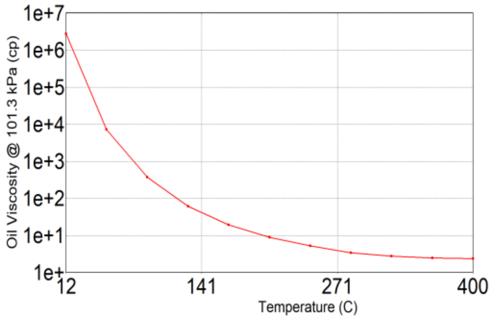


Figure 6:Viscosity of Athabasca bitumen sample versus temperature.

Generally, it is challenging to obtain information about relative permeability for different fields. Data for relative permeabilities are set manually in table form in CMG Builder. Two-phase relative permeabilities for liquid-gas and water-oil are shown in Figure 7 and Figure 8 respectively. The datasets have been calculated based on the Stone II model.

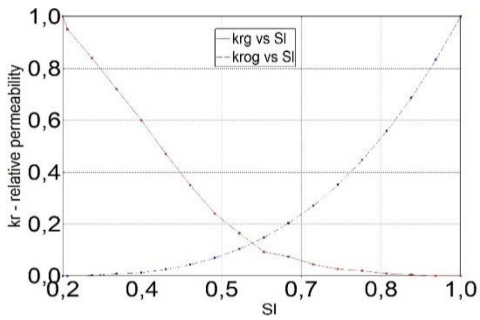


Figure 7: Liquid - gas relative permeability curves.

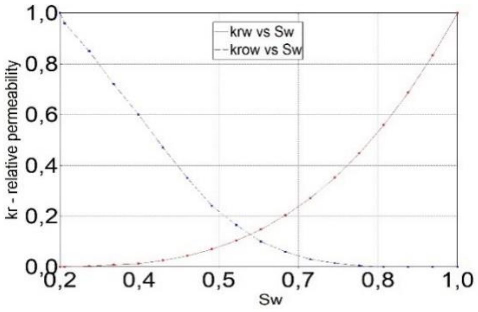


Figure 8: Water-oil relative permeability curves.

Sl is the liquid saturation, Kr is the endpoint relative permeability, krg is the relative permeability to gas at Sl, krog is the relative permeability to oil in the presence of gas at liquid saturation Sl = 1-Sg. In addition, Sw is the water saturation, krw is the relative permeability to water at Sw and krow is the Relative permeability to oil at Sw.

3.2. Well modelling in Builder

The simulation time has been set to 10 years for the SAGD operation and these 10 years have been divided into two phases. The first phase, also known as the circulation period, starts from 1st of January 2023 and continue for six months until 1st of July 2023. The SAGD period starts from 1st of July 2023 and continue until 1st of January 2033. Each well is 1201 meters long horizontally. Eight wells have been defined for accomplishing the whole SAGD process. Their names and period and mode of operation are shown in Figure 9. The FlexWell (FW) model is developed by CMG and is used to model the fluid flow in the wellbore and between the wellbore and the reservoir. FW is an advanced discretized mechanistic wellbore model which models the complex well completions (Mohd Ismail et al., 2021). The injector FWs are placed 6 meters above the producer FWs maintaining the optimum vertical distance. Figure 10 and Figure 11present the wells trajectories during the circulation phase and the SAGD phase respectively.

