A NEW ANALYTICAL METHOD TO QUANTIFY RESIDUAL FLUID CLEANUP IN HYDRAULIC FRACTURES

A Thesis

by

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ABSTRACT

A number of factors contribute to reduce the production benefits from hydraulic fracturing, including inefficient fluid design, poor proppant selection and or, the inability of fracture fluid to degrade and flow back after treatment. Undegraded hydraulic fracturing fluid has always been a major issue, and is believed to drastically undermine the performance of hydraulically fractured wells. Several attempts have been made to quantify the damage associated with residual fluid, with varying level of success. Previous approaches may include lab experiments, numerical simulation and evaluation of production data. In this work, the previous investigation results has been accounted and further improvement is made in quantifying the cleanup of residual fluid and subsequent hydrocarbon recovery. After investigating fracture fluid damage mechanism, a simple mathematical model is developed to quantify residual fluid cleanup and its effect on the gas production from a tight gas sandstone reservoir. Key solutions have been derived with the help of Mathematica, and then a simple Excel-VBA code have also been developed to better characterize the cleanup process under different reservoir conditions, hydraulic fracture dimensions and varying residual fluid rheology.

Contrary to the previous attempts we assume that the entire fracture is in a plugged initially. In addition to this we use a system approach and show that initially the available reservoir energy is used for establishing a narrow flow channel in the fracture, and the system approaches to its final productivity gradually. Results and analyses show

that higher conductivity of hydraulic fracture does not ensure 100% cleanup; if sufficient energy is not available from the reservoir to overcome the resistance exhibited by the complex rheology of residual fluid along the fracture.

This work provides a methodology that will help engineers to select the right fracturing fluid properties in tight gas. This is important because only in North America approximately 10,784Tcf of unconventional and gas reserves are present and more such reservoirs will be stimulated to fulfill the needs of future energy demand.

DEDICATION

Lovingly dedicated to the Almighty

What I would do without YOUR mercy!

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I would like to extend my sincere gratitude to my committee chair, Dr. Valko, for his valuable guidance throughout the development of my research work. I would also like to thank my committee members, Dr. Economides and Dr. Sun for their continuous support and remarks on my work.

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NOMENCLATURE

w_f	Width of fracture
H_f	Height of fracture
x_f	Half-length of fracture
I_X	Penetration ratio
w_{fg}	Cleaned up half-width of fracture
$\left(\frac{dp}{dx}\right)_f$	Pressure gradient in a wing of hydraulic fracture
$\emptyset_p$	Proppant pack porosity
u_{hb}	Velocity of residual (hb) fluid inside fracture
q_{hb}	Volume flow rate of residual fluid inside fracture
u_g	Velocity of gas inside fracture
q_g	Volume flow rate of gas inside fracture
τ_y	Yield stress of Herschel Bulkley fluid
K	Consistency index of Herschel Bulkley fluid
n	Fluid behavior index of Herschel Bulkley fluid
x_e	Length of square drainage area of reservoir
$\bar{p}$	Average reservoir pressure
T	Reservoir Temperature
H	Net pay
k_{res}	Reservoir permeability

$\emptyset$	Reservoir porosity
$OGIIP$	Gas initially in place
S_g	Gas saturation
β_g	Gas formation volume factor
μ_g	Gas viscosity
z	Gas compressibility factor
G_p	Cumulative gas production
Δt	Time period
p_{wf}	Wellbore flowing pressure

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CHAPTER I

INTRODUCTION

Hydraulic fracturing is being used extensively as an efficient stimulation technique in low permeability, low porosity (unconventional tight gas) reservoirs. However, it is a well-established fact that production from hydraulically fractured wells does not reflect the expected outcome. Post treatment production rates reveal, that the created fracture dimensions fall shorter than the designed dimensions. This is crucial since a large portion of future energy demand rely on this unconventional clean source of energy. The motivation behind this work is the presence of large natural gas reserves, 71,981Tcf [1] in the form of unconventional tight gas which cannot be produced economically until undergoing a massive hydraulic fracturing treatment. Only in north America approximately 10,784Tcf [1] of unconventional tight gas reserves are present.

Previous studies on the performance of hydraulically fractured wells can be grouped in to two categories; a category that focuses on the aspects that affect hydrocarbon yield of these wells and the other category that mainly concentrates on the inefficient flow back of fracturing fluid. This second category is involved in the investigation of all the factors that contribute negatively on the fracturing fluid cleanup. This dissertation falls in the second category. Previous studies utilize either of three approaches or a combination to investigate residual fluid cleanup process and to forecast production behavior; these approaches may include lab experiments, numerical simulation and evaluation of production data. In this work, the previous investigation results has been accounted and further improvement is made in quantifying the cleanup of residual fluid and subsequent hydrocarbon recovery.

Economics of hydraulic fracturing treatment demands optimal production rates. Therefore, elements that could contribute in damaged, uneconomical fractures have been investigated. These factors may include inefficient fluid design, poor proppant selection and or, the inability of fracture fluid to degrade and flow back after treatment etc. [2-4]. In chapter II, a detailed literature review, of all the factors that are found to affect the performance of hydraulically fractured tight gas reservoirs, is presented. However, the review will mainly discuss different approaches that have been adopted to quantify the cleanup of residual fracturing fluid and its effect on hydrocarbon recovery.

In this research, a simple analytical model is formulated to quantify fracturing fluid clean-up process, under different reservoir conditions and available drawdown, for any known propped hydraulic fracture dimensions. This model can also simulate the gas flow rate from the hydraulically fractured wells under different cleaned up states of the fractures. The model is created using simple boundary conditions. The hydraulic fracture is modeled as a porous medium – following the basic principles of the Carman-Kozeny description. However, instead of a bundle of tubes, we use a bundle of parallel-wall flow channels, as the basic building block. We assume that initially (before the onset of flow back), the hydraulic fracture is entirely filled with residual fluid. The flow back of the residual fluid can be quantified in terms of time using this model and if there exists one – it is also possible to determine the retained fluid layer thickness even after years of production. The methodology adopted in formulating this model and the calculation procedure, that will quantify the cleanup behavior and productivity of hydraulically fractured gas wells, are presented in chapter III.

Cleanup of residual fluid and hydrocarbon yield of hydraulically fractured well is affected by operating conditions, hydraulic fracture dimensions, reservoir properties and properties of residual fluid. Excessive leak off in case of very low permeability /porosity reservoir results in a residual fluid extremely rich in polymer and has a very low concentration of chemical breaker. Due to insufficient concentration of breaker in the residual polymeric fluid it doesn’t degrade to a low viscosity fluid after completion of fracing. Polymer rich residual fluid possess high static yield and requires high drawdown to initiate cleanup. Compared to a wide short fracture a long thin fracture takes longer time to clean. Considering the economics of the hydraulic fracture it is extremely important to design the fluid in such a way that cleanup becomes efficient. Using the published data of tight gas reservoirs, effects of all these factors on clean up and gas production rate are presented and analyzed in chapter IV.

A brief summary of this work and conclusion from the results are given in chapter V. Recommendations to further improve this work are also given in chapter V.

A thorough literature review is completed that facilitated in understanding these damage mechanisms and also helped in formulating the objectives and organization of this dissertation.

Objectives of this dissertation are:

1. Carry out a detailed literature review to understand the mechanism of residual fracture fluid damaging performance and its cleanup process.

2. Develop a mathematical model to quantify the cleanup of residual fluid and also to calculate the cleanup time.
3. Perform a sensitivity analysis. Utilizing different reservoir conditions, hydraulic fracture dimensions and residual fluid properties, evaluate the effects on cleanup and on gas recovery.
4. Validate the model using actual field data.
5. Propose new concepts/ideas to improve residual fluid cleanup, minimize fracture fluid damage and to maximize the fractured well performance.

CHAPTER II

LITERATURE REVIEW

Hydraulic fracturing in tight gas reservoirs

Tight gas is a dry natural gas, reserved in low permeability/low porosity reservoirs, as shown in Figure 1, which cannot produce economically without utilizing an economically viable stimulation technique. Choice of stimulation can be made based on different geological and physical conditions of reservoir. Approximately 71,981Tcf. of tight gas reserves are found to occupy low permeability sandstone and carbonate reservoirs and a substantial volume (49,709Tcf.)[1] of it is also present as shale gas. However, this work is mainly focusing on tight gas sandstones formations.

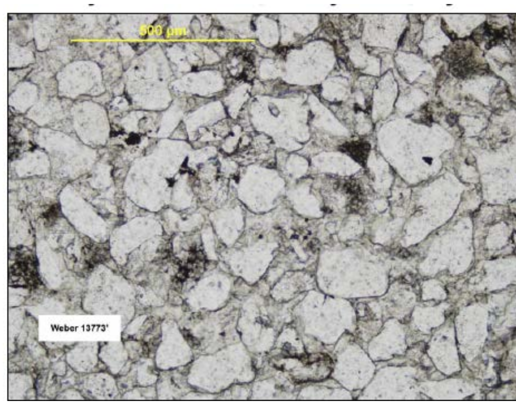

Figure 1. Low porosity Weber sandstone, Brady Field, Wyoming (www.uwyo.edu).

In tight gas sandstone reservoir the economic volumes of natural gas are achieved either with a vertical well combined with extensive hydraulic fracturing, or by drilling multilateral or horizontal wells[5]. After hydraulic fracturing treatment it is expected that the created path is conductive enough to let the gas in reservoir adopt a linear or bilinear flow pattern rather than a radial flow pattern that is typical of an un-stimulated reservoir. If the created propped fracture has high conductivity and is draining a large area the gas will flow at very high rates.

It is a common practice to assume, for calculation purpose, that a symmetric bi wing fracture is created at the end of the treatment. The injection of a highly viscous mixture of cross linked polymer solution (gel) with different additives creates this pair of wings. This viscous solution also helps in the transport of uniform sized, spherically shaped, proppant in the created fracture. The ultimate objective of proppant is to keep the created fracture open during drawdown. To technically optimize the performance of hydraulic fracturing treatment two dimensionless numbers were introduced and are considered very important; proppant number and dimensionless fracture conductivity[6]. Former is an indicator of fracture treatment size and later an indicator of fracture performance.

Since these numbers are function of the in situ permeability of the hydraulic fracture, any factor that can lead to impairment has been discussed on several forums. It has been shown that this may include residual unbroken fluid, water influx, two phase flow etc.

Damage mechanisms in hydraulic fractures

Evidence of damage, and different damage mechanisms, in hydraulic fractures have been reported extensively in the literature [3,7,8]. These damages may occur either inside the fracture or in the vicinity of fracture, inside the formation [9]. Inside the fracture the damage may occur due to inefficient fluid design, poor proppant selection and or, due to the un degraded residual fracture fluid, as shown in Figure 2, on fracture face, viscous fingering, inefficient breaker etc. [2-4].

