Calibration of NFR models with interpreted well-test k.h data

Michel Garcia
Calibration with interpreted well-test k.h data

Intermediate step between
- Reservoir characterization
  • Static model conditioned by structural, core and fracture data
- History matching
  • Dynamic model conditioned by production data

Focusing on equivalent permeabilities
- Locally measured permeabilities of the fracture system

Step specific to NFR models
- Permeability fields not directly modeled but derived (calculated) from
  • Fracture densities
  • Fracture geometric and flow properties
Aim of the calibration

Relating
- NFR model parameters defined on a fracture-set basis
  - Fracture densities
  - Geometric properties: orientation, length, height
  - Flow properties: conductivity

To
- Locally measured permeabilities of the fracture system
  - Interpreted well-test k.h

One Fracture-set

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$FD$</td>
<td>density (m$^{-1}$)</td>
</tr>
<tr>
<td>$L$</td>
<td>length (m)</td>
</tr>
<tr>
<td>$H$</td>
<td>fracture height (m)</td>
</tr>
<tr>
<td>$ke$</td>
<td>conductivity (md.m)</td>
</tr>
<tr>
<td>$n$</td>
<td>orientation</td>
</tr>
</tbody>
</table>

Fracture system = all fracture-sets

Interpreted well-test k.h

Calibration of NFR models with interpreted well-test data
Choice of a conceptual fracture system model

Discrete fracture network vs. continuous fracture model

– DFN and CFM
  • Same model parameters to characterize the fracture system
  • Equivalent flow properties are to be calculated in gridblocks or at gridblock interfaces as required for reservoir flow simulation

– Particularity of DFN
  • Realization of the fracture system is part of the model
    ō the realization should be part of the calibration

– Particularity of CFM
  • Equivalent flow properties locally derived from global or locally defined fracture parameters (local DFN, analytical solution)
  • If non-bijective relationship between fracture parameters and equivalent permeability tensor
    ō need for an additional connectivity-like parameter
Calibration issues

Evaluation of the (flow) well-test response of NFR models

– Requirements on the calculation method
  • Fast and automatic method for inversion purposes
  • **Grid support** for consistency with the reservoir flow simulator
  • Applicable to permeability **tensor** fields & anisotropic drainage areas
  • Distinction between fracture and matrix permeabilities

Optimization of model parameters

– Numerous model parameters
  • Several mechanical unit dependent directional fracture-sets
  • Each fracture-set characterized by $\geq 4$ parameters

– Poorly known fracture parameters
  • Spatial vs. non-spatial parameters
  • Single (effective) value vs. probability distribution

– Connectivity of the fracture system = missing parameter
Evaluation of interpreted well-test $k.h$

Forward problem

– Interpreted $k.h = \text{average } k.h$ corresponding to
  • Planar and radial-like flows around the well
  • Uniform homogenization of $k$ (or more precisely $k.h$) within a drainage (stabilization) area around the well
  • Instantaneous pressure equilibrium in the matrix and the fracture system
  • Average (effective) $k = (k_{\text{max}} \, k_{\text{min}})^{1/2}$
    $k(u) \approx k_f(u) + k_m(u)$

– Particularities of NFR
  • Upscaling of fracture densities
  • Permeability field = tensor field
  • Anisotropic drainage area ($R_{\text{max}} / R_{\text{min}}$ up to 10 or more)
Evaluation of interpreted well-test k.h (cont.)

Non-exhaustive list of methods for CFM

1. Numerical simulation of transient (well-test) flow responses
2. Power or other types of averaging based on calibrated data
3. Annulus ring-based calculation of apparent test-permeability
4. Steady-state flow based calculation of around-well average permeability (TOTAL/KIDOVA approach)
Evaluation of interpreted well-test k.h (cont.)

