Fracture-Matrix Flow Partitioning and Cross Flow: Numerical Modeling of Laboratory Fractured Core Flood

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Abstract: The contrast between hydro-mechanical behavior of the rock matrix and fracture network systems in fractured reservoirs results in complex flow regimes and flow partitioning between fracture and matrix systems which is affected by the In-situ stress regime in the reservoir. Fracture flow, Darcy law and free and porous media flow physics interfaces of Comsol subsurface flow module have been used in simulating a fractured core flooding test data to achieve a better understanding of fracture-matrix flow partitioning. The fracture flow interface was used along with Darcy's Law due to the capability to create fracture as a boundary within the model geometry. Alternatively, free and porous media flow interface was applied to validate the Darcy's law modeling results and analyze how the cross flow changes under overburden stress. Although there were discrepancies in the magnitudes obtained from the two physics, a fracture closure threshold and identical flow behaviors were detected in all simulations.

Keywords: Fracture-Matrix flow partitioning, Overburden stress, Cross flow.

1. Introduction

Achieving efficient fractured porous media models as mathematical representations of hydro-mechanical effects in fractured reservoirs in order to understand the flow behavior in this type of reservoirs, has always been a challenge. Presence of discontinuity features within the formation causes different permeability profiles and this tends to result in partitioning within the cumulative flux. This flow partitioning between rock matrix and the fracture channels – the contribution of overall flow through matrix porous rock and through adjacent more permeable fracture - is very important at all stages of reservoirs life cycle. At pre-development and drilling phase, flow partitioning will affect the reservoir fluids contacts and cause abnormal pressures. At the production stage again flow partitioning is a key consideration in completions selection and design and pressure maintenance planning. In the ultimate stages of the cycle flow partitioning would also be a key consideration to determine how much an enhanced recovery treatment such as a flooding can successfully sweep the unexploited regions of the reservoir.

Although so many scientific efforts have been made to illustrate flow (Lee et al., 2000), mass transfer (Reynolds and Kueper, 2001) and heat transfer (Wu et al., 2002) within fractured media, so many aspects of the flow partitioning between fracture and matrix and the cross flow between them in fractured petroleum reservoirs are still not fully understood.

Presence of the fractures as a source of stress disturbance in the intact formation bodies (Sanaee et al., 2010), demands coupling the stress-strain related physics to the dominating fluid flow physics in porous media. Some previous modeling efforts were made with the assumption that fractures are stable, and as a result, will not be affected by the prevailing stress regime (Akin and kovscek, 1998; Schembre et. al., 1998). However, a comprehensive study of fractured media is inevitably inter-related to stress investigations and the most practical models are those which are a combination of coupled hydraulic and mechanical effects.

Bai et. al., 1999 coupled analytical mechanistic modeling taking advantage of finite element simulations for fractured porous media. For these simulations porous media flow physics were used for both fracture and matrix. Recently, laminar single phase Navier-Stokes equations were used for fracture system and Darcy equations for porous medium in an attempt to incorporate fracture roughness into the flow models (Crandall et. al., 2010). Flow partitioning has also been mathematically analysed for other flow regimes such as turbulent flow within the fractures in the presence of confining stresses in fractured cores (Oluyemi and Ola, 2010).

Comprehensive coupled numerical investigations of flow partitioning and cross flow within fractured porous media will result in huge mathematical discretization issues and less memory-efficient solutions. Therefore, in this paper, a back calculation method as proposed by Stalker et al. 2009 has been used to account for the effects of confining stress on fracture-matrix flow partitioning. Consequently, two subsurface flow interfaces of Comsol finite element package have been applied to analyze the flow partitioning as well as the cross flow magnitudes in response to the dominant stress state in a fractured core.

2. Problem description

Experimental data of a fractured core flooding experiment (Stalker et. al., 2009) has been adopted to generate the fractured porous media geometry within the numerical simulations in Comsol Multiphysics. The experiment entailed low viscosity brine flooding through a Clashach sandstone core plug which was fractured longitudinally over its whole length. Table 1 presents the properties of the core and flooding brine.