Initially during pumping same residual fluid helps in maintaining the pressure in the reservoir by avoiding excessive leak off. Inside the low permeability/low porosity formation in the vicinity of fracture, damage can be caused by excessive leak off from fracturing fluid. This occurs due to the relative difference in the cross-linked complex fluid structure and the small pore throats. This leak off can alter the relative permeability and capillary effects. In the presence of clays can cause damage associated with clay swelling which can block pores [9].

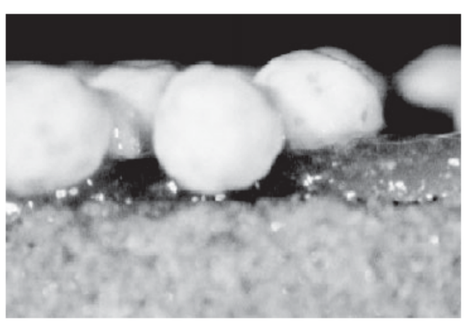

Figure 2. Cross-linked polysaccharide fluid with breaker residing on fracture face.([9] Orig. Ref: StimLab Consortia 1997-2006)

Holditch et al. [10] numerically analyze the damage mechanism and gas production in hydraulically fractured reservoirs, using 2D, two phase (gas-water) simulator. Holditch based his simulation on two different scenarios; whether the fracturing fluid caused formation permeability impairment within the vicinity of fracture or not. In the first scenario, if the drawdown can't overcome the capillary pressure in the permeability impaired area, than the water will be pulled and entrapped in this area and gas will not be able to flow. However if the permeability impairment is very severe, than a high drawdown which can overcome capillary effect, might still not be sufficient to increase gas production. In the second scenario, if the drawdown is high enough to overcome the capillary pressure, gas flow will not be affected by the water blocking; if not than fracturing liquid can imbibe into the formation. Gas production will not completely halt. However, it can be severely reduced if drawdown is not higher than the capillary pressure and the water becomes immobile at the fracture face. Cleanup process post hydraulic fracturing is directly affected by the water mobility in the vicinity of the fracture; however the fracture conductivity has no direct influence.

Liao and Lee [11], using simulation tools, studied the cleanup process of hydraulically fractured gas wells in single and multilayered formations. Their work led to the conclusion that near fracture formation damage affects cleanup process. Further, to increase gas production from such stimulated wells fracture conductivity should at least be moderately high (i.e. higher than 10) and near fracture damage must be at least reduced if can't be avoided.

This dissertation is based on the findings pointing to unbroken/un-degraded fracturing fluid inside the created and propped fracture, as the most common and lethal cause of performance loss in hydraulically fractured wells. This mostly occurs when water soluble polymer solutions are used for hydraulic fracturing. This problem is addressed by various authors using diverse approaches. Some have used experimental methods[12] some proposed mathematical models[13, 14] and some have used flow back data with history matching[15] in order to reveal the role of residual fluid.

Mathematical investigations of residual fluid damage/removal process

Cooke and others [3, 16, 17] presented the idea of conductivity impairment in the presence of residual fluid, only inside the fracture. Several other authors have presented the view that depending on the geology and the structural characteristics of the formation a filter cake can be formed inside the formation. Soliman et al[8] discussed the importance of high fracture conductivity on clean up, and suggested that fracture should be designed to achieve high conductivity.

Voneiff et al [4] used a numerical simulator to replicate clean up behavior in fractures. The damage mechanism incorporated using gas relative permeability and capillary effects in both the fracture and reservoir, effect of closure stress and residual fluid on conductivity. Through history matching, (Frontier formation) 12 years of the gas well production, it was reported that the residual unbroken fluid can reduce gas recovery by 30% and can slow down initial production rates as high as 80%. Due to slow cleanup effective fracture length becomes a function of clean up time.

May et al [18], through numerical simulation, matched production history (Cotton Valley) using different values of residual fluid yield stress. May et al showed that a high value of yield stress was required to match the actual field production trend. This value of residual fluid yield stress was at least 10 times higher than the values of injected fluid. Also, as clean up proceeds the fracture effective length increases.

Friedel et al [14] used a mathematical model to show the effect of non-Newtonian fluid (Yield stress fluid) characteristics of the residual fluid on the cleanup behavior. Friedel considered that due to very low porosity of formation, the cake forms inside the fracture only and only the liquid from injected fluid leaks off in to the formation. Therefore, he considered three phase flow (gas/water/residual fluid) in the fracture and gas /water inside formation in the vicinity of fracture. The conclusions show that capillary forces can't be considered as the main factor obstructing clean up, but high yield stress of the residual fluid is the primary cause of fracture damage. They suggested that only a fraction of the residual fluid can be removed at such a high yield stresses. In our work we accept these statements and proceed further to quantify the process.

Barati et al. [19] used Friedel et al [14]model with fine gridding approach (Bennett) around the hydraulic fracture to see the effect of different parameters on the cleanup process. This approach gave good estimation of hydraulic fractures performance in the early times. The effect of several other factors (reservoir and hydraulic fracture parameters) was found similar to what was reported by Friedel et al. However the effect of residual fluid could not be modeled in this work.

Balhoff et al [20]formulated an analytical model to account residual fluid clean up in hydraulic fractures. The model is created using Darcy's law and continuity equation for single phase unidirectional flow. The model utilizes the contrast between the available pressure differential in the hydraulic fracture and the resistance due to the yield stress of the residual fluid to account cleanup. To calculate the fracture cleanup with time, some of the parameters in the model, need to be estimated using field data. Balhoff et al also credited residual fluid yield stress as the main hindrance to cleanup.

A joint industry project was commenced in 2002 [17, 21] to ascertain the real mechanism behind fracture damage due to residual fluid and to find remedies to achieve objectives of economic production from hydraulic fracturing. Experimentally, they found the relation between the ratios of filter cake thickness to fracture width, to clean up time. It was also confirmed that this residue only forms an internal filter cake and does not leak off in to the formation. The flow initiation gradient was also linked to the static yield of the residue and proppant pack permeability and porosity.

Experimental investigation of residual fluid damage/removal process

Several experimental investigations have also been done to understand the hydraulic fracture damage mechanism and cleanup of residual fracturing fluid[12, 22]. The problem of residual fluid damage is associated with the use of polysaccharides based hydraulic fracturing fluids; one of the oldest choice for hydraulic fracturing. The reputation of polysaccharides as fracturing fluid, that may include guar, guar derivative

(HPG), and cellulose derivatives etc.[23], is based on their solubility at low temperatures and good thermal stability. The most important contribution of polysaccharides is the ability to serve as gelling agent in fracturing fluid. Gelling property is controlled through cross linking polysaccharides with different cross-linkers. Cross linking not only increases the shear viscosity but the size of the structure also increases. High viscosity of the cross-linked fluid enables it to carry proppant up to the end of the fracture; that proppant will keep the fracture open after the pumping stops. However, the size contrast between the pore throat and fluid structure causes filtration and a residue is left out at the fracture face. Several method have been reported to quantify residual fluid clean up.

Marpaung et al. [24] measured the cleanup using “dynamic fracture conductivity test”, and reported that high initial gas influx and presence of breaker increases cleanup efficiency. Bazin et al. [25] conducted special core analysis to ascertain the damage mechanisms associated with residual fluid in tight gas reservoirs. High water relative permeability compared to gas was reported as the most detrimental; and that the residual fluid did not induce any significant damage.

Ayoub et al [21, 26] using a conductivity cell, investigated efficient ways to utilize breaker to improve cleanup. Encapsulated breaker was inserted into the residual fluid directly, was found useful in degrading the residual fluid to a very low viscosity value.

Gdanski et al[27] conducted a series of rheological measurements for HPG fluids, with various molecular weight & concentration. The effect of temperature on the shear behavior of these fluids was also measured. Based on these measurements a model is proposed to calculate the viscosity of unbroken residual fluid. Author of this dissertation, has not come across any other published work that can estimate the viscosity of unbroken residual fluid.

Recently, it has been suggested that instead of using large polymeric molecules of polysaccharides, viscoelastic surfactant based fluid should be used to avoid filtration [28]. However, the size of these surfactants based structures (micelles) is very small and a high leak can’t be avoided. Most recent research has addressed this drawback by crosslinking micelles with inorganic nanoparticles[29]. The resulting pseudo cross-linked structure avoids high leak off and form a pseudo filter-cake that can easily be degraded with internal breaker system. This system is therefore reported as less damaging to formation permeability and fracture conductivity[29]. Crews at el [30]reported that as high as 90% of propped fracture conductivity can be preserved using pseudo cross-linked surfactant based fluids.

Highlights of literature review

In tight gas reservoirs,

- Economic production is dependent on the effective fracture length and fracture conductivity.
- Several factors can contribute to damaging the performance of hydraulic fractures, both inside and in the vicinity of fracture. However, the damage inside the fracture is most lethal.
- In the vicinity of the fracture, leaked off fluid may affect gas flow due to change in relative permeabilities and capillary pressure.

- Due to high leak off, the filtered fluid only resides inside the fracture with a very low breaker concentration. Rheology of residual fluid is hard to estimate. History matching shows that the static yield of residual fluid may increase up to 20 times that of the injected fluid.
- Among all factors the residual fluid is the most lethal to fracture performance. It can reduce gas recovery by 30% and can slow down initial production rates as high as 80%.
- Fracture cleanup is affected by the relative thickness of residual fluid to that of fracture width. Cleanup times increases with the increase in the thickness of residue.
- Fracture should be designed for high conductivity. Higher conductivity helps in cleaning up the residual fluid.
- To resolve the problem of low breaker concentration in the residue some arrangements should be made to inject breaker directly in to the residue.
- Using surfactant based fracturing fluids residual cake formation can be avoided, but the proppant carrying capacity of such fluids may not be sufficient.

CHAPTER III

MODELING RESIDUAL FLUID CLEANUP IN HYDRAULIC FRACTURES DESCRIPTION AND FORMULATION

Model description

We assumed a rectangular shaped, bi-wing, hydraulic fracture in the center of a dry gas reservoir. Hydraulic fracture is considered as in a plugged state, i.e. entirely filled up with filtered residual fluid, post hydraulic fracturing treatment, as shown in Figure 3.

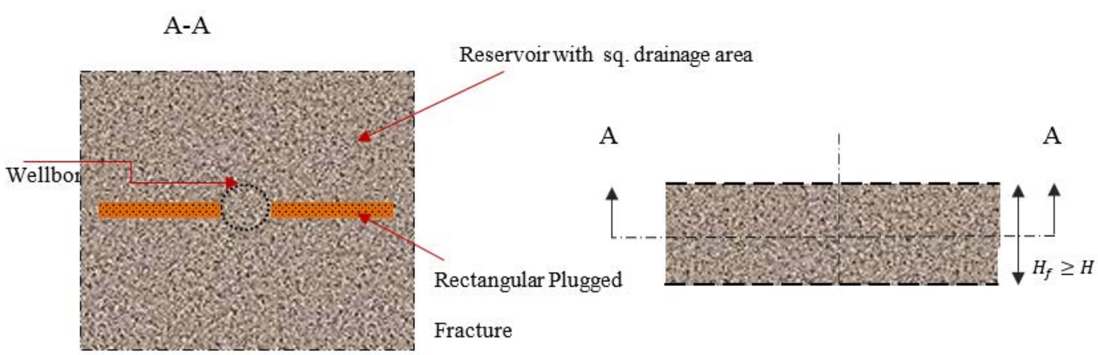

Figure 3. Schematic of reservoir and hydraulic fracture used in this model (not to scale).