Numerical simulation of transient (well-test) flow responses

– Possible comparisons
  • Automatically interpreted simulated tests vs. interpreted well-test
  • Simulated vs. experimental pressure (or pressure variation) curves
    ņ relying on raw data instead of a reservoir engineer’s interpretation

– Issues
  • Complex numerical simulations: local grid refinement, well-model
  • Transient flows = additional model parameters (e.g. fracture porosity, compressibility)
  • What about fracture/matrix exchanges?
Evaluation of interpreted well-test k.h (cont.)

Power or other types of averaging based on calibrated data

- Issues
  - Applied to scalar permeability fields (not permeability tensor field)
  - Defining drainage volumes (generally cylindrical)
  - Relying and depending on (inferred) spatial statistics
  - Same calibration function applying everywhere

Evaluation of interpreted well-test k.h (cont.)

Annulus ring-based calculation of apparent test-permeability

- Issues
  - Applied to scalar permeability fields (not permeability tensor field)
  - Defining equi-travel time rings (generally circular)
  - Calibration of the weighting function that should apply everywhere

Effective-gradient based averaging (TOTAL/KIDOVA method)

- Steady-state flow solution relying on:
  - Appropriate simulation domain (taking into account a local anisotropy)
  - Appropriate boundary conditions (notion of energy)
  - Appropriate calculation of average k.h vs. Rd (equivalent drainage radius) around the well (notion of effective gradient)

\[
k_\Gamma = \frac{\int_{\Gamma} q(\gamma) d\gamma}{\int_{\Gamma} q(\gamma) \|K(\gamma)^{-1} n(\gamma)\| d\gamma}
\]


KIDOVA

Calibration of NFR models with interpreted well-test data
Evaluation of interpreted well-test k.h (cont.)

Effective-gradient based averaging (TOTAL/KIDOVA method)

– Flow simulation
  • Need for a flow simulator allowing full permeability-tensors

– Permeability tensors defined at gridblock interfaces

\[
FF_{i,j} = \frac{ff_{i,j} + ff_{i+1,j}}{2}
\]

On the FF grid

\[
FF_{i,j} = <ff|, \bullet, \cdot>
\]

Easy upscaling to a coarser grid
Evaluation of interpreted well-test k.h (cont.)

Illustration of the effective-gradient based averaging method

Appropriate simulation domain: based on local k anisotropy + drainage radius

Flow simulation: based on appropriate boundary conditions + full k-tensor simulator

Effective-gradient based calculation of k.h
Calibration of model parameters

Position of the problem

– \( N_d = \) nb of interpreted well-test (k.h) data
  
  Well location + interpreted k.h + associated \( R_d \)

– \( N_p = \) nb of model parameters
  
  = nb of fracture-sets \( \times \) nb of fracture parameters
  
  + nb structural parameters

– Typically: \( N_p > \) if not >> \( N_d \)
  
  "under determined" problem

  multiple solutions
Choice of an uncertainty model for each parameter

– Single value vs. probability distribution function (pdf)
  • pdf 2 or more distribution parameters (central and dispersion statistics) for each (probabilistic) model parameter

– Spatial vs. non-spatial (global)

Usual practice

– Layer thickness \( (T) \): spatial + deterministic structural model

– Fracture parameters on a (directional) fracture-set basis
  • Fracture density (FD): stochastic spatial distribution (realization)
  • Orientation \((\text{dir}, \text{dip})\): pdf + possibly spatially varying mean direction
  • Other fracture properties \((L, ke, H \text{ or } Pij)\): different options
    – Single (effective) value often sufficient
      Ex. effective length (Masihi & King 2008)
    – Spatially defined: if correlated to a well-known spatial variable
      Ex. \( ke \propto e^{-\lambda \times FD} \) (Pollard & Segall 1987, Pollard & Gross 2000)
Calibration of model parameters (cont.)