Table 1: Core flooding experimental data

Core diameter	*3.79 cm*
Core length	*7.54 cm*
Matrix porosity	*0.154*
Matrix permeability	*315 mD*
Oil viscosity	*1 cp*
Oil Density	*850 kgm^{-3}*

3. Darcy's law interface

In order to numerically investigate the effect of overburden stress on the flow partitioning between fracture and matrix of a fractured core, Darcy's law interface of Comsol multiphysics finite element package has been utilized primarily. Fracture flow boundary condition, as an auxiliary feature in this interface, delivers the capability of generating the fracture as a boundary within the model geometry. This approach eliminates the excessive meshing requirements and results in a faster and improved solution. It is worth mentioning that although the fracture is introduced to the model as a boundary, within the physics of the simulation as indicated in the governing equations, the fracture aperture is considered.

3.1 Governing equations

Darcy's law theory assumes that the variation of the velocity field when a fluid passes a porous medium is caused by the fluid pressure gradient, viscosity and the trajectory that the fluid travels through as given below in equation (3-1):

$$u = -\frac{k}{\mu}(\nabla P + \rho g \nabla D) \qquad (3\text{-}1)$$

In the above equation u is the fluid Darcy velocity, k is the porous medium permeability, μ the fluid dynamic viscosity, ∇P is the pressure gradient, ρ is the fluid density, g is the gravitational acceleration and ∇D is the unit vector in the direction over which the gravity would take effect. In this study, gravity effect has been ignored and therefore the pressure gradient acts as the sole source of brine movement in the core plug. Equation (3-1) is combined with the continuity equation in Comsol to provide the generalized governing equation given by equation 3-2:

$$\frac{\partial}{\partial t}(\rho\varphi) + \nabla.\rho\left[-\frac{k}{\mu}(\nabla P + \rho g \nabla D)\right] = Q_m$$
(3-2)

φ in these equation represents the porous material porosity and Q_m is a mass source term. Since our simulations were carried out on the basis that the core was fully saturated prior to flooding, a steady state solution with no flow accumulation was considered.

The fracture flow boundary condition feature contributes to the problem physics through fracture flow interface of Comsol Multiphysics. This interface uses tangential derivatives to calculate the flow along the interior boundary representing the fracture within the model. Fracture flow interface uses a tangential form of Darcy's law (equation 3-3):

$$q_f = -\frac{k_f}{\mu} d_f (\nabla_T P + \rho g \nabla_T D) \qquad (3\text{-}3)$$

The subscript f represents the fracture parameters, q_f is the volumetric flow rate per unit length of the fracture, d_f is the fracture aperture and subscript T indicates that the gradient is measured on the tangential plane of the fracture. Fracture permeability (k_f) has been calculated based on its aperture size using Schechter formulation (Stalker et. al., 2009). This equation, in combination with the continuity equation, provides an identical governing equation similar to the Darcy's law governing equation as:

$$d_f \frac{\partial}{\partial_t} (\varphi_f \rho) + \nabla_T.(\rho q_f) = d_f Q_m \qquad (3\text{-}4)$$

Fracture porosity (φ_f) has been calculated based on a slide fracture model concept (Van Golf-Racht, 1982).

3.2 Flow partitioning investigation

As discussed earlier core flooding experiments were simulated in Comsol in order to measure flow partitioning between fracture and matrix. Fractured core geometry was created taking the advantage of implemented fracture flow boundary condition. This feature enabled the introduction of fracture as an internal boundary to the model geometry, helping to avoid fine meshing requirements in the vicinity of the fracture. This approach made the solution more efficient and provided reduced runtime and truncation errors.

A parametric sweep type of analysis was performed for different overburden stress magnitudes on the core while flooding and the effects on the outflow contributions of fracture monitored (Figure 1). Since the poro-elasticity effect was not considered, the overburden stress did not have any direct impact on the matrix flow under same differential pressure constraints.