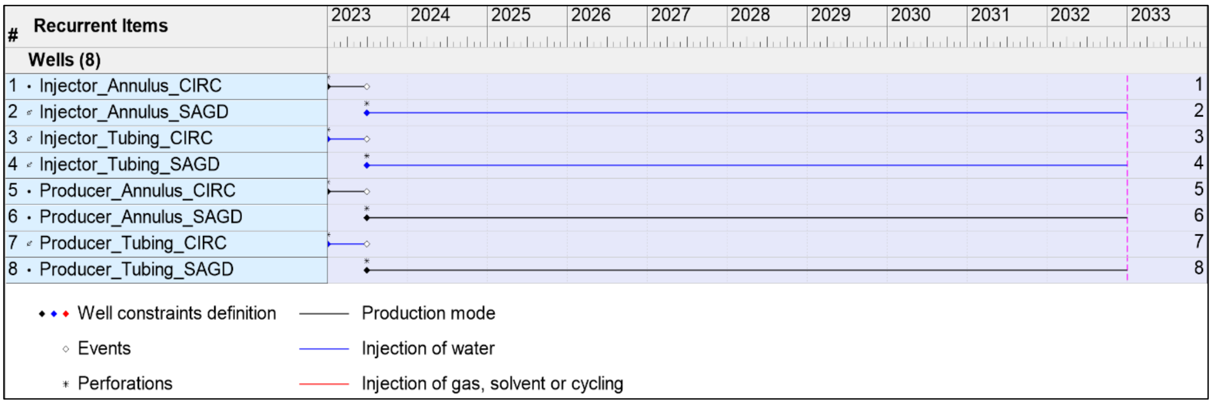


Figure 9: Timeline view of well operation data.

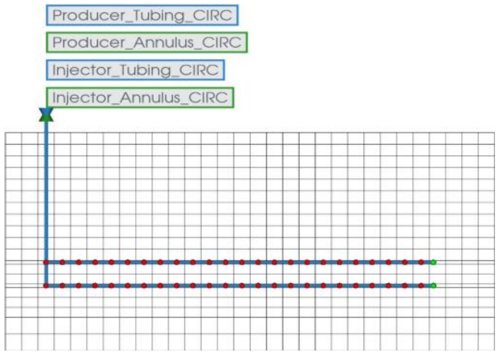


Figure 10: Well trajectories during circulation phase.

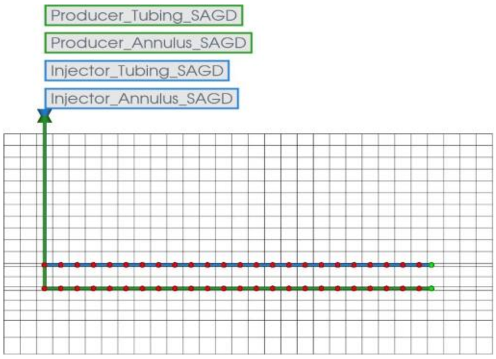


Figure 11:Well trajectories during SAGD phase.

The wells have been modeled this way in order to maintain similarity with the real-world conditions as the wells working during the circulation stage are completely turned off as the SAGD stage starts, rendering them nonexistent by CMG. Essentially, the wells present during the circulation stage are neither active nor present during the SAGD stage.

The well constraints for circulation and SAGD phases are listed in Table 4 and Table 5.

Table 4 : Circulation period well constraints.

FWs	Name	Function	Constraints
Injector FW_ CIRC	Injector_ Annulus _CIRC	Producer	MIN BHP 3500 kPa
			MAX STL 150 m^3/day
	Injector_ Tubing _CIRC	Injector	MAX BHP 4000 kPa
			MAX STW 100 m^3/day
			Injection temperature 250ºC
			Steam quality 0.9
Producer FW_ CIRC	Producer_ Annulus _CIRC	Producer	MIN BHP 3500 kPa
			MAX STL 150 m^3/day
	Producer_ Tubing_ CIRC	Injector	MAX BHP 4000 kPa
			MAX STW 100 m^3/day
			Injection temperature 250ºC
			Steam quality 0.9

Table 5: SAGD period well constraints.

FWs	Name	Function	Constraints
Injector FW_ SAGD	Injector_ Annulus_ SAGD	Injector	MAX BHP 4000 kPa
			MAX STW 500 m^3/day
			Injection temperature 250ºC
			Steam quality 0.9
	Injector_ Tubing_ SAGD	Injector	MAX BHP 4500 kPa
			MAX STW 500 m^3/day
			Injection temperature 250ºC
			Steam quality 0.9
Producer FW_ SAGD	Producer_ Annulus_ SAGD	Producer	MIN BHP 2000 kPa
			MAX STL 1500 m^3/day
	Producer_ Tubing_ SAGD	Producer	MIN BHP 2000 kPa
			MAX STL 1500 m^3/day

BHP is bottom hole pressure, STW is the surface water rate, and STL is the surface liquid rate.
The dimensions of the annulus and tubing are listed in Table 6.

