# COMPARATIVE STUDY OF WELL SOAKING TIMING (PRE VS. POST FLOWBACK) FOR WATER BLOCK REMOVAL FROM MATRIX-FRACTURE INTERFACE

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ABSTRACT

Water block after hydraulic fracturing is one of the major challenges in shale oil recovery which affects the optimal production from the reservoir. The water blockage represents a higher water saturation near the matrix-fracture interface, which decreases the hydrocarbon relative permeability. The removal of water blockage in the field is typically carried out by soaking the well (i.e., shut-in) after hydraulic fracturing. This soaking period allows water redistribution, which decreases the water saturation near the matrix-fracture interface. However, previous field reports show that there is not a strong consensus on whether shut-in is beneficial in term of production rate or ultimate recovery. Due to the large number of parameters involved in hydraulic fracturing and tight formations, it is challenging to select which parameter plays the dominant role in determining the shut-in performance. Furthermore, literature on field case studies does not frequently report the parameters which are of researchers' interest. In other words, the challenge of evaluating shut-in performance not only lies on the complexity of parameters and effects involved within the reservoir, but also the limited number of field case studies which report a comprehensive list of fracturing and reservoir parameters.

This paper aims to investigate the effect of well soaking timing on shut-in performance. This question is motivated by the fact that in the field, shut-in can take place either immediately after hydraulic fracturing but before the first flowback (i.e., pre-flowback) or sometime after the first flowback (i.e., post-flowback). The timing of shut-in is believed to influence the production performance, because it dictates how much water will imbibe from the fractures. A numerical core-scale model is built and validated by a successful history match with numerous experimental data. Our model demonstrates that shut-in performed after the first flowback (i.e., post-flowback) can help ensure a higher regained oil relative permeability than shut-in performed before the first flowback (i.e., pre-flowback). A discussion on the water blockage mitigation from these two shut-in timings is also presented. As a result, this study proposes that flowback should be carried out immediately following hydraulic fracturing, even if an extended shut-in is to be performed later.

INTRODUCTION

To produce hydrocarbon from shale reservoirs, hydraulic fracturing has nowadays become an inevitable stimulation technique. A large volume of water is injected under high pressure to create fracture network in the formations. However, it is widely known that only a small fraction of the injected water is recovered during flowback period. Many researchers argued that the unrecovered water imbibes into the matrix through forced imbibition during fracturing and creates a formation damage called "water blockage," represented by a higher water saturation near the matrix-fracture interface. As a result, the hydrocarbon relative permeability around the matrix-fracture interface decreases and affects the optimal production from the reservoir.

This water blockage is formed near the matrix-fracture interface due to the capillary discontinuity between the matrix and the fracture. Tight formations often demonstrate a capillary pressure of up to thousands of psi, whereas fractures show less than ten or often zero psi. Therefore, to remove this type of water blockage from the matrix-fracture interface, the drawdown should be higher than the matrix threshold capillary pressure or even higher than the maximum capillary pressure at the irreducible water saturation for a full water blockage cleanup. However, the available drawdown in the field may not be adequate to remove such blockage. As a result, shut-in is often performed subsequent to hydraulic fracturing, because it redistributes the high water saturation near the matrix-fracture interface deeper into the matrix through capillary imbibition. As the water saturation near the matrix-fracture interface is lower, the required drawdown to initiate and sustain the flowback is reduced. This reduction in the required drawdown is arguably the main benefit of shut-in.

Nevertheless, another problem arises from the water redistribution itself. Typically, the relative permeability curves in tight formations are highly depressed that a slight increase in water saturation causes a large reduction in the hydrocarbon relative permeability. This implies that while the water redistribution solves the water blockage issue at the matrix-fracture interface, it causes a reduction in the hydrocarbon relative permeability in the deeper matrix. Regardless of the possible reduction in the hydrocarbon relative permeability, shut-in is still often performed by operators, either due to logistical constraints or the perceived benefit that shut-in could contribute to an incremental hydrocarbon recovery factor.

For shut-in performance evaluation, some field data are revisited. Some reports claim that shut-in is beneficial because it results in a higher initial hydrocarbon production rate upon bringing the well back online. It also lowers the drawdown required to perform flowback and lowers the water handling cost [1-4]. However, other reports suggest that shut-in is detrimental because it allows the unrecovered water to imbibe deeper into the matrix causing the reduction in the hydrocarbon relative permeability [3, 5, 6, 7]. Overall, it seems that shut-in benefits mostly take place during the early-time production (i.e., higher initial hydrocarbon production rate and lower required drawdown to perform flowback), while they may not affect or even potentially harm the long-term production (i.e., reduced hydrocarbon relative permeability, lower matrix absolute permeability due to clay swelling, and production loss during the extended shut-in).