Two-step approach for non-spatial and spatial parameters

- Static data: fracturing + geo-model
  - Spatial and multivariate statistics
    - FD fields on a fracture-set basis
      - Fracture properties on a fracture-set basis
        - Equivalent k-tensor fields
          - Compliance with short-scale dynamic data
            - Optimize non-spatial fracture properties
              - Stop
          - Compliance with large-scale dynamic data
            - Optimize spatial fracture densities
Assisted and automatic approach (TOTAL/KIDOVA)

– Sensitivity analysis
  • Characterization of parameter uncertainty

– Inversion/optimization of non-spatial parameters
  • Experimental design (random starting points)
  • Gradient-based method (use of NPSOL)
  • Objective function

\[
O(\mathbf{np}) = \left( \sum_{r=1}^{N_r} 1/O^0_r(\mathbf{np}) \sum_{i=1}^{N_d} w_i \left[ d_i - \frac{d^*_i(s(\mathbf{np}) s^r(u))}{\sigma_i} \right]^\omega \right)^{1/\omega}
\]

– Aim
  Finding non-spatial parameter values matching at best dynamic data
  Identifying “best” fracture density realizations
  Managing local minima or non-unique solutions (multiple starting points)
Uncertainty characterization and sensitivity analysis

– Objectives
  • Identifying the most consequential uncertain model parameters
  • Fine-tuning their possible range
  • Eliminating parameters without or with limited effects on matching

– Tools
  • Latin hyper-cube Monte Carlo sampling
  • Uni and multivariate statistical analyses of results
Calibration of NFR models with interpreted well-test data

Uncertainty characterization and sensitivity analysis

– Typical results


KIDOVÁ
Uncertainty characterization and sensitivity analysis

Typical results

Ref. M.E. Luna Orosco Garcia, MSc. Reservoir Geosciences and Engineering, IFP School, 2007
Calibration of model parameters (cont.)

Automatic calibration of non-spatial parameters

Choice of FD realizations and dynamic data

Choice of optimization method(s)
Automatic calibration of non-spatial parameters

- Grid – 200*200*6 cells
- Four zones with FD of 0.3, 1.5, 3 & 7 m⁻¹
- Two fracture sets N70 & N150
  - N70: \( L = 10 \text{ m}, \ k_e = 400 \text{ mD.m} \)
  - N150: \( L = 15 \text{ m}, \ k_e = 250 \text{ mD.m} \)

<table>
<thead>
<tr>
<th>Fracture set</th>
<th>Parameter</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>TRUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>N70</td>
<td>( L )</td>
<td>170.1</td>
<td>348.0</td>
<td>871.8</td>
<td>400</td>
</tr>
<tr>
<td>N70</td>
<td>( k_e )</td>
<td>19.5</td>
<td>11.8</td>
<td>11.5</td>
<td>10</td>
</tr>
<tr>
<td>N150</td>
<td>( L )</td>
<td>125.6</td>
<td>909.1</td>
<td>136.2</td>
<td>250</td>
</tr>
<tr>
<td>N150</td>
<td>( k_e )</td>
<td>13.8</td>
<td>22.3</td>
<td>28.7</td>
<td>15</td>
</tr>
</tbody>
</table>

- Ref. Egor Mikhaylenko, MSc. Reservoir Geosciences and Engineering, IFP School, 2008
Calibration of model parameters (cont.)

About the need for a connectivity parameter

– Calculation uncertainty between fracture-set parameters and equivalent permeability tensor

Non-bijective relation = sensitivity to some DFN realizations

$FD-N70 \ (m^{-1}) = \text{only non-constant parameter}$

– Connectivity parameter = additional (locally or globally) defined model parameter to discard calculation uncertainty
Acknowledgements:

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Discussion

• Evaluation of interpreted k.h test data on NFR models
  – Easy forward problem, complex evaluation task

• Automated vs. assisted model parameter calibration
  – Practice of sensitivity analysis and optimization

• Which support for calibration: DFN vs. CFM?
  – Consistency of model calibration with history matching

• Multisolution of NFR model parameters
  – Trade-off between model complexity and available data
References

**Conditioning to well-test data**
- Garcia M., Gouth F. & Gosselin O (2006). New developments in GoFraK to condition naturally fractured reservoir models on dynamic data, in 26th gOcad Meeting, Nancy.

**Effective properties**