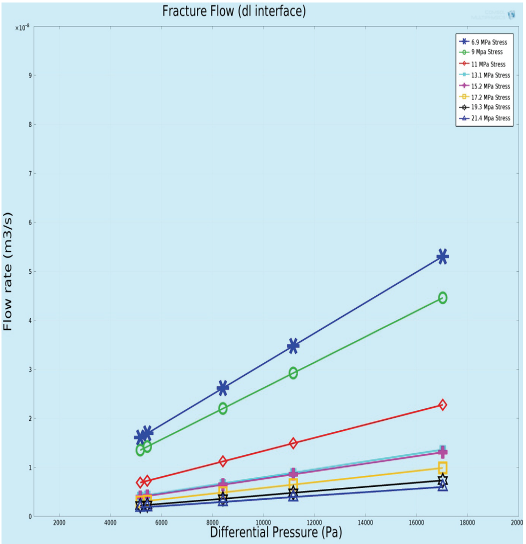

Figure 1. Overburden stress effect on fracture flow in Darcy's law interface.

Fracture flow partitioning, defined as the ratio in percentage of flow through the fracture volume to the cumulative flow through the whole fractured core plug, decreases as the overburden stress increases from about 40 percent under 6.9 MPa overburden stress to 7 percent under 21.4 MPa overburden stress (Figure 2). The results indicate that fracture flow partitioning dependency on overburden stress shows an inconsistent trend at around 13 MPa overburden stress. Such an inconsistency can also be detected in fracture flow against differential pressure plot (Figure 1).

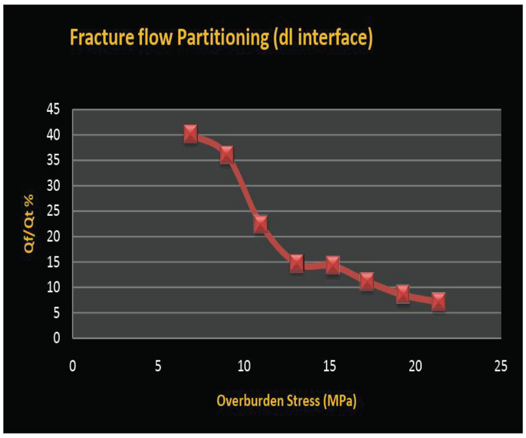

Figure 2. Overburden stress effect on fracture flow partitioning using Darcy's Law physics.

A comprehensive understanding of overburden stress effect demands testing other flow regimes such as free Navier-Stokes flow within the fracture volume. This also enables detection of the cross flow variation under various overburden stress levels.

4. Free and porous media flow interface

Due to the lack of laboratory flow partitioning data, it was decided to investigate other flow physics within the fracture. Consequently, free and porous media flow interface was applied to investigate the stress effect on fracture flow partitioning while considering more realistic laminar flow regime within the fracture volume.

4.1 Governing equations

This interface considers a continuous velocity and pressure field in the interface of a porous medium and a free flow domain. Brinkman equation which is an extension of Darcy law as an appropriate formulation for the transition zone between a porous medium and a free flow channel was used for the matrix phase in this interface. Brinkman equation for a steady-state flow neglecting the inertial forces and any mass generation or accumulation can be written as (Martys and Hagedorn, 2002):

$$\nabla P = -\frac{\mu}{k}u + \mu_e \nabla^2(u) \qquad (4\text{-}1)$$

In this equation μ_e is the effective density of the fluid in the porous medium and free flow domains in such a manner that $\mu\frac{du}{dy}$ in free flow domain equals $\mu_e\frac{du}{dy}$ in the porous medium domain when $y = 0$ represents the interface between the domains.