A comparative analysis among this field data to determine which factors dominantly affect shut-in performance is difficult due to the complexity of parameters and effects involved within the reservoir and the limited amount of information reported. For example, the field reports seldom mention the desiccation effect which is shown to affect shut-in performance [7]. In addition, they seldom mention whether the corresponding shut-in was performed immediately after hydraulic fracturing (pre-flowback) or after a short period of flowback (post-flowback). Therefore, this paper aims to enrich the literature by investigating the effect of shut-in timing (i.e., pre- vs. post-flowback) on shut-in performance in removing the water blockage. This is motivated by the fact that some operators perform the extended shut-in before the initial flowback, while others after the initial flowback.

## MODEL VALIDATION

To conduct this study, a numerical core-scale model is built based on a coreflood experiment which simulates an invasion and flowback process [2]. To simulate the water leakoff/ invasion into the matrix, water is injected from one side of the core at a constant rate. Meanwhile, to simulate the flowback, oil is injected from the other side of the core at a constant rate. The coreflood experiment was conducted inside a CT scanner to record the real-time water saturation profile evolution during the invasion, shut-in, and flowback. Table 1 lists the rock and fluid properties used in the experiments and thus modeling.

The numerical model is validated through a successful history match with the experimental results in term of the water saturation profile at different time slices during immediate flowback (Fig. 1), pressure drop during flowback (Fig. 2), and regained oil relative permeability ($k_{ro}$) (Fig. 3) [7]. Figs. 1-3 demonstrate that although our model is numerical, it successfully captures the physics or mechanisms of water blockage because it matches the water saturation profile at different time slices, instead of a typical rate or pressure plot which cannot visualize the water saturation distribution. In fact, because of the abundant parameters matched between the experiment and the model, it is concluded that the non-uniqueness of the history match could be effectively improved by calibrating against the $k_{ro}$ plot measured in the experiment (Fig. 3). This validation attempt is paramount in this study because most papers perform a numerical study on similar topics based on a synthetic and invalidated mechanistic model, which may result in misleading observations. Readers, if interested, are encouraged to refer to the previous work for the model development and history matching attempt [7].

## WATER BLOCKAGE REMOVAL PROCESS

For convenience, this section revisits the water blockage removal mechanisms previously proposed in the literature [2, 7]. As illustrated in Fig. 2, two drawdown plateaus are observed during flowback: early- and late-time drawdown plateau. The early-time drawdown plateau represents the period in which the water saturation near the matrix-fracture interface is high, which causes the drawdown to remain high. In other words, the early-time drawdown plateau represents the period in which the trapped water at the matrix-fracture interface is still present, indicated by the concave-up water saturation profile near the interface, such as for the 3-hr time slice in Fig. 1. As soon as this high water saturation near the matrix-fracture interface is removed, the late-time drawdown plateau will gradually form. This late-time drawdown plateau represents the period in which the water saturation near the matrix-fracture interface is much lower that the trapped water at the matrix-fracture interface is removed, indicated by the absence of the concave-up water saturation profile near the interface, such as for the 15-hr time slice in Fig. 1.

Given the constant water and oil injection rate, steady-state flow is achieved (shown by the constant pressure drop in each plateau in Fig. 2. Therefore, the evolution/ increase of hydrocarbon relative permeability ($k_{ro}$) during the flowback period can be calculated using Darcy law. This parameter is called “regained hydrocarbon relative permeability” or regained $k_{ro}$ (Fig. 3). This parameter quantifies how well the different shut-in timings remove the water blockage. Lastly, since further flowback does not significantly decrease the value of the late-time drawdown plateau, the late-time drawdown plateau corresponds to the “maximum” regained hydrocarbon relative permeability.

## SHUT-IN PRE- VS. POST-FLOWBACK

After the model is validated, the effect of shut-in timing (i.e., pre- vs. post-flowback) is investigated in this section. Shut-in pre-flowback refers to the case in which shut-in takes place before any flowback occurs (i.e., immediately after water injection stops). Meanwhile, shut-in post-flowback corresponds to the case in which shut-in takes place after a certain period of flowback subsequent to the water injection. In this study, the duration of the initial flowback in the case of shut-in post-flowback is set at 10 hours. In both shut-in pre- and post-flowback cases, the simulated shut-in duration is 24 hours. To accommodate the long shut-in duration and thus the greater imbibition depth, the core-scale model is extended from 25.4 to 200 cm to prevent the imbibing front from breaking through the other end of the core. The initial water saturation is set at the irreducible water saturation.

