Numerical simulation model adaptability research for fractured reservoir

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Abstract. Characterization and forecasting in fractured reservoirs is one of the most challenging topics in oil and gas industry. Due to significant difference of fluid flow mechanism in fracture and in matrix, managing such reservoirs requires construction of representative reservoir models. Dual porosity & dual permeability model (DPDP) is the first choice of fractured reservoirs, but history matching and plan prediction of this model facing poor convergence and long running time. Other models like dual porosity & single permeability model (DPSP), single porosity & single permeability model (SPSP) sometimes can replace DPDP and can be able to improve convergence and save calculation time, but lack of model equivalence criterion. In this study, 84 cases of 4 reservoir models has been built and simulated to study the equivalence criterion. Permeability difference and oil viscosity are considered to be the main influencing factors affecting model equivalence. With the application of the equivalence criterion, weak convergence and time consuming of fractured reservoir simulation can be improved.

1. Introduction
Fractured reservoir generally exists two medium systems, high porosity and low permeability matrix system and low porosity and high permeability fracture system [1]. Due to the strong heterogeneity and anisotropy of fractured reservoir, numerical simulation is difficult to conduct and simulation model choose is of vital importance [2-3]. There are three types of simulation model of fractured reservoir, dual porosity and dual permeability model (DPDP), dual porosity and single permeability model (DPSP) and equivalent single porosity and single permeability model (ESP) [4].

For DPDP, matrix is the main fluid storage space, and fracture is main fluid flow space, both matrix and fracture have their own physical properties, and fluid flow both in matrix and fracture, and between them. DPDP can good characterize fractured reservoir, however poor convergence and long running time are common problems of this model since real reservoir can have millions and even ten millions grids [5-6]. DPSP is a simplified DPDP, it can characterize fractured reservoir by ignoring matrix permeability, therefore matrix system is main storage space and fracture system is main flow space, fluid can flow from matrix to fracture, and from fracture to wellbore but fluid can’t flow from matrix to wellbore. The numerical simulation of this model has better convergence and faster running speed compared with DPDP at the sacrifice of complex flow.

ESP have two different types, equivalent single matrix model (ESM) and equivalent single fracture model (ESF). ESM ignores the storage and flow effect of fracture and is suitable for those fracture less developed reservoirs. On the contrary, ESF ignores the storage and flow effect of matrix and is suitable for those fracture more developed reservoirs. Obvious, the flow mechanism of ESM and ESF...
are much simpler, therefore the convergence is better and running time is shorter. However, these models may encountered low accuracy when matrix and fracture have flow exchange. The four mechanism models are shows in Figure 1.

Although there are some qualitative studies of model selection for fractured reservoir, until now, no quantitative model selection criteria has been built. For a certain fractured reservoir, how to choose simulation model and what are the differences between the four models still confusing simulators. Therefore in this paper, hundreds of numerical simulation cases using different models have been conducted to study the model adoptability for different fractured reservoirs, and quantitative model selection criteria has been built for fractured reservoir. By using this criteria, simulators will not be working in dark to choose model for a certain fractured reservoir, and lots of manpower and time will be saved.

![Figure 1. Different models for fractured reservoir.](image)

2. Model setup

For fractured reservoir, the key factors affect flow mechanism is permeability difference and oil viscosity, here permeability difference is the ratio of fracture permeability to matrix permeability. Using Petrel platform, four types model have been built. Both DPDP and DPSP using matrix and fracture properties, relative permeability and capillary pressure. ESM using matrix and fracture total porosity (volume average), total permeability (volume average), matrix relative permeability and matrix capillary pressure. ESF using matrix and fracture total porosity (volume average), fracture permeability and fracture relative permeability.

![Figure 2. Description of DPDP.](image)

Basic parameters of the models refer to a typical fracture carbonate reservoir K oil field, and the parameters can represent most fractured reservoir, based the statistics study of typical kind of fractured reservoir. Take DPDP as an example, the basic parameters are as follows: (1) grid number \( \text{NX} \times \text{NY} \times \text{NZ} = 20 \times 20 \times 10 = 4000 \), and 1, 2, 3, 4, 5 layers are matrix system, 6, 7, 8, 9, 10 are fracture system, two systems coupling in a set of grids; (2) grid size \( \text{DX} \times \text{DY} \times \text{DZ} = 50m \times 50m \times 10m \); (3) permeability and porosity of matrix are \( 1 \times 10^{-3} \mu \text{m}^2 \) and 0.2, porosity of facture is 0.002, and permeability of fracture is determined according to permeability difference; (4) six horizontal wells are located in the middle of the reservoir with horizontal well length of 300 m and well spacing of 300 m; (5) conventional reservoir development history is simulated, that is, early depletion development and when reservoir pressure reduce to saturation pressure then two oil wells (H2 and H5) in the middle converted to water injection wells. The models are shown in Figure 2.
Matrix and fracture use the same PVT data as shown in Figure 3a, the PVT data is from laboratory testing of K oil field. When considering the influence of oil viscosity, keep oil saturation pressure constant, adjust viscosity according to the measured curve trend. Matrix and fracture using different relative permeability, matrix relative permeability data and capillary pressure data are from laboratory resting of K oil field, and fracture relative permeability is two skew lines with no irreducible water and no residual oil, as shown in Figure 3b.