On the other hand, within the fracture volume the laminar form of Navier-Stokes equations was solved; this can be written for an incompressible, constant viscosity fluid as:

$$\nabla P = -\rho\frac{Du}{Dt} + \rho g + \mu\nabla^2 u \qquad (4\text{-}2)$$

Where the substantial time derivative is defined as:

$$\rho\frac{Du}{Dt} = \rho\frac{\partial u}{\partial t} + \rho(u.\nabla u) \qquad (4\text{-}3)$$

It is worth mentioning that Comsol general formulation is simplified for our steady state problem neglecting fluid compressibility and gravitational forces.

4.2 Effect of overburden stress on fracture flow partitioning

Although Darcy's law interface provides an efficient solution in treating a fractured porous medium, it is not as realistic as a solution achieved using free and porous media interface. This is due to the fact that in the latter interface cross flow will occur and can be measured between matrix and the fracture volume. It is worth mentioning that even free and porous media interface does not simulate the exact solution since it assumes a continuous pressure and velocity field between rock matrix and fracture which is a simplification of the real case.

As a result of generating fracture volume, meshing the problem geometry would be complex due to the large aspect ratio between fracture aperture size (in microns) and the core plug dimensions (in Centimeters). This large aspect ratio could cause excessive runtime and a low memory-efficient solution. Therefore a quarter of the core and fracture volume was investigated numerically taking the advantages of symmetry features augmented with a mapped and swept mesh and direct solvers (Figure 3).

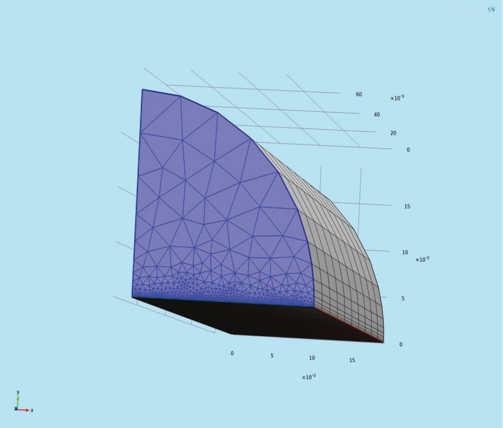

Figure 3. The geometry and mesh in free and porous media interface.

Core flooding experiments were simulated by defining pressure boundary conditions in the inlets and outlets of fracture and matrix. Flow partitioning magnitudes were integrated at the outlet boundaries (Figure 4).

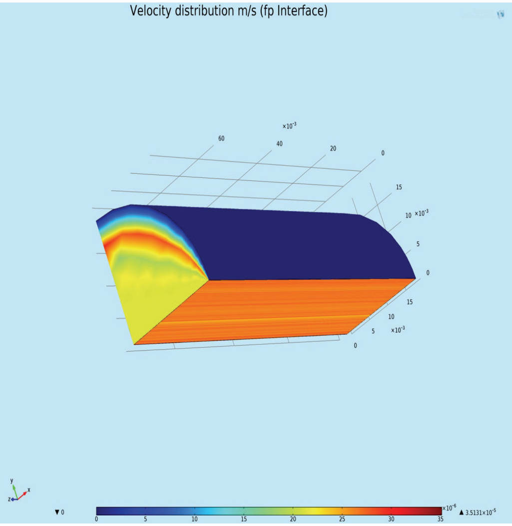

Figure 4. Brine velocity distribution along the fractured core length.

Similar to the Darcy's law interface results fracture flow decreases as the overburden stress increases with identical trends (Figure 5); however, the flow rates are higher in free and porous media flow interface. Consequently, the fracture flow partitioning magnitudes are higher (Figure 6) in this interface in comparison to the Darcy's law interface. These higher fracture flow partitioning results are not only an indication of more realistic Navier-Stokes flow within the fracture volume compared to a tangential derivation of Darcy flow in Darcy's law interface but also a representation of the cross flow occurring between porous rock matrix and more permeable fracture channels. Fracture flow results in both interfaces exhibiting rather a unique slope for fracture flow rates under overburden stresses above 13Mpa while below this level the flow rate trends have more disperse slopes which can be an indication of a shift in stress effects.

