The Importance of coupling wellbore hydraulic & simultaneous fractures propagation in multistage design

Brice Lecampion

https://gel.epfl.ch/
Poor production distribution between fractures

~ 30-40% of fractures are found not producing at all!


Unconventionals:
producing nanoD reservoirs through a series of high conductivity channels.

Is it just all about formation heterogeneities? Are there any inefficiencies intrinsic to the completion technique?
Treatment Observations (during one stage)

- **DTS/DTA**
  - Variation in flow rate entering the different clusters during treatment (cooling)
  - Variation of producing rates between clusters during clean-up (warm up)

- **Microseismic**
  - Different fractures length in a stage

---

**Working Hypothesis:**
The heterogeneity in **fracture production rates** is strongly linked to the heterogeneity in **propped fracture areas**, thus to a heterogeneity of **entering flow rates during a stage**.

---

From Molenaar et al. (SPE 140561)

Cipolla et al., SPE 146876
Multiple fracture propagation: Is it stable?

Growth of parallel (dry) cracks in a glass plate (Thermal-shock)

(Geyer and Nemat-Nasser, 1982)

Interaction kicks in when Spacing ≈ Height or Length

Stress perturbation around a crack

(Sneddon, 1946)

Fracture shielding occurs due to stress interactions.

Hydraulic fractures are not dry cracks / constant pressure: viscosity plays an important role

Fluid partitioning during a stage is key

Entry friction
\[ \Delta p_i(Q) = f_{p,i} Q_i^2 \]
[e.g. Reservoir Stimulation book 2000]

- One control the surface pump rate not the rate entering each of the fractures. This fluid partitioning is unknown & evolves with time.
- Competition between the following:
  - Stress interactions between fractures (aka stress shadow)
  - Well/Fracture entry pressure drop (entry friction)
  - Length of the stages (N clusters and spacing) & associated pressure drop in the well.
- One needs to couple
  - Hydraulic fracture propagation solver
  - Wellbore flow solver
Single Hydraulic Fracture Initiation

theory vs experiments

Lecampion et al., JGR 2017

Experiment in cement with silicone oil (TU Delft 1998)
Fluid flow in the well

Cross-sectional averaging, neglect small transient effects (e.g. water hammer type)

Mass balance
\[
\frac{\partial \rho A}{\partial t} + \frac{\partial \rho AV}{\partial s} = \delta(s)\rho Q_o - \sum_{i=1}^{N} \delta(s - s_i)\rho Q_i
\]

Momentum balance
\[
\frac{\partial p}{\partial s} = -\frac{2\pi a}{A} \tau_w + \rho g \sin \alpha(s)
\]

Local steady-state wall shear-stress
\[
\tau_w = \rho \frac{f(Re, \varepsilon)}{4} \frac{V|V|}{2}
\]

Zero flux at the bridge plug location
\[
V(s = L, t) = 0
\]

Classic 1D Finite Volume scheme
Solving for fluid partitioning – very stiff

- Within a full implicit scheme (Backward Euler)

- Wellbore / Fracture(s) coupling

  \[ \Delta p_i(Q) = p_{w,i}(Q) - p_{f,i}(Q) = f_{p,i}Q_i^2 + f_{t,i}Q_i^{\beta_i} \]

  Quasi-Newton iterations
  - For each trial values of entry flow rates in different fractures
    - Solve for wellbore flow (given \( Q \)) to find cluster outlet pressure(s) \( p_{w,i}(Q) \)
    - Solve hydraulic fractures propagation step (given \( Q \)) to estimate HF inlet pressure(s) \( p_{f,i}(Q) \)
    - Compute residuals \( \mathcal{R}_i(Q) = p_{w,i}(Q) - p_{f,i}(Q) - (f_{p,i}Q_i^2 + f_{t,i}Q_i^{\beta_i}) \)
    - Compute Jacobian \( \frac{\partial \mathcal{R}_i}{\partial Q_j} \) (using finite difference approx.)
    - Compute increments of \( Q \)
  - Iterate until convergence (on residuals & subsequent estimates of \( Q \))
A simple case – 3 fractures – no entry friction