Fig. 4 shows the effect of shut-in and its timing on the drawdown required to perform flowback. Using Darcy law, this drawdown plot is converted to a $k_{ro}$ “restoration” plot, presented in Fig. 5. Fig. 5 shows that shut-in does not create a higher late-time $k_{ro}$ than immediate flowback (with no shut-in at all). In fact, immediate flowback seems to restore $k_{ro}$ as quickly as shut-in. However, since flowback occurs during the early production in the field in which $k_{ro}$ is still very low, the required drawdown will be very high. In other words, Figs. 4-5 demonstrate that shut-in benefits are mostly during the early-time flowback by lowering the required drawdown to initiate the flowback.

Fig. 5 also emphasizes that not only that shut-in does not create a higher late-time $k_{ro}$ than immediate flowback, it may even decrease the late-time $k_{ro}$. Fig. 5 demonstrates that while shut-in post-flowback results in virtually the same quality of water blockage removal as immediate flowback (shown by the similar late-time $k_{ro}$ value), shut-in pre-flowback worsens the water blockage issue (shown by a much lower late-time $k_{ro}$ value than immediate flowback). As a result, it seems that the decision on whether to shut-in the well after fracturing depends on the availability of drawdown in the field: if the large drawdown required to perform flowback is available, immediate flowback should be priority to ensure a higher late-time $k_{ro}$, even if an extended shut-in is to be performed later.

## MECHANISTIC ANALYSIS OF SHUT-IN TIMING EFFECT

To explain the contradictory shut-in performance between shut-in pre- and post-flowback, we compare the water saturation profile between the two shut-in timings (i.e., pre- vs. post-flowback) at different time slices (Figs. 6a-c). Fig. 6a illustrates the evolution of water saturation profile for shut-in pre-flowback; Fig. 6b for shut-in post-flowback; Fig. 6c for the combination of both cases. First, in Fig. 6a, since the case of shut-in pre-flowback does not have any immediate flowback before the shut-in period, water saturation profile at the start of 24-hr shut-in is the same as that by the end of water injection.

In Figs. 6a-b, the water redistribution is visually illustrated by the decreasing water saturation within the invaded region and the increasing water saturation within the originally-uninvaded region. More importantly, Fig. 6c shows that the maximum water invasion depth for both cases is almost the same at around 500 mm from the fracture face. Given that the case of shut-in post-flowback already experiences another 10 hours (i.e., the predetermined duration of the initial flowback) before the subsequent 24-hour shut-in, the fact that the maximum water invasion depth is similar for both shut-in pre- and post-flowback cases is interesting. This suggests that the capillary imbibition during shut-in in the case of shut-in post-flowback is slower than that of shut-in pre-flowback. This could occur in the case of shut-in post-flowback because the water that resides in the fractures has been previously cleaned up. Therefore, there is a smaller amount of available water which will serve as the source of the proceeding water capillary imbibition. As the water imbibition volume in the shut-in post-flowback case is lower than that in the shut-in pre-flowback case, the water redistribution in the shut-in post-flowback case will reach to an equilibrium more quickly than in the shut-in pre-flowback case. In this section, the equilibrium represents the condition in which the water redistribution is virtually complete that the water saturation profile at further time slices does not show a significant increment of redistribution.

In other words, the imbibition rate in the shut-in post-flowback case is lower than that in the shut-in pre-flowback case. This could occur because in the shut-in post-flowback case, there is a shorter length/ interval of high water saturation near the matrix-fracture interface before the subsequent shut-in takes place. The high water saturation is critical in generating a high imbibition rate due to its high saturation gradient between the invaded and the uninvaded region, while the long length of regions with such high water saturation helps ensure that the high imbibition rate can be sustained for a longer period of water redistribution. For shut-in post-flowback case, the high water saturation still exists at the start of shut-in, but at a very short length/ interval in the closest vicinity of the matrix-fracture interface. As the proceeding imbibition continues to pull this water saturation near the fracture down, the water saturation value near fracture will quickly decrease and reach the equilibrium water redistribution.