Residual fluid in the hydraulic fracture is considered as a non-Newtonian fluid that is assumed to follow Herschel Bulkley fluid model, as shown in Figure 4. The gas is a Newtonian fluid.

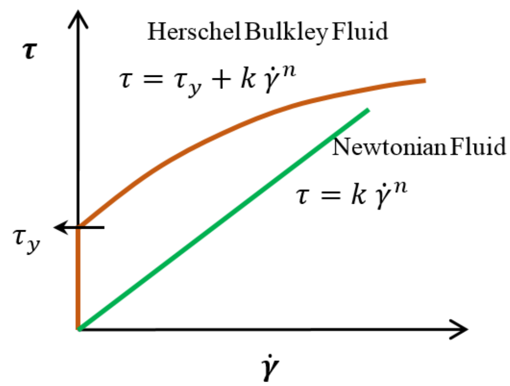

Figure 4. Non-Newtonian (Hershel-Bulkley) and Newtonian fluid shear behavior

Cleanup is perceived as a displacement problem; displacement of a non-Newtonian fluid by means of a Newtonian fluid flow, inside the hydraulic fracture. A simple analytical model will be derived to quantify cleanup with time using following assumptions.

Assumptions

- Hydraulic fracture is represented by a system of (2-10) flow channels, bounded by parallel plates. The sum of the individual width is equal to the width*porosity product of the hydraulic fracture. Length of plate is same as the half length of fracture.

- Residual fluid (filter cake) rheology is described by the Herschel Bulkley model. The filter cake is considered homogenous.

- Uniform pressure gradient in the plane of the fracture that causes one dimensional flow. Therefore, only the horizontal component of velocity is considered.
- At time zero the entire fracture is filled with residual fluid.
- Cleanup is quantified in terms of cleaned up width of the fracture, as the length and the height of each cleaned up width will be same as that of fracture.
- After initial cleanup gas will flow from reservoir to fracture. Residual fluid (next to the plate) and gas from reservoir (in the center of two parallel plates) will flow concurrently.
- The fluids are immiscible. There is no mass exchange between the gas and residual fluid.
- No adsorption, sorption or any other interaction of fluid and rock is considered here.
- For sake of simplicity, Pseudo steady state is assumed in the reservoir during the entire production period.

Hydraulic fractures are mostly modeled assuming a uniform rectangular shaped block. The flow starts from the face of the fracture rather than the tip of the fracture. Here we assumed the flow starts from the tip; this assumption needs to be rectified in the future.

Most recent result from JIP showed that the influence of damage caused by the residual fluid is lethal compared to the damage of the filtered fluid in the vicinity of the fracture. Therefore the walls are considered impervious.

Since the objective of this work is to quantify the cleanup cause by the available energy from the reservoir, we assumed that the residual fluid was non-reactive.

Herschel Bulkley model, that shows fluid behavior under steady shear, is selected. This selection is based on the literature survey, which illustrates highly concentrated gel residue inside the fracture requires a minimum pressure (shear) gradient to start flowing. While flowing, the shear stress is high at the wall, and decreases towards the center of the flow. It is likely that the value of shear stress become so small that the fluid resistance to flow resembles a solid (un-yielded plug). This is another reason that may replicate the situation of residual fluid in fractures, when chunks of fluid may become immobile and need enough pressure drop to be displaced like a solid.

In the author's view, this is not the only constitutive model that can estimate the behavior of residual fluid. Another approach would be to consider polymer rich fluid behavior possessing both viscous and elastic properties. Measured rheological properties of such fluids under oscillatory shear will be different from that of the steady shear (e.g. shear thinning Herschel Bulkley fluid). But this would require complete rheological measurement of polymer rich residual fluids.

Literature review shows that usually a uniform thickness of residual fluid is estimated based on flow back quantity or the experimentally determine filtered fluid residing on the fracture surface. That approach results in an unrealistic short clean up time. Therefore, in this work it is assumed that initially hydraulic fracture is entirely filled with polymer rich residual fluid. A separate equation is used to calculate initial clean up.

In this chapter we will first derive a flow equation to quantify for initial cleanup of residual fluid. Later a set of equation is derived for both the gas and residual fluid flow. These equations are derived while simultaneously solving constitutive equations (for gas and residual fluid) with Navier-Stokes equation.

The model is than combined with inflow performance equation of the fractured reservoir to link pressure drop in the reservoir to that in the fracture.

Finally, the model will be used to estimate gas flow from hydraulically fractured reservoir in the presence of residual fluid using several scenarios.

Model to quantify startup of residual fluid cleanup

For easier understanding, we introduce the equations for the case, when the porous material fracture is represented by one flow channel. However, in actual calculations we used 2-10 flow channels. In order to obtain the equation to quantify for initial cleanup, the derivation starts with a fixed volume of residual fluid equal to the volume of the fracture, i.e. the product of the area of the plate and the distance between the two plates, as shown in Figure 5.

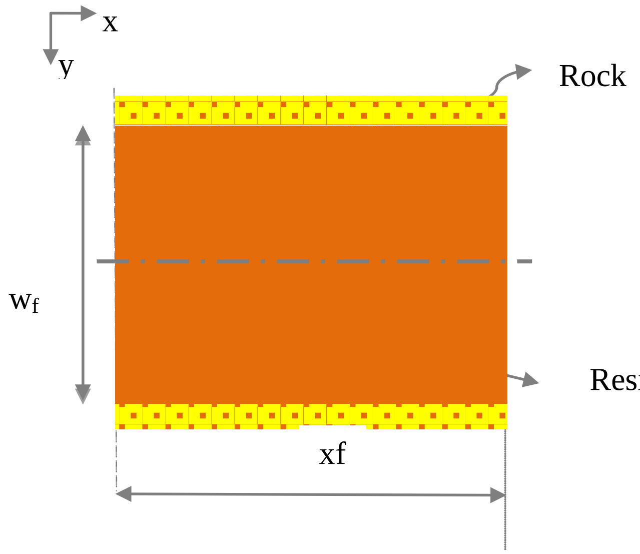

Figure 5. Physical model used to derive initial cleanup equation. (Fracture is entirely filled with hb fluid.)

Boundary conditions used to derive equation for initial cleanup are:

1. Single phase flow, with no slip at the wall @ $y = 0, \quad u_{hb} = 0$
2. In the presence of a plug @ $y = s \ , \gamma_{hb} = 0 \ or \ \tau_{yx,hb} = \tau_Y$

Herschel Bulkley (hb) model describes the flow behavior in terms of three parameters given as equation (1).

$$\tau_{yx,hb} = \tau_y + K\ (u_{hb}{}'[y])^n \qquad (1)$$

In Herschel Bulkley model τ_y is the minimum value of shear stress that is required for the inception of flow. Beyond this value the fluid rheology follow as of a power law fluid, as shown in Figure 4. K is the consistency index. And the value of flow behavior index (n) in this case is mostly less than 1, which shows the shear thinning behavior of the fluid. $\gamma_{hb}$is the value of shear rate. $\gamma_{hb} = 0 \; if \; \tau_{yx,hb} \leq \tau_y$ and fluid will behave like a semi solid.

Force balance is given as equation (2).

$$\tau_{yx,hb} = -\left(\frac{\partial p}{\partial x_f}\right) y \tag{2}$$

Solving equation (1) and equation (2) using the above boundary condition 1, we get the equation for the velocity of (hb) fluid, given as equation (3).

$$u_{hb}[y] = \frac{n\left(\frac{\partial p}{\partial x_f}\right)^{\frac{1}{n}}}{(1+n)K^{\frac{1}{n}}}\left(-\left(\frac{w_f}{2} + \frac{\tau_y}{\left(\frac{\partial p}{\partial x_f}\right)}\right)^{1+\frac{1}{n}} + \left(y + \frac{\tau_y}{\left(\frac{\partial p}{\partial x_f}\right)}\right)^{1+\frac{1}{n}}\right) \tag{3}$$

Using boundary condition 2,

$$s = -\frac{\tau_y}{\left(\frac{\partial p}{\partial x_f}\right)} \tag{4}$$

Flow rate of hb fluid leaving the fracture can be quantified using equation (5)

$$q_{hb} = 2H_f \int_0^s u_{hb}[s]dy + 2H_f \int_s^{wf/2} u_{hb}[y]dy \tag{5}$$

Applying the conditions we get the initial flow rate of residual fluid from hydraulic fracture, as given in equation (6). The flow rate will be dependent on the available pressure gradient and the resistance of the residual fluid. In case of high resistance and lower pressure gradient hb fluid may not flow at all.

$$q_{hb} = 2H_f\, s \frac{n\left(\frac{\partial p}{\partial x_f}\right)^{\frac{1}{n}}}{(1+n)K^{\frac{1}{n}}}\left(\frac{w_f}{2} - s\right)^{1+\frac{1}{n}}\left(-1 + \left(-1 + \frac{n}{(2n+1)}\right)\left(\frac{w_f}{2} - s\right)\right); \quad if\ \left(\frac{\partial p}{\partial x_f}\right) > \frac{\tau_y}{\frac{w_f}{2}} \tag{6}$$

$$q_{hb} = 0;\ if\ \left(\frac{\partial p}{\partial x_f}\right) < \frac{\tau_y}{\frac{w_f}{2}}$$

Model to quantify subsequent cleanup of residual fluid and gas production

After initial cleanup gas will start flowing into the hydraulic fracture from the reservoir. Now for the simultaneous flow of gas and residual fluid, as shown in Figure 6, we need another set of equation.

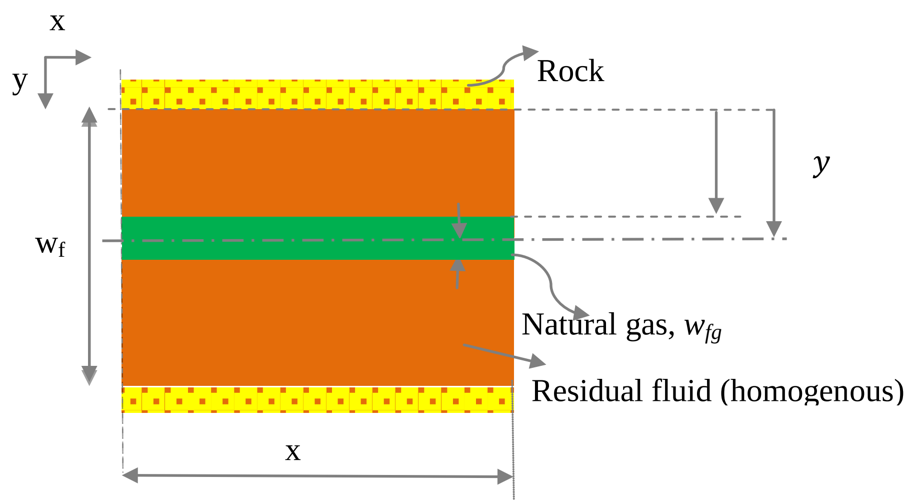

Figure 6. Physical model used to quantify the concurrent flow of residual fluid and gas.