Example of 3 fractures 80 ft apart without perforation friction

“Kicks in” when Spacing ≈ Height or Length

Middle fracture is shut down…
A simple case – 3 fractures – entry friction

Example of 3 fractures 80 ft apart with 200 psi perforation friction

“Kicks in” when Spacing ≈ Height or Length

Even flux for all fractures...
Uniform vs localized growth

- Uniform growth is promoted when \( \Delta P^\text{entry} \gg \sigma^\text{Int} \).
- Introducing \( \Gamma = \sigma^\text{Int} / \Delta P^\text{entry} \), we can estimate its order of magnitude from system parameters (when \( R \sim S \)) for a given regime of propagation:
  \[
  \Gamma = \frac{\sigma^\text{Int}}{\varphi_p \times (Q_o/N)^2} = \frac{E'^{3/4} \mu'^{1/4}}{\varphi_p S^{3/4} (Q_o/N)^{7/4}}
  \]
- Series of simulations (3 fractures array), looking at the standard deviation of fracture volume scaled by the volume of a single fracture.

![Graph showing Uniform vs Localized growth](image)

Lecampion & Desroches, JMPS 2015
Remark #1 - Stress shadow

- The effect of stress shadow between fractures can be counterbalanced by typical perforation friction. (i.e. when perforation pressure drops are larger than the interaction stress)

- Perforation erosion decreases entry friction, which may result in stress shadow kicking in.

- Something else than stress shadow? Is formation heterogeneity the cause for production heterogeneity?
How do we handle heterogeneity in practice?

Geometric Spacing

![Graph showing Frac gradient (PSI/ft) vs. MD (ft) with geometric and engineered spacing]

Eagle Ford example (taken from Slocombe et al., SPE 166242)
How do we handle heterogeneity in practice?

Engineered Spacing

Minimizing stress variation between clusters in a stage (while limiting by-pass pay)
How do we handle heterogeneity in practice?

Limited Entry Design

**Uniform**

\( N_{\text{perf}} = 8 \)

**Engineered**

\( N_{\text{perf}} = [6, 6, 8, 9, 7, 8] \)

Choking down clusters in front of lower stress to balance entering fluxes (taking \( Sh \) as the fracturing pressure)

(Lagrone & Rasmussen, 1963)
Geometric Spacing

Uniform Limited entry

Engineered Limited entry

One fracture does not initiate

50% Spread

15% Spread

$R_i$ (ft)

$t$ (sec)

$Q_i$ (BPM)

$Q_o/N$

$\sigma_h/z$ values:
- #1 (0.8 psi/ft)
- #2 (0.83 psi/ft)
- #3 (0.81 psi/ft)
- #4 (0.83 psi/ft)
- #5 (0.86 psi/ft)
- #6 (0.85 psi/ft)
Engineered Spacing

Uniform Limited entry

Engineered Limited entry

All fractures initiate

On design

40% Spread

\[ R(t) \text{ (ft)} \]

\[ Q(t) \text{ (BPM)} \]

\[ t \text{ (sec)} \]
Remark #2 - Stress Heterogeneity

- Stress heterogeneity can be managed
  - 100% balancing of the entering fluxes and all fractures propagating is achievable but it is not very robust (slight changes in entry friction directly impact fluid partitioning) see e.g. Lecampion & Desroches RMRE 2015
  - 80% entering flux balancing should be achievable
  - Heterogeneity needs to be properly quantified

- However production performance seems worse from field observations 😞

- Let’s have a look at a field experiment without much stress heterogeneity
Field Case – Single Entry Experiment
Eagle Ford Shale

- Horizontal well, 6000ft lateral drilled in the direction of $S_h$
- From cuttings analysis: mineralogy, elastic properties, stress index → fairly homogeneous along the lateral length
- 93 single entry clusters
  Bottomhole pressure gauges on each stage
- 14 diagnostics stages with step downs