Table 6: Diameters of annulus and tubing.

Parameter	Size
Tubing wall inner diameter	0.104 m
Tubing wall outer diameter	0.114 m
Annulus wall inner diameter	0.166 m
Annulus wall outer diameter	0.177 m

4. Results and Discussions

The main well of interest for this study is the Producer_Annulus_SAGD, the annulus of Producer FW_SAGD. Depending on the case definitions, Producer_Annulus_SAGD annulus will either have only perforations or be equipped with ICDs or AICVs for comparing oil recovery. The rest of the wells will operate with well perforations.

4.1 Simulation cases

Six cases have been established for simulation purposes. The simulation cases are well perforations (without any inflow controllers), well completed with 4 ICDs in each 50 meters of the horizontal length, and well completed with 4 AICVs in each 50 meters of the horizontal length in both homogenous and heterogeneous reservoir. The horizontal permeability of the homogeneous reservoir is 1800 mD in all blocks. The permeability distribution of the heterogeneous reservoir is illustrated in Figure 12.

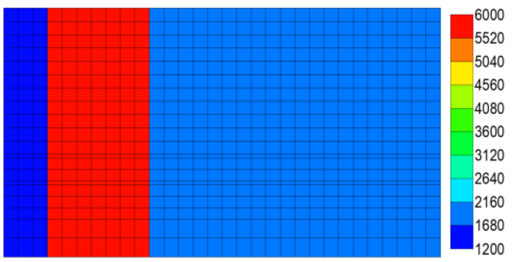


Figure 12: Permeability distribution of heterogeneous reservoir (I-K plane view).

4.2 Simulation results in the homogenous reservoir

During the circulation period, steam is injected from both wells. This is to establish thermal communication between the injector and producer and warm up the reservoir. Figure 13 shows the temperature distribution at the end of the circulation period which is between 70-100 ºC.

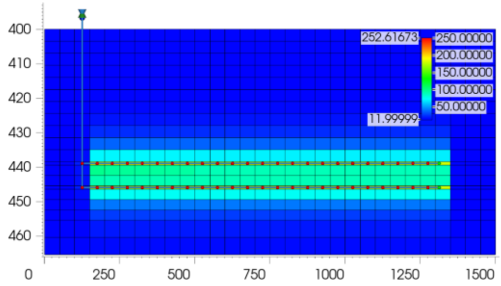


Figure 13: Temperature distribution at the end of the circulation period (I-K plane view).

In order to study the performance of ICD and AICV, the accumulated oil, gas (steam), and water for the AICV and ICD completion cases are compared to the case without any inflow controllers (perforations), see Figure 14. Under homogeneous conditions, the perforation case (red line) falls behind the case with ICDs (dashed green line) and the case with AICVs (solid green line), having the lowest cumulative oil production for the highest cumulative gas and water production. Based on cumulative oil and gas production, the AICV case outperforms the ICD case having higher oil production and lower gas production as shown in Figure 14.