To derive these equations following boundary conditions are used here:

1. No slip condition for hb fluid at the wall i.e. $@\ y = 0,\ \ u_{hb} = 0$

2. at the interface of two fluids $@\ y = \frac{w_f}{2} - w_{fg},\ \ u_{hb} = u_{g},\ \ \tau_{yx,hb} = \tau_{yx,g}$

3. At the center of the channel the stress is zero and the gas velocity is maximum:

$@\ y = \frac{w_f}{2}\ ,\gamma_g = 0\ or\ \tau_{yx,g} = 0$

Rheology of residual fluid is described through Herschel Bulkley model as given in equation (1):

$$\tau_{yx,hb} = \tau_y + K\,\gamma_{hb}^n$$

For gas, Newtonian fluid is used to describe its rheology, given as equation (7).

$$\tau_{yx,g} = \mu_g\,\gamma_g = \mu_g\frac{du_g}{dy} \qquad (7)$$

Where, μ_g is the gas viscosity and γ_g is the shear rate.

The governing momentum equation for this unidirectional flow is

$$\left(\frac{dp}{dx}\right)_f = \left(\frac{d\tau_{yx}}{dy}\right) \tag{8}$$

Note: Here $\left(\frac{dp}{dx}\right)_f = \left(-\left(\frac{dp}{dx}\right)\ \right)$assumed just for calculations.

The total effective viscosity in case of Herschel Bulkley fluid can be calculated as:

$$\mu_{eq} = \frac{\tau_y}{\gamma_{hb}} + K\gamma_{hb}^{n-1} \tag{9}$$

Using equations (7) and (9), equation (8) becomes

$$\left(\frac{dp}{dx}\right)_f = \frac{d}{dy}\left(\mu_{eq}\frac{du_{hb}}{dy}\right)\ and\ \left(\frac{dp}{dx}\right)_f = \frac{d}{dy}\left(\mu_g\frac{du_g}{dy}\right) \tag{10}$$

Integrating equations given as (10), we get the equations for the velocity of hb fluid and gas:

$$u_{hb}[\mathrm{y}] = \mathrm{B} + \frac{n\left(\mathrm{A}\ K\ n + y\ \left(\frac{dp}{dx}\right)_f\right)^{1/n+1}}{K^{\frac{1}{n}}(1+n)\left(\frac{dp}{dx}\right)_f} \tag{11}$$

$$u_g[\mathrm{y}] = \mathrm{C} + \mathrm{D}\ y + \frac{y^2\ \left(\frac{dp}{dx}\right)_f}{2\ \mu_g} \tag{12}$$

Equations (11) and (12) can be solved using the boundary conditions. The volumetric flow rate of both fluids from one wing of fracture can then be calculated using

$$q_{hb} = 2H_f \int_0^{\frac{w_f}{2} - w_{fg}} u_{hb}[y]\, dy \tag{13}$$

$$q_g = 2H_f \int_{\frac{w_f}{2} - w_{fg}}^{\frac{w_f}{2}} u_g[y]\, dy \tag{14}$$

Based on the discussion above, the simultaneous flow of 'hb' fluid and gas can be simplified further in to three flow scenarios while considering the competing forces at the plane of interface of two fluids,

$$flow\ driving\ force = 2\, w_{fg} dp\ ,$$

$$flow\ resisting\ force = 2\, \tau_y dx$$

Scenario 1: $\left(\frac{\partial p}{\partial x}\right)_f > \frac{\tau_y}{w_{fg}}$

Driving force has overcome the resistance force completely. No un-yielded center plug will be present, or a very little resistance force is present.

$$q_{hb} = \frac{2 * H_f * K^{-1/n}\, n * \tau y^{2+\frac{1}{n}}}{\left(\frac{\partial p}{\partial x}\right)_f^2 * (1+n)(1+2n)} \left(n \left(\left(\frac{\partial p}{\partial x}\right)_f - \frac{\tau_y}{w_{fg}} \right)^{2+\frac{1}{n}} \right.$$

$$+ \left(\left(\frac{\partial p}{\partial x}\right)_f - \frac{2 * \tau_y}{w_f} \right)^{1+\frac{1}{n}} \left(n \right. \tag{15}$$

$$\left. \left. + \frac{\left(\frac{\partial p}{\partial x}\right)_f (-2w_{fg} - 4w_{fg}n + w_f + nw_f)}{2\,\tau_y} \right) \right)$$

$$q_g = \frac{w_{fg} * H_f \left(\frac{K}{\tau_y}\right)^{-\frac{1}{n}}}{3\,\mu_g} \left(2\left(\frac{\partial p}{\partial x}\right)_f w_{fg}^2 \left(\frac{K}{\tau_y}\right)^{\frac{1}{n}} \right.$$

$$+ \frac{6\,n\,\mu_g\,\tau_y}{\left(\frac{\partial p}{\partial x}\right)_f (1+n)} \left(-\left(\left(\frac{\partial p}{\partial x}\right)_f - \frac{\tau_y}{w_{fg}} \right)^{1+\frac{1}{n}} \right. \tag{16}$$

$$\left. \left. + \left(\left(\frac{\partial p}{\partial x}\right)_f - \frac{2 * \tau_y}{w_f} \right)^{1+\frac{1}{n}} \right) \right)$$

Scenario 2: $\left(\frac{\partial p}{\partial x}\right)_f \le \frac{\tau_y}{w_{fg}}$, $\left(\frac{\partial p}{\partial x}\right)_f > \frac{\tau_y}{\frac{w_f}{2}}$

Driving force has overcome the resistance force**;** both the yielded and the un-yielded center plug will be displaced. Resistance to flow is higher than flow scenario1.

$$q_{hb} = \frac{H_f * K^{-1/n}\, n}{\left(\frac{\partial p}{\partial x}\right)_f^2 * (1+n)(1+2n)} \left(\left(\left(\frac{\partial p}{\partial x}\right)_f - \frac{2 * \tau_y}{w_f}\right)^{1+\frac{1}{n}} \left(\left(\frac{\partial p}{\partial x}\right)_f * \left(-2w_{fg} - 4w_{fg}n + w_f + nw_f\right) + 2\, n\, \tau_y\right)\right) \tag{17}$$

$$q_g = H_f \left(\frac{2\, \left(\frac{\partial p}{\partial x}\right)_f\, w_{fg}^3}{3\, \mu_g} + \frac{2^{-\frac{1}{n}}\, n\, w_{fg}\, K^{-\frac{1}{n}} \left(\left(\left(\frac{\partial p}{\partial x}\right)_f w_f - 2 * \tau_y\right)^{1+\frac{1}{n}}\right) \tau_y}{\left(\frac{\partial p}{\partial x}\right)_f\, (1+n)} \right) \tag{18}$$

Scenario 3: $\left(\frac{\partial p}{\partial x}\right)_f \leq \frac{\tau_y}{w_{fg}}$, $\left(\frac{\partial p}{\partial x}\right)_f \leq \frac{\tau_y}{\frac{w_f}{2}}$

Resistance force is very high, the residual (hb) fluid will not move at all. Resistance to hb fluid flow is highest in this case.

$$q_{hb} = 0 \tag{19}$$

$$q_g = \frac{2\ H_f \left(\frac{\partial p}{\partial x}\right)_f\ w_{fg}^3}{3\ \mu_g} \tag{20}$$

The cleanup/production model

From the literature review of several sources, it appears that a higher conductivity fracture should contribute positively in cleaning up the residual fluid. Therefore, in this section we will utilize the definition of infinite conductivity to estimate the productivity index of a hydraulically fractured reservoir, and its effect on gas recovery. However, such an infinitely conducive fractured reservoir is only theoretically possible. The production potential of such a reservoir is calculated as:

$$PI = q_g \frac{2\pi k_{res} H}{\overline{\beta_g}\,\overline{\mu_g}} J_{D,inf} = \frac{q_g}{\Delta p_{res}} \tag{21}$$

Here, $J_{D,inf}$ is the dimensionless pseudo-steady state productivity index of an infinitely conductive fracture of the same size in the same reservoir.

For the purpose of calculation we utilized the above production potential (i.e. PI) of infinitely conductive hydraulically fractured reservoir to describe the deliverability of gas from the reservoir to the fracture. In this hypothetical reservoir, with a maximum production potential, we will consider a bi-wing fracture that is initially filled with (post hydraulic fracturing) residual fluid. The main goal here is to show the cleanup of this bi wing hydraulic fracture by the inflow of gas, and to understand the reason of retained fluid even after years of production.

In the preceding sections, the equations to quantify the flow rates of residual fluid and gas under the effect of a given pressure gradient are presented. We now will link the performance of the reservoir to the hydraulic fracture residual fluid cleanup process.

Using the hypothetical, infinitely conductive fracture, the pressure drop inside the reservoir can be calculated from the available inflow equation:

$$\Delta p_{res} = \frac{q_g}{PI} = \frac{q_g}{\frac{2\pi k_{res} H}{\overline{\beta_g}\,\overline{\mu_g}} J_{D,inf,}} \tag{22}$$

$$\overline{\beta_g}, \overline{\mu_g} \text{ are calculated at,} \qquad p = \frac{\overline{p} + pwf}{2}$$

The pressure gradient inside a fracture is that part of the available drawdown that is not consumed by the reservoir as given in equation (23), also shown as a sketch in Figure 7.

$$(\partial p)_f = (\bar{p} - p_{wf} - \Delta p_{res}) \tag{23}$$

Subsequently, within a first order approximation, the pressure gradient in 1 wing of the fracture is given in equation (24):

$$\left(\frac{\partial p}{\partial x}\right)_f = \frac{\bar{p} - p_{wf} - \Delta p_{res}}{x_f} \tag{24}$$

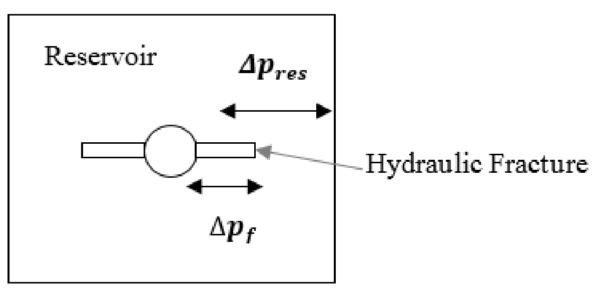

Figure 7. Sketch (not to scale) showing the pressure drop inside the system.

The additional pressure drop in the fracture will be a function of the production rate and the clean-up-state of the fracture. Therefore, the total dimensionless productivity of the system will be always less than the $J_{D,inf,}$.

$$J_{D,inf} = \frac{1}{ln\frac{r_e}{x_f/2} - \frac{3}{4}} \tag{25}$$

though, Prats warned that the equation (25) is valid only if the fracture penetrates less than half of the reservoir. The infinite conductivity productivity index for a fracture with $x_f > x_e/4$ can be obtained, for instance, from the Frac-PI calculator of Romero and Valko[31].