Fracture Gradient from cuttings (DRIFTS Mineralogy + rock physics)

Very different breakdown pressures

Details in SPE 171667
WB-HF coupling & fluid partitioning

- WB-HF coupling via entry friction: perf + near-wellbore

\[ \Delta p_i(Q) = p_{w,i}(Q) - p_{f,i}(Q) = f_{p,i}Q_i^2 + f_{t,i}Q_i^{\beta_i} \]

(Taken from Van der Ketterij et al., SPE 38149)

Very sensitive to local heterogeneities (stresses, rock fabric, cementing...)
Eagle Ford Shale – Model Calibration

- For each treatment, determine from bottom-hole pressure record
  - $\Delta P_{NWB}$ (from correlation with breakdown)
  - $\Delta S_h$ (local re-orientation)

- All the remaining parameters from the characterization & treatment data

What if the well had been stimulated with N (>1) clusters per stage?
Playing scenarios

Reconstructing the entire well with 4 cluster stages

Flow rate in (BPM)

Cluster #

30% > 30 BPM (most sand)
25% between 15 and 25 BPM (design)
30% < 10 BPM (proppant settling?)
Playing scenarios

Histograms of fluid intake in each clusters as a function of number of clusters per stage
Conclusions

- Fluid partitioning between fractures within a stage is unknown a-priori
  - Part of the solution
  - Very stiff non-linearity between wellbore flow, hydraulic fracture growth and entry friction
- Stress interactions between fractures (and stages) can be completely counteracted by entry friction
  - A word of caution... as long as $S_H > S_h + 1$MPa (100psi)
- Entry friction: perf + near-wellbore fracture re-orientation
  - Vary from cluster to cluster,
  - Huge effect on fluid partitioning & final well completion
- Inefficiencies intrinsic to the simultaneous propagation of hydraulic fractures from a well
Can we do something about it?

- In practice – *currently the options are*
  - Live with the inefficiencies and optimize the ‘supply’ chain
  - Spend a test well & do single entry HF treatment to:
    - Sample the heterogeneities of the entry friction (Near-wellbore fracture geometry) via rate step down tests
    - Perform MC HF multistage simulations with proper well/HF coupling to choose the optimum stage length & number of clusters (in a probabilistic sense)
  - Fluid diverters – far-from achieving full efficiency (just allow larger stages in terms of clusters)

- Gaps in our understanding to be filled in order to go a step further are
  - 3D HF growth in the near-wellbore
    - Nasty fracture mechanics problem (mixed mode I+III front splitting etc.) very sensitive to local heterogeneities difficult to characterized
  - Effect of rock anisotropy/laminations on HF growth both at:
    - Large scale (sensitivity to layering, preferred growth direction, induced flow roughness etc.)
    - Near-wellbore scale – initiation from perforations etc.
- 3 principal stresses
- Pore-pressure
- 25cm*25cm*25cm sample
- Any materials
- Extensive acoustic monitoring
  - 64 piezos
    (32 sources / 32 receivers)
  - 16 piezos for passive AE
Questions ?

Four critical issues for successful hydraulic fracturing applications.

Experiments versus theory for the initiation and propagation of radial hydraulic fractures in low permeability materials.

[4] Lecampion, B. & Desroches, J.
Simultaneous initiation and growth of multiple radial hydraulic fractures from a horizontal wellbore

Robustness to formation geological heterogeneities of the limited entry technique for multi-stage fracturing of horizontal wells

Can we engineer better multistage horizontal completions? Evidence of the importance of near-wellbore fracture geometry from theory, lab and field experiments
SPE Hydraulic Fracturing Technology Conference, 2015 (SPE 173363)

Benefits of Controlled Hydraulic Fracture Placement: Theory and Field Experiment
SPE/CSUR Unconventional Resources Conference, 2014 (SPE 171667)