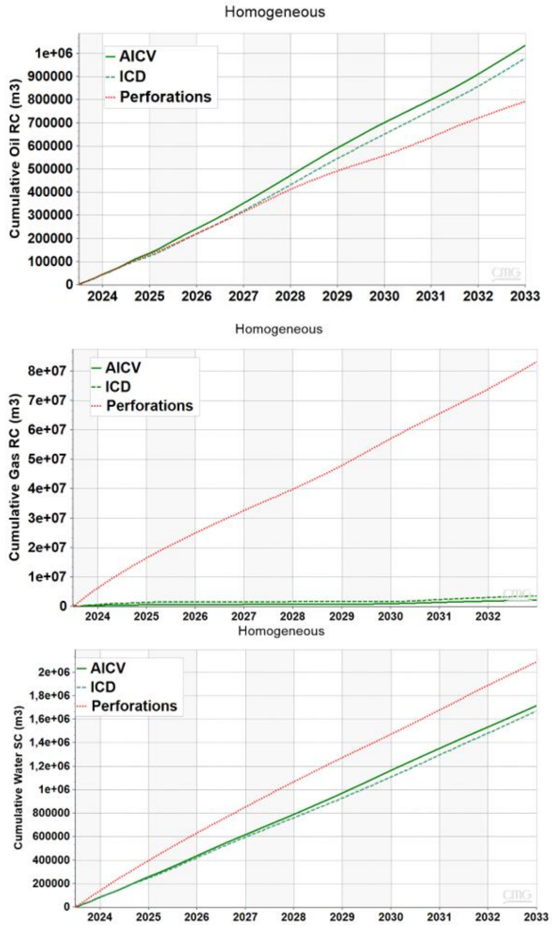


Figure 14 : Cumulative oil, gas, and water production for perforations, ICDs and AICVs in a homogenous reservoir.

Understanding the formation of steam chambers and temperature distribution across the reservoir is an important aspect of the SAGD process. Steam chamber patterns and temperature distributions can also be used to indicate in which case there is more steam production. From Figure 15, it can be interpreted that due to the high steam production for well perforations, the steam chamber has not reached the maximum temperature after 5 years, see Figure 15a. Looking closely along J-K plane shown in Figure 15c, illustrates that the AICV case has a slightly better steam distribution than the ICD case shown in Figure 15b. This means that AICVs are better in handling steam breakthroughs than ICDs and well perforations.

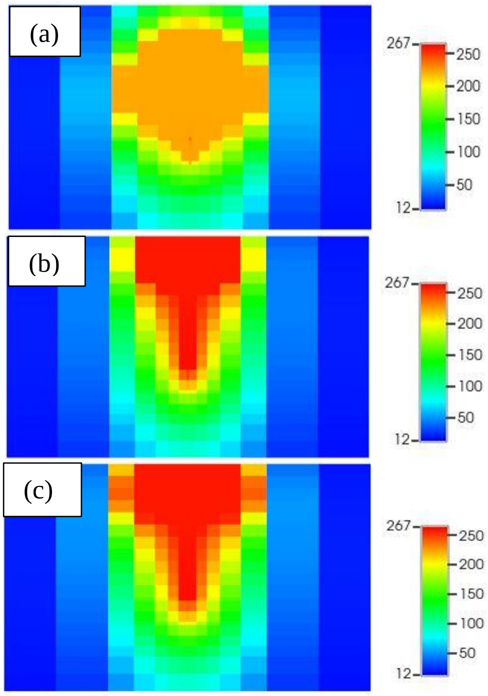


Figure 15 : Steam chamber conformance along J-K plane for (a) perforations, (b) ICDs, and (c) AICVs.

4.3 Simulation results in the heterogeneous reservoir

Figure 16 illustrates that the AICV case outperforms the ICD and perforations cases in terms of having the highest cumulative oil production and the least cumulative gas and water production. The perforation case (red line) falls behind the case with ICDs (dashed green line) and the case with AICVs (solid green line), having the lowest cumulative oil production for the highest cumulative gas and water production.

