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A systematic investigation into the flowback cleanup of hydraulic-fractured wells in unconventional gas plays

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ABSTRACT

This paper conducts an extensive investigation into fracture cleanup efficiency by considering several pertinent parameters instantaneously over a wide practical range. Injection, shut-in and production stages of the fracturing operation were simulated for 32 sets consisting of 113,072 runs. To perform such a large number of simulation runs, a computer code was utilised to routinely read input data, implement the simulation runs and produce output data. In each set (which consists of 4096 runs), instantaneous impacts of twelve different parameters (i.e., fracture and matrix permeability, Brooks matrix capillary pressure (Pc) parameters, and Brooks-Corey relative permeability parameters) were investigated. To sample the domain of variables, full factorial experimental design (two-level FFS) was employed. The linear surface methodology was used to map the simulation output, which is the loss in gas production (GPL), compared to the clean case (i.e., 100% clean-up) after three production periods of 10, 30 and 365 days.

The impact of various combinations of fracture fluid injection volume, fracture length, shut-in soaking time, matrix permeability variation range and drawdown on GPL were studied in different sets. Additionally, more simulation sets were performed to capture the impact of hysteresis, layering and mobile formation water on the clean-up efficiency.

Results indicated that in line with some literature data, factors that controlled the mobility of FF inside the fracture had the most significant impact on cleanup efficiency. It was also noted that injecting high volumes of FF, into very tight formations significantly delayed clean-up and impaired gas production. The effect of varying other parameters such as extending soaking time or increasing pressure down in such a case delivered negligible GPL improvement. Introducing hysteresis made clean-up slightly faster in all production periods.

The impact of the gravity segregation was discussed in this study. Considering the layered systems, it was indicated that in the top layer, the fracture mobility coefficients were more important than the ones in the bottom layer whist capillary pressure seems to become more important in deeper layers compared to the top layers.

Additionally, a slower clean-up was observed for sets with larger initial water saturation compared to those cases with immobile water saturation due to the detrimental effect of mobile water on gas production. In some cases, with significantly high values of water saturation, using chemicals (which IFT reducing agents) to reduce Pc could reduce GPL and improve cleanup efficiency.

These findings contribute to the further understanding of the fracture fluid cleanup process and provide practical guidelines to achieve economically successful hydraulic fracturing operations, which are popular but expensive for tight and ultra-tight reservoirs.

1. Introduction & literature review

Hydraulic fracturing (HF), also known as Hydro-fracking, is one of the most widely used stimulation techniques in the oil and gas industry to enhance the production from unconventional fields. A hydraulic fracture is initiated and propagated by injecting a fluid with high pressure into the formation. The injection fluid also referred to as fracturing fluid (FF), is typically water albeit with suspended solid

Abbreviations: LRSM, linear response surface model; ILRSM, linear response surface model with interaction; FVR, the ratio of injected fracture fluid to fracture volume; IFT, interfacial tension; FF, fracture fluid; DP, Pressure drawdown; GPL, gas production loss; Kmr, Matrix Permeability Ratio, i.e., if Kmr = 10 mean the Km variation range is reduced by factor of 10; ST, Shut-in/Soaking time; VW, Vertical Well; HF, Hydraulic Fracturing

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Nomenclature

K	absolute reservoir permeability
Kmax	end point of the Corey relative permeability formula
P	pressure
Pc	capillary pressure
S	saturation
n	exponent of the Corey relative permeability formula
x	x direction
y	y direction
z	z direction

Subscript

g	gas
w	water
r	residual
f	fracture
m	matrix

materials, usually sand or another type of proppants added to keep the fracture open. After fracturing, oil, gas and FF flow towards the well much more easily because of the presence of the fractures.

Hydraulic fracturing is widely employed to increase the productivity of wells in tight and ultratight fields. However, this encouraging approach sometimes is not successful to meet the predicted production enhancement. The most common cause is an inefficient cleanup of the previously injected fracturing fluid.

Several studies have been conducted to understand this underperformance and to capture the impact of the pertinent parameters affecting the efficiency of FF cleanup.