In this research we will consider $x_f = 0.4\, x_e$. For such a fracture half length, the dimensionless productivity index of an infinite conductivity fracture is already near to the theoretically maximum, i.e. $J_{D,inf,} = \frac{6}{\pi} \sim 1.909$.

Methodology to quantify residual fluid cleanup

Startup of residual fluid cleaning

The initial flow rate of residual fluid from hydraulic fracture is positive only, if $\left(\frac{\partial p}{\partial x}\right)_f > \frac{\tau_y}{\frac{w_f}{2}}$. Therefore, initial flow rate (q_{hb}) is calculated using equation (6) whereas, the available pressure gradient is calculated using equation (26).

$$\left(\frac{\partial p}{\partial x}\right)_f = \frac{\bar{p} - p_{wf}}{x_f} \tag{26}$$

Since no gas can leave the reservoir in the presence of a completely blocked fracture, the full drawdown is available to be consumed by the hydraulic fracture. From the hb fluid flow rate (q_{hb}) we can quantify the amount (w_{fg}) of residual fluid cleaned up during an initial time step (Δt), using material balance (here Δt is taken as 1 minute).

$$w_{fg} = \frac{q_{hb} * \Delta t}{x_f * H_f * 2} \tag{27}$$

During this time no gas is produced. Also, the calculated cleaned up thickness (w_{fg}) is considered uniform throughout the length of the fracture. It is important that the full drawdown must provide enough pressure-gradient to overcome the yield stress. If this criterion is not met, the cleaning process does not start and the fractured well "dies" without ever producing.

Simultaneous flow of gas & hb fluid and further residual fluid cleanup

Now we consider the simultaneous flow of gas and residual fluid in the hydraulic fracture. From the available drawdown and cleaned up width,w_{fg}, we calculate the pressure gradient inside one wing of the fracture, $\left(\frac{\partial p}{\partial x}\right)_f$ using equation (28).

$$\left(\frac{\partial p}{\partial x}\right)_f = \frac{\bar{p} - p_{wf} - \frac{q_g}{\frac{2\pi k_{res} H}{\overline{\beta_g}\,\overline{\mu_g}} J_{D,inf}}}{x_f} \tag{28}$$

where q_g is the total gas flow rate coming from the reservoir. It is assumed, that half of the total flow goes through one wing. This flow rate can be calculated using the set of equations developed in the preceding sections ((15) to (20)). From the available full drawdown and w_{fg} at the start of the period we calculate$\left(\frac{\partial p}{\partial x}\right)_f$, by solving equations (28) and the equation of q_g (from the set of the equation (15) to (20)) simultaneously.

With the resulting $\left(\frac{\partial p}{\partial x}\right)_f$ the flow rate of residual fluid q_{hb} leaving the fracture is calculated using equation of q_{hb} (from the set of the equation (15) to (20)).

Using the material balance of the hb fluid, we calculate the amount of residual fluid leaving the fracture and will determine the new uniform cleaned up width of the fracture w_{fg} using equation (27).

Updating average reservoir pressure

With the continuous withdrawal of gas average reservoir pressure will gradually decrease. Therefore, to correctly calculate the pressure gradient inside the fracture, the average reservoir pressure will be updated at the end of each production time period.

Gas material balance method is used to update average reservoir pressure, using equation (29).

$$\left(\frac{\bar{p}}{z}\right)_{new} = \left(1 - \frac{G_p}{OGIIP}\right)\left(\frac{\bar{p}}{z}\right)_i, \qquad OGIIP = AH\emptyset \frac{Sg}{Bgi} \qquad (29)$$

To determine the gas compressibility factor ‘z’, Dranchuk and Abou-Kassem correlation (1975) quoted by McCain (1990) is used. Since ‘z’ is a function of pressure, the above equation of material balance is simultaneously solved with the ‘z’ factor correlation to find average reservoir pressure $\bar{p}$. In the gas material balance equation G_p is the total produced gas at the end of any time period.

Cleanup in an infinite and limited conductivity hydraulic fracture

Following these four steps cleanup is quantified for two different cases of hydraulic fractures.

Case1: Hydraulic fracture with infinite conductivity

For this case we assume that the fracture is filled with a very large diameter proppant or that porosity inside the fracture is almost 1. Figure 8 shows the sketch of this case whereas the flow in the hydraulic fracture is depicted as a flow in a channel.

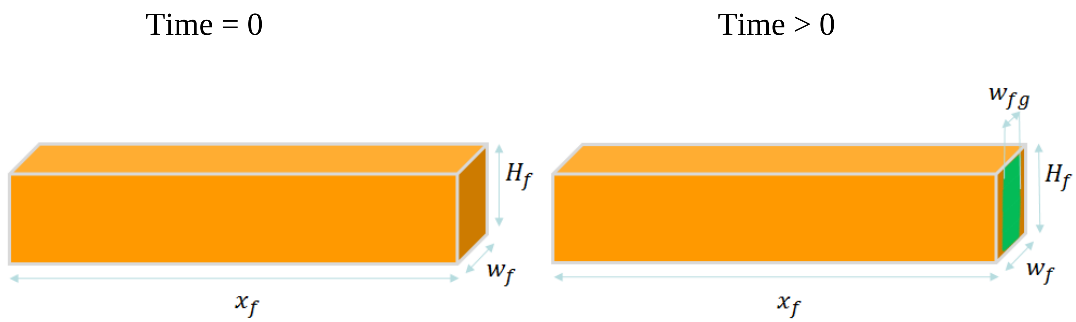

Figure 8. In a highly conductive fracture, cleanup is simulated as in a rectangular channel of same dimension as that of a hydraulic fracture. (In the beginning the entire fracture is filled with residual fluid (L), following cleanup gas is flowing in the cleaned up width ($\boldsymbol{w_{fg}}$) of the fracture (R))

Case2: Hydraulic fracture with limited conductivity

In this case the fracture is of limited conductivity and flow in the fracture is modelled as the result of flow through several parallel channels (Carman-Kozeny representation of porous media) with the additional condition that in each flow channel gas and hb fluid flow simultaneously. However, for simplicity the thickness of each layer is considered equal and uniform. Number of layers will depend on the width of fracture and proppant size. In Figure 9, flow in each layer is depicted as a flow in a set of parallel fracture of same size. Width of each layer can be calculated using equation (30).

$$width\ of\ each\ layer = \frac{\emptyset_p * w_f}{no.of\ layers} \tag{30}$$

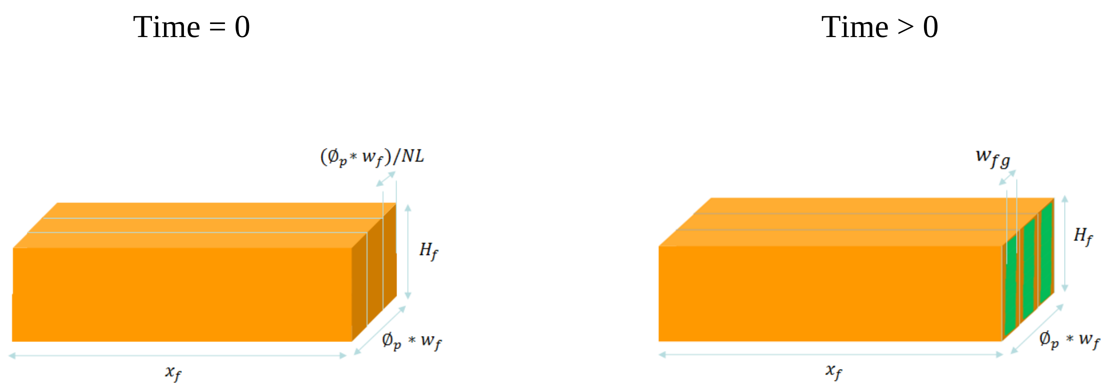

Figure 9. A limited conductive fracture is simulated as a bundle of several parallel rectangular channels of same dimension, following the concept of Carman-Kozeny. (In the beginning each layer is filled with residual fluid (L), following cleanup gas is flowing in the cleaned up width ($\boldsymbol{w_{fg}}$) of each layer (R))

For illustrative purposes we select a representative set of reservoir parameters, typical in the Cotton Valley formation [11]. The selection of this particular formation is made after the published field test data that showed only 35% of the injected polymer recovery during flow back from Cotton Valley[32]. This is lower than the recovery in another hydraulically fractured tight gas formation, Codell formation of Colorado, where the field data showed polymer recovery, in different wells within 48 hours of flow back, reached up to 24 % to 56%[15]. Permeability and porosity of Codell formation is similar to Cotton Valley, however the reservoir pressure is lower. Therefore we selected Cotton Valley as a model for this study.

In the next chapter we will use the published data of a hydraulically fractured well in the Cotton Valley formation, and will see the effects of different reservoir properties, hydraulic fracture dimensions and properties of the residual fluid on the cleanup time and gas recovery.

CHAPTER IV

RESULTS AND DISCUSSION

In this work several reservoir and hydraulic fracture parameters have been identified that effect residual fluid cleanup process. These factors include fracture width and half length, residual fluid rheology. In addition to this, reservoir parameters including average reservoir pressure, permeability, and drainage area that would affect the energy contribution from the reservoir are also included. The results are presented as two different cases. Case1 represents an infinite conductivity hydraulic fracture whereas the cleanup is quantified as the displacement of residual fluid by gas in a rectangular channel which has the same physical dimensions as of a hydraulic fracture. While case2 represents a limited conductivity fracture and the cleanup is quantified as the displacement of residual fluid by gas in a bundle of rectangular channels, to simulate the propped hydraulic fracture in the same manner described by Carman-Kozeny. In this case a hydraulic fracture is represented as a bundle of narrow flow channels, with similar uniform dimensions. Results from these two cases are presented and analyzed in this chapter.

Cotton Valley formation

For this study published data of Cotton Valley formation[18], a tight gas sandstone reservoir located in East Texas, is used. Properties of this low permeability and low porosity formation are listed in Table 1. For sensitivity analysis different values are selected for different properties/parameters. These values are listed in Table 2. All the inputs are used in Metric system for calculation purpose. All the equations are dimensionally balanced.

Table 1. Typical Cotton Valley formation data.

Absolute Permeability (md)	0.01
Porosity	7.2 %
Water saturation	38%
Gas gravity	0.65
Reservoir Pressure (psi)	5830
Reservoir Temperature (F)	270
Net Pay (ft)	40
Drainage Area (acre)	160
Fracture width (inch)	0.25
Fracture height (150ft)	150
Fracturing fluid	Zr crossed linked guar
Porosity of prop. Pack (20/40 sand)	31.5%

Table 2. Data for sensitivity analysis.