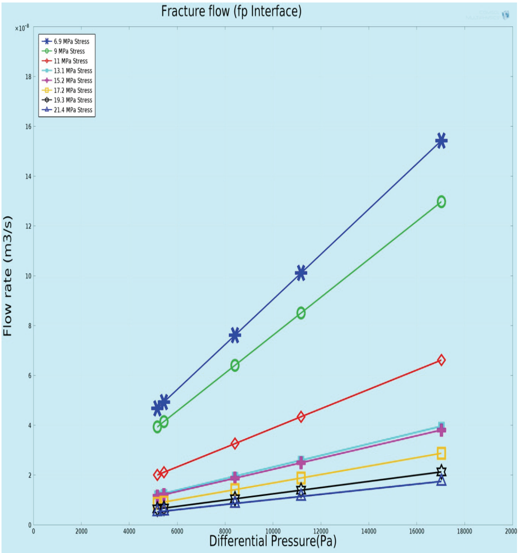

Figure 5. Fracture flow rates using free and porous media interface physics versus differential pressure for various overburden stress levels.

Fracture flow partitioning variation versus overburden stress level has been plotted for both Comsol interfaces in Figure 6. Although the fracture flow partitioning results obtained from free and porous media physics are higher, the trends are identical and again the discontinuity in the partitioning results in response to overburden stress can be detected after 13 MPa overburden stress level.

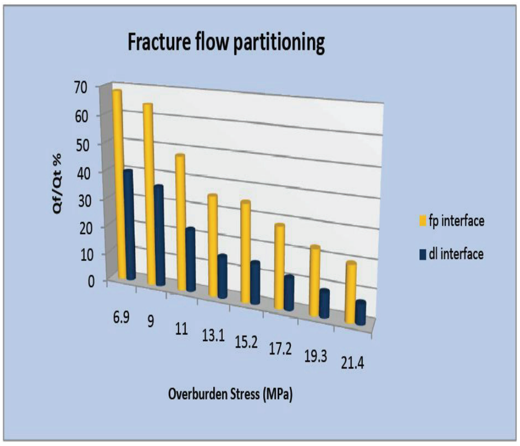

Figure 6. Fracture flow partitioning variation in response to overburden stress level using the two Comsol interfaces.

Careful consideration of flow partitioning results obtained from free and porous media flow interface reveals that the dominant flow path for stresses under 11MPa is the fracture which accounts for more than 50 percent of the overall flow whereas Darcy’s law flow partitioning results indicate that even for the lowest stress magnitude the dominant flow path is the matrix responsible for minimum of about 60 percent of the overall flow. This inconsistency emphasizes the need for laboratory experimental data to calibrate and validate the numerical results.

5. Fracture-matrix cross flow investigation

Simulating fracture as a volume in the free and porous media flow interface enables cross flow measurement between the porous rock matrix and fracture. Cross flow is the vertical flow exchange in the interface between matrix and fracture as provided in Figure 7 for various stress levels magnitudes for which the fracture flow variation has been monitored in previous sections.

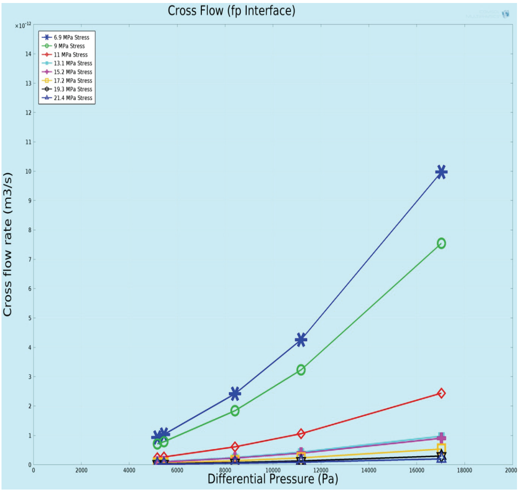

Figure 7. Cross flow variation in response to the overburden stress level.