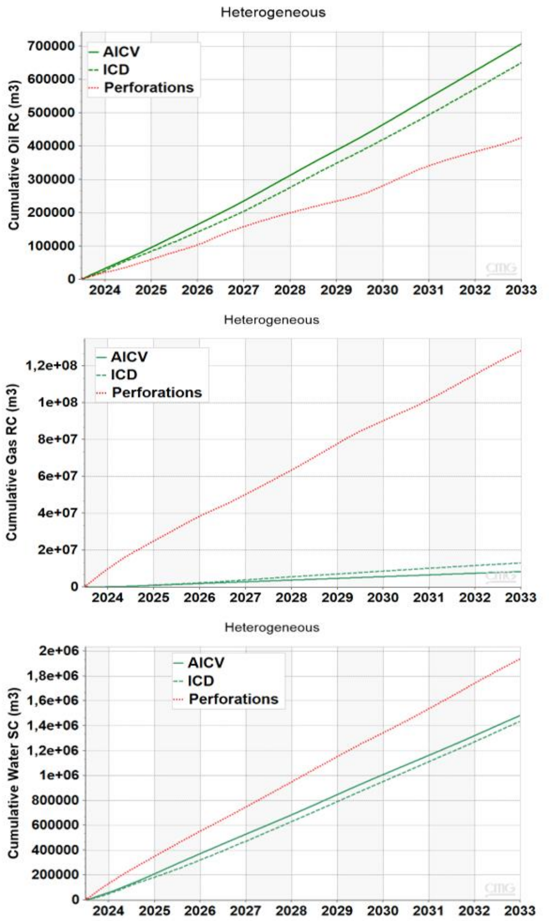
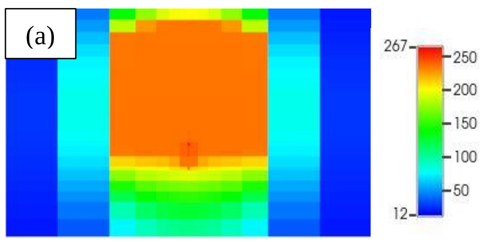


Figure 16: Cumulative oil, gas, and water production for perforations, ICDs and AICVs in a heterogeneous reservoir.

This directly indicates that AICVs are better in recovery of heavy oil and in resisting gas (steam), and water production compared to ICDs and well perforations when subjected to heterogeneous reservoir conditions, similar to that under homogenous conditions.

As illustrated by Figure 17a, the perforation case does not have a uniform steam chamber conformance and temperature distribution after 5 years. Both ICDs and AICVs show uniform steam chamber conformance which has reached maximum temperature after 5 years as shown in Figure 17b and Figure 17c respectively.



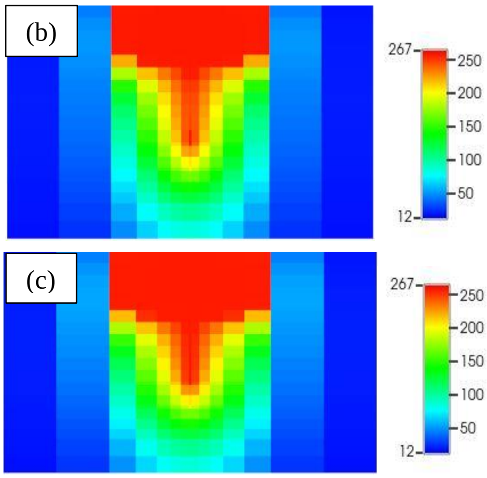


Figure 17 : Steam chamber conformance along J-K plane for (a) perforations, (b) ICDs, and (c) AICVs.

Analysis of Figure 15 and Figure 17 demonstrates that ICDs and AICVs are much better in maintaining proper temperature distribution across the reservoir and in formation of uniform steam chamber compared to well perforations. When looked from the J-K plane, it is seen that steam chamber conformations with well perforations in both homogeneous and heterogeneous cases do not reach the maximum steam injection temperature. On the contrary, ICDs and AICVs evidently show better steam chamber conformance by reaching maximum injection temperatures.

5. Conclusions

The impact of AICV on enhanced oil recovery in a SAGD production well is investigated. This is achieved by developing a wellbore-reservoir model in the CMG STARS simulator.

Both homogenous and heterogeneous reservoirs are studied by considering ICD and AICV completion and well perforations only.

The simulation results demonstrate that utilizing AICV in a SAGD reservoir will lead to higher oil production, less steam production, and a more uniform temperature distribution, and steam chamber conformance.

Reduction in steam production, will improve the overall SAGD operation performance. This will also result in more cost-effective oil production, as less steam is needed to be generated for production of each barrel of oil. Less steam generation means less energy demand, that consequently contribute to lower the intensity of greenhouse gas emissions.

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