Yield stress of HB fluid (lbf/100ft2)	2 to 800
Consistency index (lbf/100ft2.min^n)	0.2 to 10
Exponent, n	0.4
Penetration ratio,Ix	0.8 ,0.7, 0.5
Fracture width (inch)	0.35,0.25,0.15
Drainage Area (acre), (assumed square)	160,120, 80, 40
$J_{D,inf}$	1.909
Pwf (psi)	10% of reservoir pressure
Average reservoir pressure (psi)	5830, 4830

Case1: Cleanup in a hydraulic fracture with infinite conductivity

Residual fluid flow in a hydraulic fracture simulated as flow through a rectangular channel with same dimensions as that of a fracture. In this case we assumed that the entire channel is filled with the residual fluid and no proppant porosity is considered here. Even though such an infinite conductivity fracture is not realistic, but it would help us understand the flow of residual fluid in case of poor proppant distribution and regions of lumps of residual fluid are present.

Effect of residual fluid (hb fluid) rheology

Very high values of yield stress were selected to see the effect of cleanup in a channel. Figure 10 show that very little cleanup occurs in case of very high value of yield and consistence index. After that, cleanup occurs gradually by a very small percent. This happen because initially in the hydraulic fracture available pressure gradient is high. With gradual cleanup, gas influxes and pressure drops gradually, until a stage comes when pressure gradient in fracture becomes almost constant, as shown in Figure 11.

If it is assumed that the flow rate of residual fluid leaving the channel is constant after the above initial cleanup of 12 minutes, the cleanup time for different values of static yield stress will differ greatly, provided all the other rheological parameter stay same in each case. Table 3 shows assumed values of rheological parameters and the effect on clean up time. Assuming that the initial gas flow rate is sufficient to clean up the entire fracture, very short clean up time is calculated. However, with very high yield stress the fluid cannot flow at all.

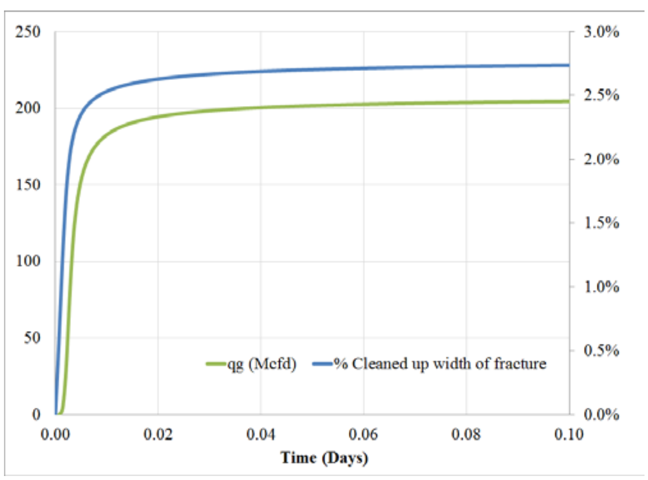

Figure 10. A very high total effective viscosity of residual fluid, will clean up a small portion and then the cleaned up width stays constant (or in other words the clean-up process stops prematurely).

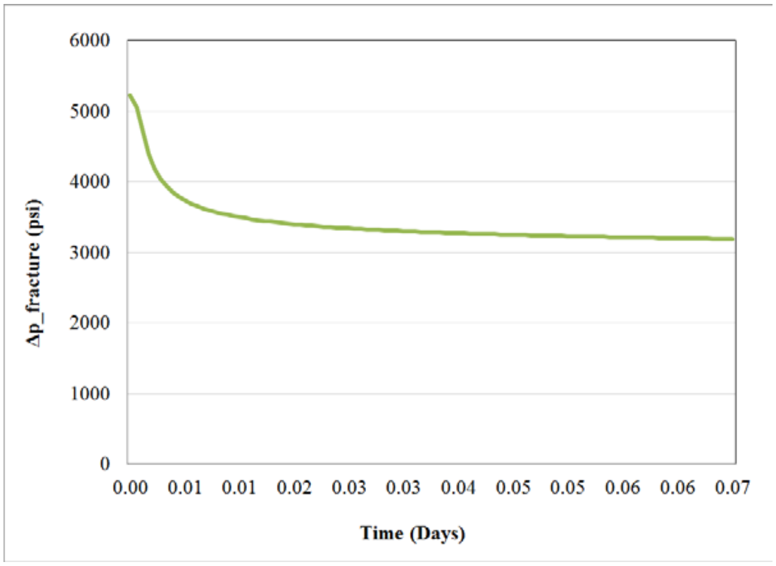

Figure 11. Pressure decline in fracture following cleanup in case1(page33).(τy=418 lbf/100ft^2, K=10 lbf/100ft^2.min^n. and n=0.4)

Table 3. Residual fluid cleanup time in an infinite conductivity hydraulic fracture in Cotton Valley.

$\tau_y\left(\frac{lbf}{100ft^2}\right)$	800	261	209	105	42
$K\left(\frac{lbf}{100ft^2}min^n\right)$, $n = 0.4$	10	10	10	10	10
Time for 100% fracture width Cleanup	No cleanup	97 days	1 day and 4 hrs.	15 hrs.	11 rs

Effect of hydraulic fracture dimensions

Effect of different fracture width and half-length are also investigated to analyze the effect on the cleanup time. For this high values of rheological parameters are used and the results are given in Table 4.

Table 4. Effect of fracture dimensions on cleanup. ($\boldsymbol{\tau_y}$ =260$\frac{\boldsymbol{lbf}}{\boldsymbol{100ft^2}}$, K=10$\frac{\boldsymbol{lbf}}{\boldsymbol{100ft^2}}\boldsymbol{min^n}$, n=0.4)

w_f	0.15 inch	0.25 inch	0.25 inch	0.15 inch
$I_x\left(=\frac{2x_f}{x_e}\right)$	0.8	0.8	0.7	0.7
Time for 100% fracture width cleanup	18.1 hrs.	97 days	19.7min	9.9 hrs.

Effect of reservoir parameters

Average reservoir pressure is a very important parameter to determine the available influx of gas from the reservoir. For the Cotton Valley formation changing the reservoir pressure changed the %cleanup and the rate of cleanup as well.

Table 5. Effect of average reservoir pressure on cleanup. ($\boldsymbol{\tau_y}$=260$\frac{\boldsymbol{lbf}}{\boldsymbol{100ft^2}}$, K=10$\frac{\boldsymbol{lbf}}{\boldsymbol{100ft^2}}\boldsymbol{min^n}$, n=0.4)

$\bar{p}$ (psi)	Time for 100% cleanup
5830	97 Days
4830	150 Days

Case2: Cleanup in a hydraulic fracture with limited conductivity

In this case the fracture is of limited conductivity and cleanup flow in a fracture is modeled as flow through several parallel channels. Considering the width of hydraulic fracture (w_f) and the diameter of the proppant we calculated the width and equivalent number of such rectangular channel-like fractures.

Effect of residual fluid rheology

The residual fluid is modeled as Herschel Bulkley fluid. Three parameters of this model n, K, and Ʈy are used for sensitivity analysis in the Cotton Valley formation. The transient cleanup and the subsequent gas recovery are presented here. Figure 12 shows the effect of static yield stress on the cleanup. Higher the static yield stress slower will be the cleanup process, Figure 12 & Figure 13. Compared to the flow in channel in previous case, the % cleanup is slower and quantitatively less in this case. It is observed that maximum cleanup occurs in the early times of the production and then becomes almost constant.

Flat plateau of constant % cleanup width and subsequently of production rate was observed after a brief production period. After few days of production in the limited conductivity fracture, 7 layer scheme the effect is shown as Figure 14& Figure 15. Once the gas starts flowing after initial cleanup, pressure starts dropping in the fracture therefore the subsequent gas flow rate is also dropping.

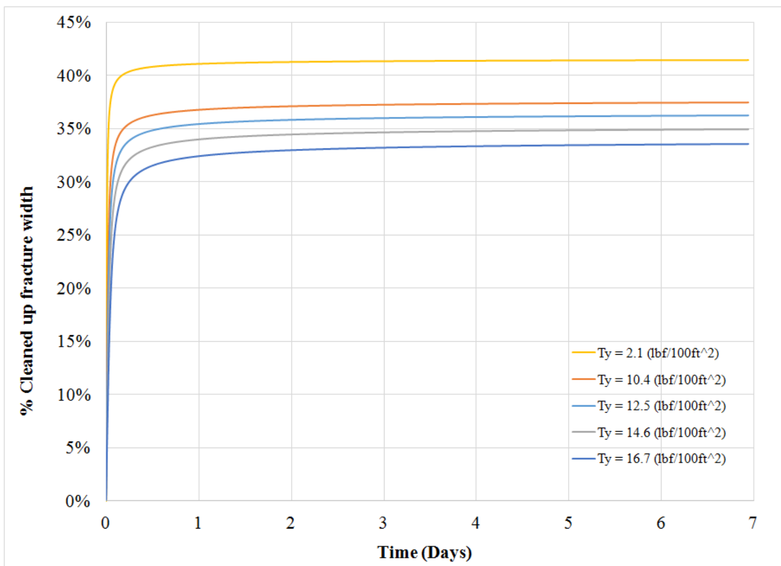

Figure 12. Slower cleanup is observed in limited conductivity fracture even with lower static yield stress of residual fluid. (K=0.2$\frac{lbf}{100ft^2}min^n$, n=0.4 in a 7 layer scheme)

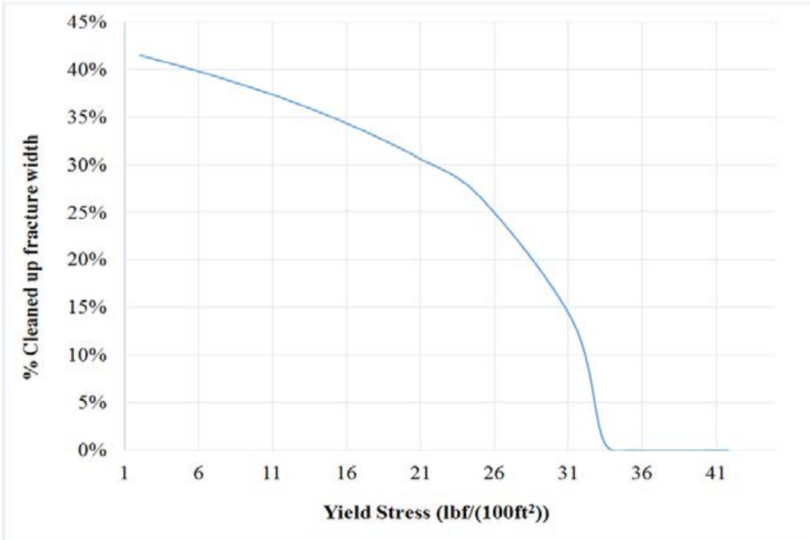

Figure 13. Effect of residual fluid yield stress on cleanup after two months of production. (K=0.5 $\frac{lbf}{100ft^2}\boldsymbol{min^n}$, n=0.4 in a 7 layer scheme)