Nevertheless, although the imbibition rate in the shut-in post-flowback case diminishes much earlier than that in the shut-in pre-flowback case, Fig. 6c demonstrates that the water saturation profile by the end of simulation (i.e., 42 days after water injection starts) between the pre- and post-flowback shut-in case is visually similar. However, Fig. 6 still shows that the water saturation profile in shut-in pre-flowback at the end of simulation is technically higher than that in shut-in post-flowback. Since Fig. 5 shows that the regained $k_{ro}$ in shut-in post-flowback is still higher than that in shut-in pre-flowback, the comparison between Fig. 5 and Fig. 6 suggests that this tiny difference in water saturation profile at the end of simulation is yet substantial in quantifying the regained $k_{ro}$. In other words, this tiny difference in water saturation profile corresponds to a large difference in regained $k_{ro}$ because of the $k_{rw}$ depression. Fig. 7 shows the matrix relative permeability curves obtained from history matching; Fig. 7 shows the high depression level of $k_{rw}$. This implies that a slight water saturation increase results in a large oil relative permeability reduction. As a result, the fact that shut-in pre-flowback results in both higher water saturation profile at all locations along the core and deeper invasion depth than shut-in post-flowback at any time slice indicates that early flowback is critical to ensure better water blockage removal. In other words, the attempt to minimize the amount of mobile water within the matrix should be priority, which can be carried out by flowing back the injected water immediately following hydraulic fracturing, even if an extended shut-in is to be performed later.

## CONCLUSIONS

Regardless of the timing, shut-in is demonstrated to not generate any incremental regained oil relative permeability over immediate flowback with no shut-in at all. In fact, improper shut-in timing may even result in a much lower maximum regained oil relative permeability. Our simulation results demonstrate that shut-in performed after an initial flowback (i.e., post-flowback) can help reach a higher regained hydrocarbon relative permeability than shut-in performed before an initial flowback (i.e., pre-flowback). A mechanistic analysis on the water saturation profile suggests that this observation is attributed to the high depression level of the relative permeability curves. The high depression level implies that a slight water saturation increase causes a large hydrocarbon relative permeability reduction. As a result, this study proposes that flowback should be carried out immediately following hydraulic fracturing, even if an extended shut-in is to be performed later.

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Table 1 – Core plug and fluid properties used in the experiment [2]

| Permeability (mD) | Porosity | Diameter (cm) | Length (cm) | $\mu_o$ (Pa.s) | $\mu_w$ (Pa.s) |
|---|---|---|---|---|---|
| 14.4 | 0.168 | 7.62 | 25.4 | 2.4E-4 | 1E-3 |

Figure 1 – Water saturation profile match at two different time slices during immediate flowback: experiment vs. modeling [7]

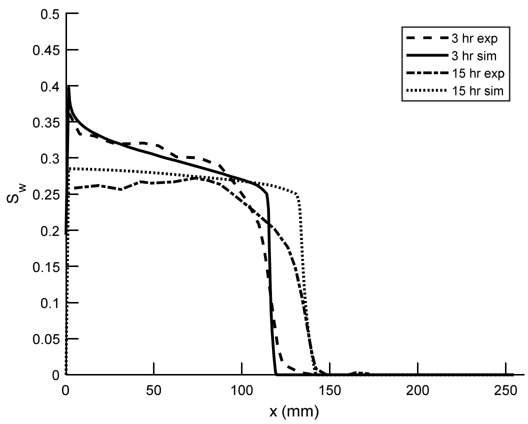


Figure 3 – Regained $k_{ro}$ history match: experiment vs. modeling for immediate flowback and shut-in case [7]

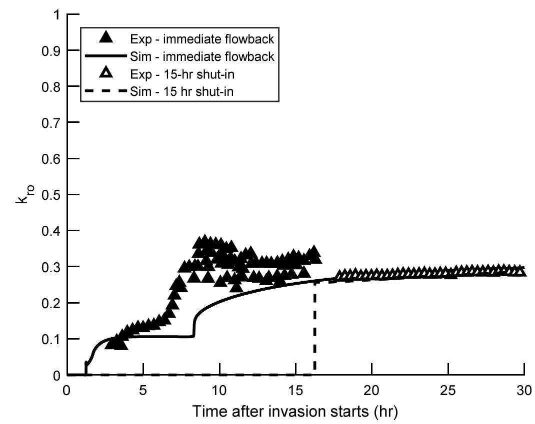


Figure 2 – Pressure drop during immediate flowback (blue) and flowback after 15-hr shut-in (red): experiment vs. modeling [7]