Tannich (1975) reported that the production loss due to FF presence in the fracture and matrix is more significant at the early production periods. Tannich also indicated that as the fracture length increases it takes a longer time for the well to cleanup. Additionally, he showed that the lower the fracture conductivity, the slower the cleanup process. Cooke Jr., and C.E., C. (1973) and Cooke Jr. and Cooke (1975) investigated the cleanup efficiency experimentally and concluded that the FF presence in the fracture could substantially reduce the fracture conductivity. Numerous numerical and parametric works were conducted on the FF cleanup and its failure to further study the HF operation. (Ahmed et al., 1979; Montgomery et al., 1990; Bennion et al., 2000; Mahadevan and Sharma, 2005; Jamiolahmady et al., 2009, 2014; Bazin et al., 2010; Gdanski and Walters, 2010; Ghahri et al., 2009, Ghahri, 2010; Ghahri et al., 2011; Nasriani et al., 2014a,b; Nasriani and Jamiolahmady, 2018a,b).

Cheng (2012) highlighted that the flow of the fracturing fluid and water within the created and natural fractures has a substantial influence on the efficiency of hydraulically fractured wells. He also reported that a number of mechanisms govern the flow of water within a fracture. He constructed a numerical model to study the water saturation distribution within the fracture over production time and demonstrate its detrimental impact on gas production. He concluded that capillary forces and gravity segregation could have a significant impact on gas production.

Agrawal and Sharma (2015) constructed a three-dimensional planar hydraulic fracture numerical model to study the impact of different mechanisms within the fracture, i.e., capillary forces, viscous forces (relative permeability) and gravity forces. They concluded that liquid loading is very likely to occur in ultratight gas fields when the well is produced under the regular operational constraints. They recommended some guidelines to minimalize the impact of liquid loading on the gas production.

Ghanbari and Dehghanpour (2016) studied the governing parameters on FF and gas production during the clean-up period using numerical simulations. They noticed that the imbibition of FF deeper into the matrix during the shut-in time could increase the gas productivity at early production times. Therefore they highlighted that the early time flowback and gas production depends on capillary forces, the fracture networks' complexity and the shut-in time. They noted that having higher capillary forces could result in higher gas production rates only during the early production times but the complexity of the created fracture networks has a significant impact on flowback recovery and gas production rates.

Xu et al. (2016) developed a mathematical model to simulate the early time FF flowback and gas production. They considered several drive mechanisms during the shut-in time including expansion of gas build-up, water expansion and fracture closure. They concluded that the gas-water ratio (GWR) plots for shale gas formations follow a V-shaped trend, the first region, i.e., decreasing GWR during early gas production stage indicates the two-phase production from the fracture. The second region, i.e., increasing GWR during late gas production indicates the water displacement by the gas that flows from the matrix into the fracture.

Zhou et al. (2016) selected a set of different wells (187 wells) of four different geological settings. From this set of wells, they considered different factors that affect FF flowback-production including the number of hydraulic-fracture stages, lateral length, vertical depth, proppant mass applied, proppant size, fracture-fluid volume applied, treatment rate, and shut-in time. They studied the correlation between flowback data and well completion for the four different geological groups. They estimated FF flowback volume in a spatial domain as a function of the aforementioned factors.

Wang and Leung (2016) conducted a quantitative investigation of the fluid and rock properties and geomechanics that control flowback recovery. They noticed that there is an important interaction between imbibition and geomechanics during FF and gas production. They highlighted that fracture cloture could increase the imbibition process and reduce the fracture conductivity due to a reduction in the pressure within the fracture.

Lai et al. (2017) conducted a numerical simulation to capture the impact of wettability, the viscosity of FF and FF filtration on water blockage and gas productivity in hydraulically fractured wells. They showed that FF is retained within the matrix at high surface tension values. They showed that a reduction in the interfacial tension could increase the flowback recovery and consequently improve the gas recovery. They also demonstrated that higher FF viscosity could significantly increase the damage and consequently impair the gas productivity.

(Fu et al., 2017) constructed diagnostic plots to highlight the physics of flow in two different regions. Region 1 refers to the pressure reduction duration within the fractures, and Region 2 denotes the breakthrough of oil & gas into the active fracture network. They indicated that the duration of Region 1 is governed by original field pressure and the type of hydrocarbon. They concluded that total injected FF volume, perforation intervals, and the number of clusters are the most important parameters to optimise the fracturing operation.

Although these works were significant steps to better understand the flowback cleanup in post-fracturing operation, they did not consider the impact of all pertinent parameters instantaneously over a wide practical range on the post-fracturing cleanup.

In the Gas Condensate Recovery (GCR) team at Heriot-Watt University, Ghahri et al. (2009) conducted a single parameter analysis on the cleanup efficiency of the fracture in tight formations. This line of study was then extended to investigate the impact of sixteen different but pertinent parameters simultaneously for two simulation sets (with