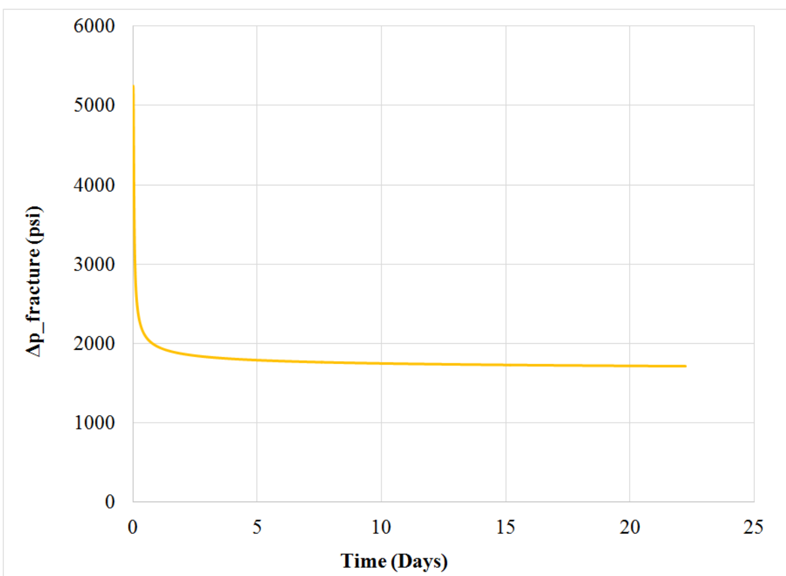

Figure 14. Typical pressure drop profile in hydraulic fracture during cleanup process. (Ʈy=11 $\frac{lbf}{100ft^2}$., K=0.2 $\frac{lbf}{100ft^2}\boldsymbol{min^n}$, n=0.4 in a 7 layer scheme)

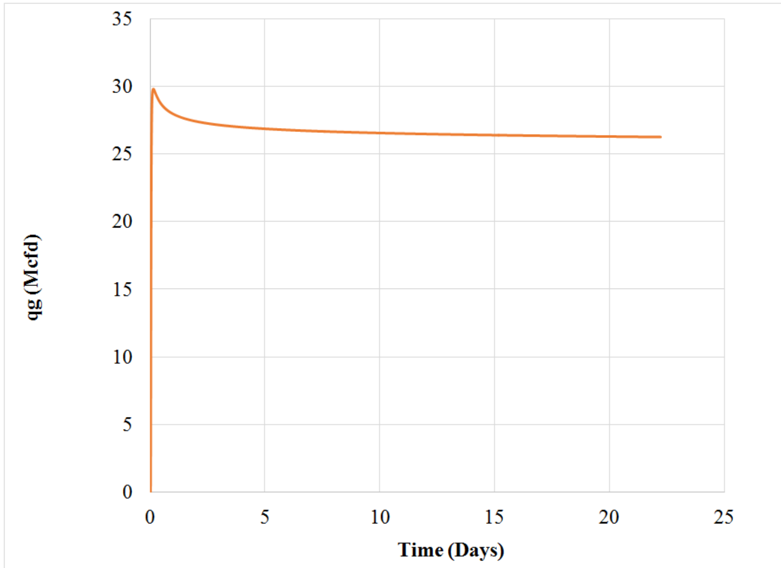

Figure 15. Typical production trend post hydraulic fracturing in a tight gas well; a flat production profile following a production peak. (Ʈy=11 $\frac{lbf}{100ft^2}$., K=0.2 $\frac{lbf}{100ft^2}min^n$, n=0.4 in a 7 layer scheme)

Consistency index, K, of Herschel Bulkley, can increase the total effective viscosity of the residual fluid. This affect is significant when the value of static yield stress of residual fluid is high, as shown in Figure 16.

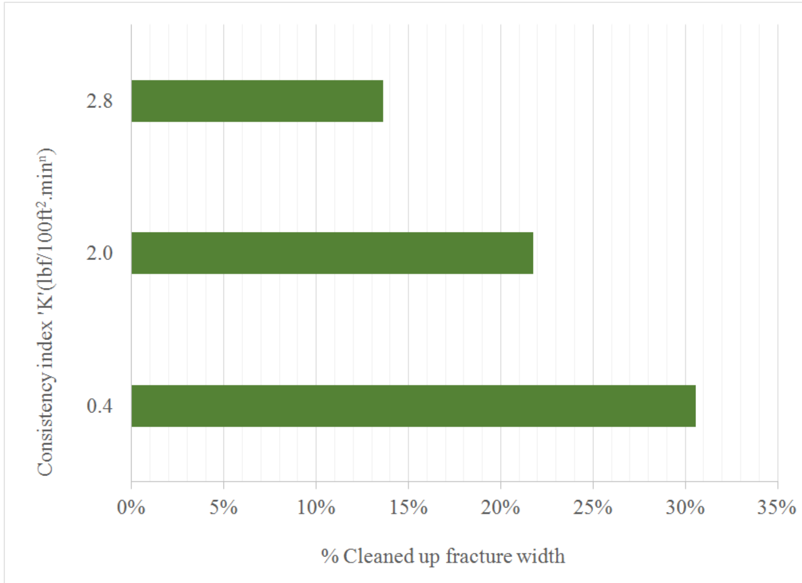

Figure 16. At higher yield stress, consistency index value affects % cleaned up width of fracture after 2 months of production. (7 layer simulation scheme. $\tau y=21 \frac{lbf}{100ft^2}$, n=0.4)

Effect of hydraulic fracture dimensions

In case2 the flow in fracture is simulated as flow through a bundle of thin channels or fractures. The thickness of these channels depends on the width of hydraulic fracture and the size of proppant. The smaller is the thickness of the channel longer is the time to clean up the restricted path, even if the total width is kept fixed.

Figure 17 shows this effect, whereas the no. of layers in each case is different and so is the thickness, the porosity is kept constant. As the width decreases the cleanup becomes difficult. The half length of the fracture was also checked to see the effect on cleanup. Longer the fracture length longer it will take to cleanup, as shown in Figure 18.

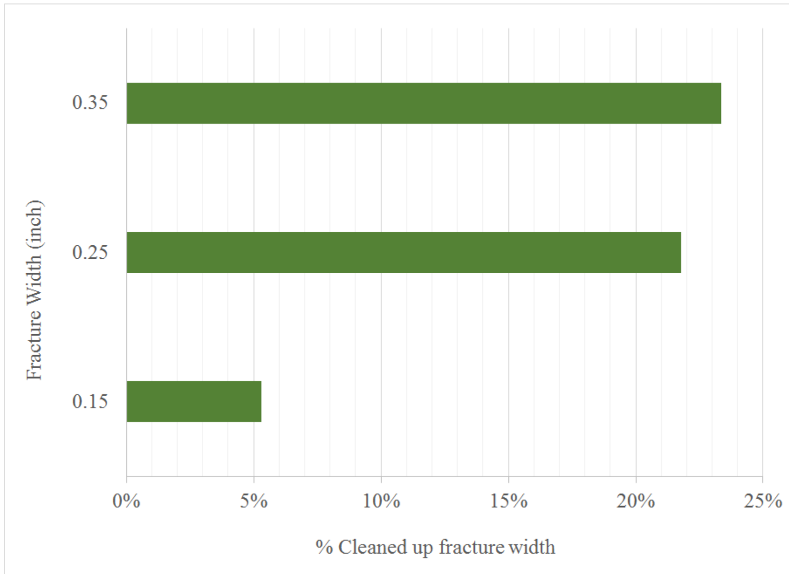

Figure 17. Effect of hydraulic fracture width on cleanup after two months of production. ($\tau_y=21\frac{lbf}{100ft^2}$, K=0.2 $\frac{lbf}{100ft^2}\boldsymbol{min^n}$, n=0.4, Ix=0.8 in a 7 layer scheme)

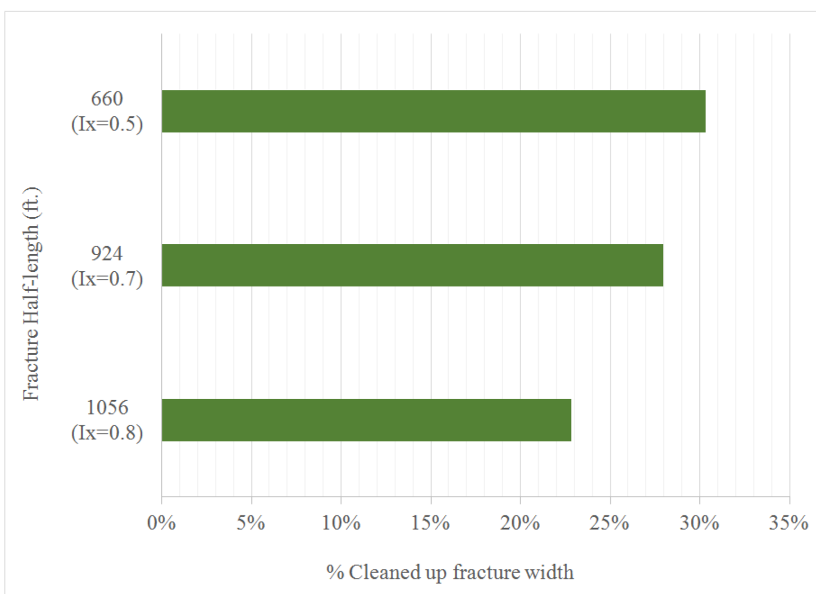

Figure 18. Effect of hydraulic fracture half length on cleanup after two months of production. ($\tau_y=21\frac{lbf}{100ft^2}$, K=2 $\frac{lbf}{100ft^2}\boldsymbol{min^n}$, n=0.4, wf=0.25 in, in a 7 layer scheme)

Effect of reservoir parameters

For same Cotton Valley formation sensitivity analysis is done on drainage area to check the cleanup behavior. Higher value of drainage area means that average reservoir pressure will decline at a lower rate and gradual cleanup will occur. However, small drainage area reservoir will deplete faster, rapid cleanup occurs and then stays almost constant. This behavior is shown in Figure 19 & Figure 20. Summary of this result is given in Table 6.