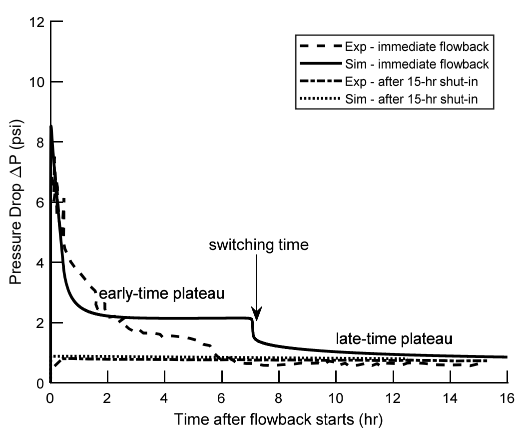


Figure 4 – Effect of shut-in and its timing on drawdown during flowback

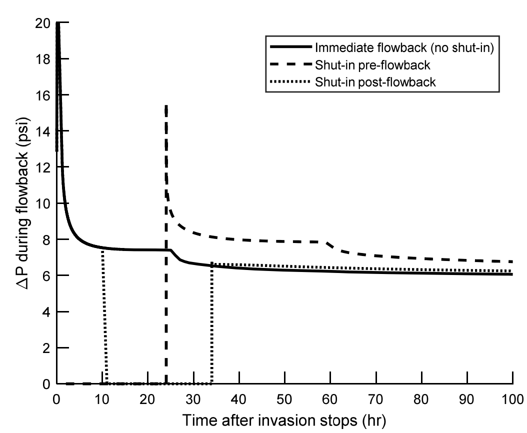

Figure 5 – Effect of shut-in and its timing on the restoration of $k_{ro}$

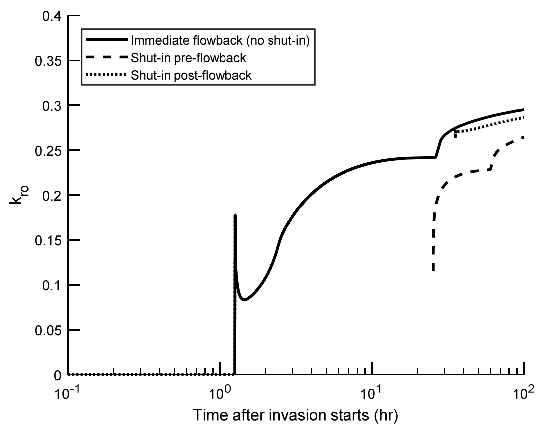


Figure 6a – Evolution of water saturation profile: shut-in pre-flowback

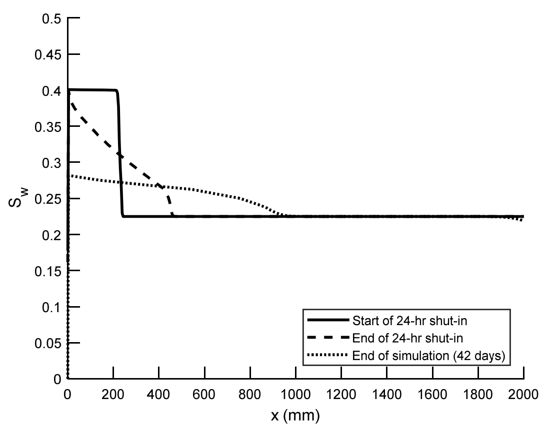


Figure 6b – Evolution of water saturation profile: shut-in post-flowback

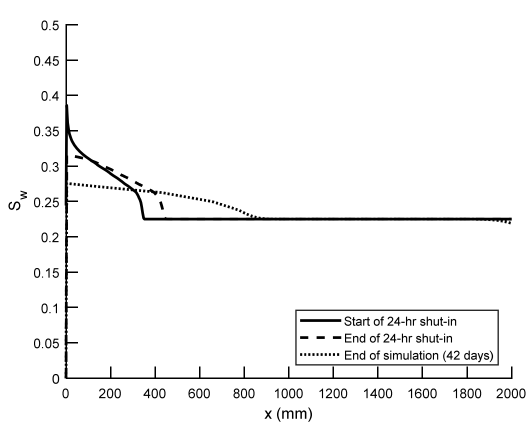


Figure 6c – Water saturation profile comparison between shut-in pre- and post-flowback

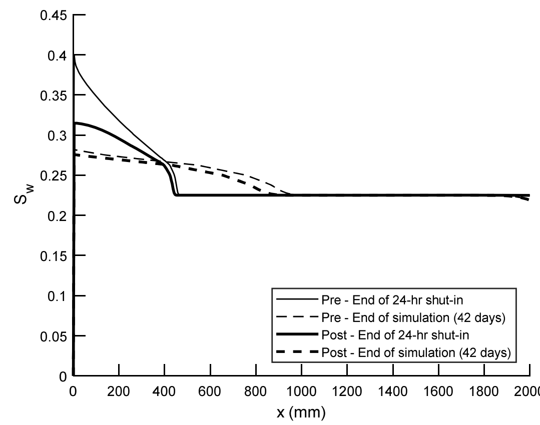


Figure 7 – Matrix relative permeability and capillary pressure curves