As can be seen in figure 7, similar to the fracture flow rate results, cross flow magnitudes also decrease in response to increased overburden stress. Cross flow measurements indicate that especially for high differential pressure magnitudes, cross flow severely changes in response to overburden stress. This is much more significant again for stress magnitudes below 13MPa. Furthermore, for these lower stress levels cross flow varies as a polynomial function of differential pressures and is several orders of magnitudes higher.

The cross flow measurements in combination with the fracture flow partitioning investigations in both interfaces prove that at a certain overburden stress level, the fracture can be considered as a semi-closed fracture. After this stress level the cross flow between rock matrix and fracture volume would reduce tremendously and the developed pressure drop within the fracture is not large enough to overcome the capillary effects in the rock matrix pore spaces, therefore, the flow partitioning for these overburden stresses are more affected by the initial saturation and the viscous forces.

6. Discussion and conclusion

Fracture flow partitioning variations has been monitored using two different Comsol Multiphysics interfaces. Reasonably as the overburden stress increases, the flow contribution through fracture decreases, however, an inconsistency was detected when different flow physics were applied (Figures 8 & 9). The dashed blue marker free line in these figures represents matrix flow and since poro-elasticity effects were not considered in our modeling, it is rather unchanged for all stress magnitudes.

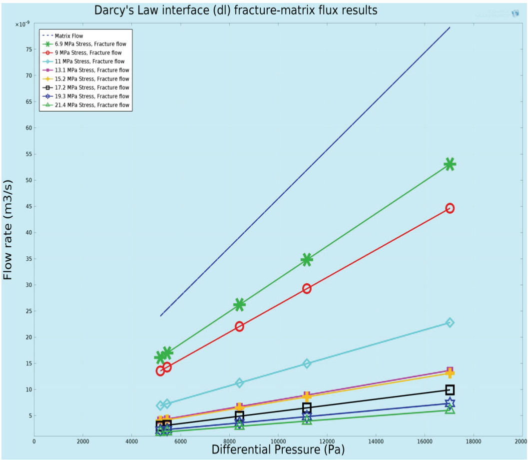

Figure 8. Fracture and matrix flow partitioning versus overburden stress obtained using Darcy’s law interface.

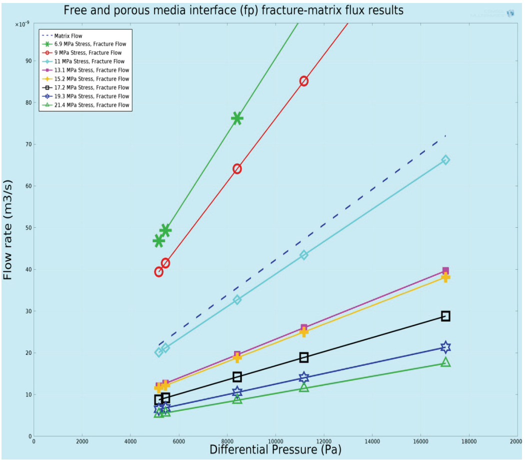

Figure 9. Fracture and matrix flow partitioning versus overburden stress obtained using free and porous media interface.

Not only are the fracture flow partitioning results higher in free and porous media interface but also more interestingly, fracture flow exceeds matrix flow for the lower stress magnitudes. This fact emphasizes that laboratory experiments are needed to obtain the most realistic physics that can illustrate flow behavior in fractured porous media and secondly to confirm the critical overburden stress beyond which fracture flow would not decrease significantly and can be considered as a threshold for fracture closure.

On the other hand, according to the cross flow modeling it is evident that below this fracture closure stress threshold cross flow magnitude changes exponentially in response to pressure drop while beyond that certain overburden stress it varies linearly in response to pressure drop magnitude. Understanding of cross flow variation due to overburden stress magnitudes is especially of prime importance in dual permeability models where the wellbore is producing from both fracture and matrix systems. However more laboratory validation is required and these simulation results would provide precise design for fracture-matrix flow partitioning laboratory investigations.

8. References

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