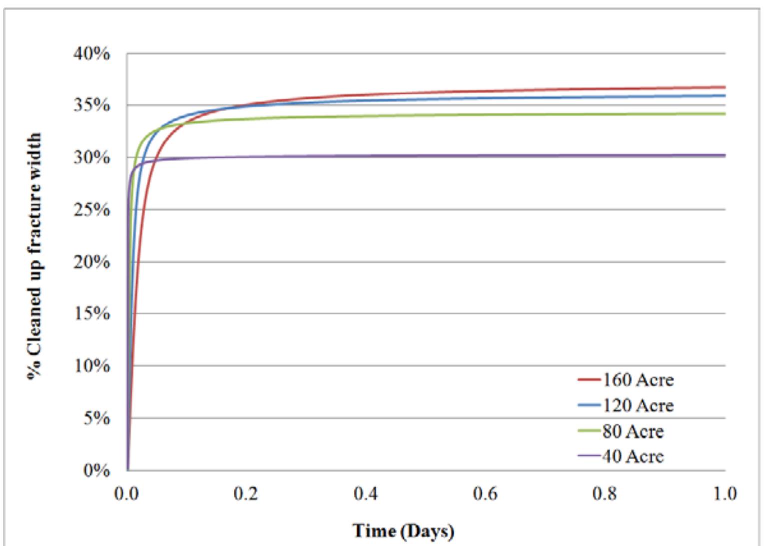

Figure 19. Fast depletion in small drainage area compared to large drainage area will lead to rapid but less clean up. (Here n=0.4, Ʈy=11$\frac{lbf}{100ft^2}$, K=0.2 $\frac{lbf}{100ft^2}min^n$=0.5, wf=0.25 inch, Ix=0.8 in a 7 layer scheme)

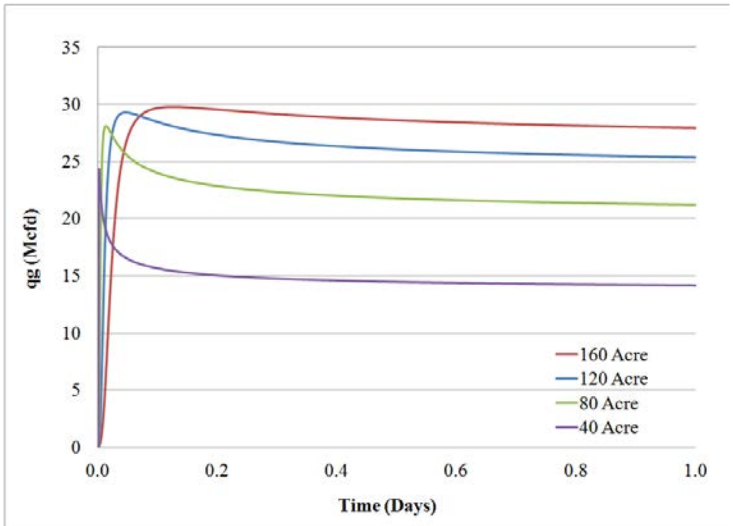

Figure 20. Effect of drainage area on production rate. (Here n=0.4, Ʈy=11$\frac{lbf}{100ft^2}$, K=0.2 $\frac{lbf}{100ft^2}min^n$=0.5, wf=0.25 inch, Ix=0.8 in a 7 layer scheme)

Table 6. Effect of drainage area on cleanup/gas recovery in Cotton Valley formation. (Here n=0.4, Ʈy=11$\frac{lbf}{100ft^2}$, K=0.2 $\frac{lbf}{100ft^2}min^n$=0.5, wf=0.25 inch, Ix=0.8 in a 7 layer scheme)

Area (Acre)	% Cleaned up width of fracture	GP (Mcf) @ the end of 60 days	qg(Mcfd) @ the end of 60 days
160	37.69%	11039.6518	25.9046
120	36.51%	9985.3635	23.37211
80	34.54%	8384.8706	19.58864
40	30.39%	5638.6894	13.12012

Reservoir permeability affects the mobility of gas from reservoir to hydraulic fracture which affects the cleanup of residual fluid. Effect of this parameter is given as Figure 21.

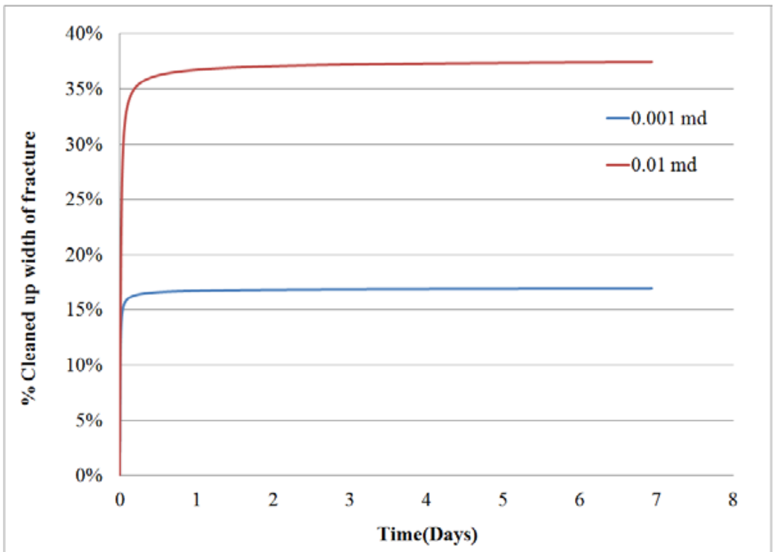

Figure 21. Effect of tight gas reservoir permeability on cleanup.

Following cleanup the productivity of limited conductivity fracture increases and later attains a flat plateau with premature termination of cleanup. Dimensionless productivity index (JD) shows that hydraulically fractured wells in the presence of residual fluid will gradually moves towards pseudo-steady state and JD value will remain less than 1. Figure 22 shows trend of JD in Cotton Valley formation.

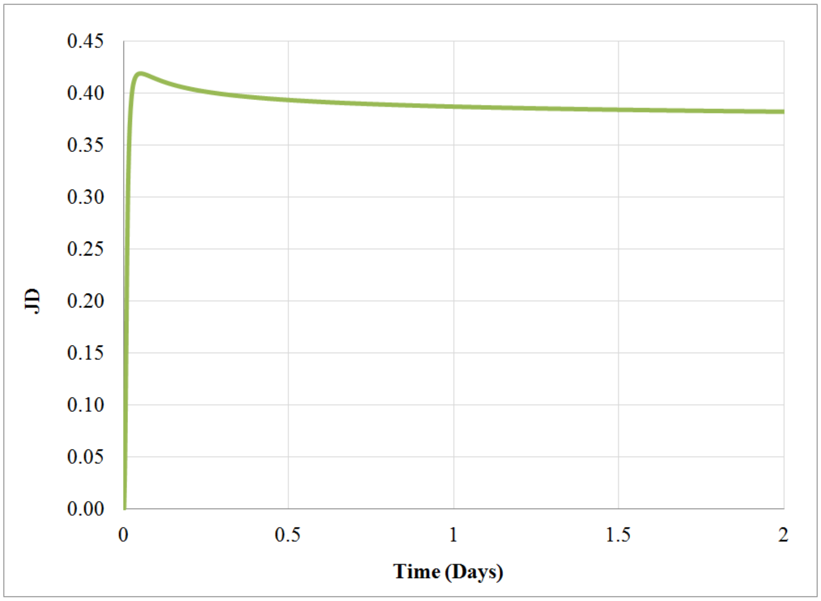

Figure 22. Dimensionless productivity index remains less than 1 in a damaged limited conductivity fracture. (Here n=0.4, Ʈy=11$\frac{lbf}{100ft^2}$, K=0.2 $\frac{lbf}{100ft^2}\boldsymbol{min^n}$=0.5, wf=0.25 inch, Ix=0.8 in a 7 layer scheme)

In this research an attempt is made to understand and quantify the cleanup process of residual fluid in hydraulic fractures. Through a simple mathematical model different scenarios of residual fluid cleanup are compared for a tight sandstone gas formation. From initial results it appears that understanding the residual fluid rheology is very important to quantify cleanup process. Every single parameter of the constitutive relation, i.e. Herschel-Bulkley fluid model that is used to simulate the rheology of residual fluid, affects the cleanup process. However the effect of static yield stress is the most significant. Cleanup is greatly influenced by the initial reservoir condition, drawdown and the conductivity of the fracture. Therefore, most of the cleanup happens in the early times of production, and following initial cleanup quantity of fluid leaving the fracture may become insignificant or may not happen at all. We are able to show that even when the reservoir is flowing at its full potential, the cleanup process may not be significant owing to conditions described above.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Residual fracturing fluid cleanup process, post hydraulic fracturing, in unconventional tight gas wells is quantified using the methodology described in previous chapters of this dissertation. The methodology used simple mathematical equations developed in Chapter III and a simple Excel-VBA code. A systematic approach is adopted to study the cleanup process by varying formation properties, available drawdown, fracturing fluid rheology, and hydraulic fracture dimensions. Results of this work are very stimulating, and would be very useful for engineers designing a hydraulic fracturing treatment in unconventional tight gas reservoir. Following are the main conclusions from this study:

a. In low permeability, low porosity unconventional tight gas reservoirs, filtration and retention of fracturing fluid, with a very low concentration of breaker, is unavoidable. Leak off of breaker substantially increases the undegraded polymer concentration in the retained fluid; therefore the rheology of fluid will be very different from that of the injected fluid.
b. In the absence of information about residual fluid rheology and thickness in the hydraulic fracture, it is observed that the cleanup is predominantly a combined effect of the thickness of residual fluid layers and yield stress that describes cleanup with available energy from reservoir.

c. Previous published results, that suggested an increase of 10- 20 times of static yield stress of residual fluid, might not be correct. In a typical Cotton Valley formation that showed 35% cleanup, previous estimated values of yield stress was 30 $\frac{lbf}{100ft^2}$, through history matching of field data. However, our results show that if only the residual fluid yield stress is responsible for production impairment, than this value can even be less than 20 $\frac{lbf}{100ft^2}$; if the residual fluid strength is 35 $\frac{lbf}{100ft^2}$; or above, it won't cleanup at all.

d. Once the cleanup starts and gas starts flowing in to the fracture, pressure drops both in the fracture and in the reservoir. With gradual decrease in available pressure cleanup starts reducing. Therefore, previous modeling approaches assuming a uniform thickness of residual fluid gives a short cleanup time. Contrary to this, the approach assuming a hydraulic fracture in plugged state with limited conductivity better describes the cleanup process. Further, it helped in explaining why in some cases cleanup happen slowly or may never happens it all.

e. Cleanup is dependent on the available reservoir energy that can overcome the flow resistance force in hydraulic fracture. Decreasing the reservoir permeability, reservoir pressure, drainage area and drawdown will decrease the reservoir force to cleanup. However, increasing fracture width, decreasing fracture half length, and efficient use of breaker can reduce the resistance to cleanup. On the other hand mobility contrast in reservoir and in the fracture can affect cleanup as well.

f. Comparing the cases of limited and infinite conductivity hydraulic fracture it is shown that the later will give an unrealistically short cleanup time. Also such an infinite conductivity hydraulic fracture is impossible to achieve realistically.

g. We suggest that in tight gas hydraulic fracture design should consider the cleanup mechanism as a constraint. In a given case, one may need to depart from the default optimum dimensions, if the clean-up would prove unfavorable and would not let to reach the optimum potential. Putting it into another perspective: clean-up behavior should be considered already quantitatively, when decision is made on the formulation of the fracturing fluid.

To further improve the outcome of this work, it is recommended that following should also be accounted to better understand the cleanup process and its effect on gas production.

a. Effect of water influx in initial cleanup

b. Effect of water blocking in gas-water flow

c. Effect of proppant crushing

d. Effect of variable rheology (static yield stress) along the width of fracture

e. Using more accurate description of the complex fluid rheology, including dynamic properties (such as G', and G''.)

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