Using single factor analysis method, the adaptability of different model to different fractured reservoir has been studied, a total of 84 cases has been designed. It is notable that ESF is suitable for these more fracture developed reservoirs, therefore permeability difference is high, and so ratio of oil volume in fracture and total oil volume is considered the main influence factor. Simulation cases are shown in Table 1. Since DPDP is the accepted model for fractured reservoir simulation, for each DPSP, ESF and ESM case, corresponding DPDP case was built for comparison.

Table 1. A table with details of the simulation cases.

| Model | Permeability difference | oil viscosity, cp | Case Quantity |
|-------|-------------------------|-------------------|---------------|
| DPSP  | \(R^a=1, 2, 5, 10, 15, 25\), \(\mu_o=1, 5, 25, 50, 100, 150\) | \(6 \times 6 = 36\) |
| ESF   | \(R=50 \& Nf^b/N^c=0.3, 0.5, 0.7, 0.9\), \(\mu_o=1, 5, 25, 50, 100, 150\) | \(4 \times 6 = 24\) |
| ESM   | \(R=1, 5, 8, 10\), \(\mu_o=1, 5, 25, 50, 100, 150\) | \(4 \times 6 = 24\) |

\(^a\)R means permeability difference, which is \(K_f/K_m\) (fracture system permeability/matrix system permeability);  
\(^b\)Nf means oil volume in fracture system;  
\(^c\)N means oil volume in the whole reservoir of both fracture and matrix system.
3. Simulation results

3.1. **DPDP and DPSP comparison**

Figure 4 to Figure 6 show some simulation results of oil recovery comparison in DPDP and DPSP under different permeability difference and oil viscosity. As can be seen, when oil viscosity is constant, with permeability difference increase, the difference between the two recovery curves is smaller. And they almost the same when permeability difference is higher than 15, because there is almost no fluid flow from matrix to wellbore. When permeability difference in matrix and in fracture is small, fluid flow from matrix to wellbore can't be ignored, and the recovery difference is obvious. When permeability difference is constant, the influence of oil viscosity only works when permeability difference is less than 10 and influence mechanism is very complicate. The recovery curve difference is affected by fluid exchange difference and viscosity difference, obviously with the viscosity increase, the fluid exchange is more difficult both from matrix to fracture and from matrix to wellbore.

![Figure 4. DPDP and DPSP comparison under different permeability difference when \( \mu_o = 1 \text{cp} \).](image1)

![Figure 5. DPDP and DPSP comparison under different permeability difference when \( \mu_o = 25 \text{cp} \).](image2)
Figure 6. DDPDP and DPSP comparison under different permeability difference when $\mu_o=100$cp.

Table 2 shows oil recovery errors of DPSP under different permeability difference and oil viscosity. As can be seen from the table, oil recovery errors is mainly affected by permeability difference, when permeability difference is higher than 15, the oil recovery errors are less than 3%, and DDPDP can be equivalent to DPSP.

Table 2. Oil recovery errors of DPSP.

| $\mu_o$ | R=1   | R=2   | R=5   | R=10  | R=15  | R=25  |
|--------|-------|-------|-------|-------|-------|-------|
| 1cp    | 13.02%| 11.47%| 5.05% | -3.87%| -0.24%| 0.25% |
| 5cp    | 19.57%| 17.87%| 6.73% | 8.11% | 2.87% | 3.41% |
| 25cp   | 39.57%| 28.76%| 6.52% | 2.94% | 0.49% | 2.08% |
| 50cp   | 44.81%| 26.79%| 9.14% | 2.67% | 0.30% | -0.34%|
| 100cp  | 46.34%| 27.97%| 15.14%| 7.14% | 2.24% | 2.01% |
| 150cp  | 47.37%| 29.27%| 14.19%| 5.34% | 2.79% | 1.00% |

Figure 7. DDPDP and ESF comparison under different $N_f/N$ when $\mu_o=1$cp and 5cp.

3.2. Comparison between DDPDP and ESF

Figure 7 and Figure 8 show some simulation results of oil recovery comparison in DDPDP and ESF under different oil volume ratio and oil viscosity. Normally, the permeability difference is higher than 500 for the reservoir with fracture widely developed. In these cases, and oil volume ratio between fracture and total is considered an important factor influence the flow. As can be seen in Figure 4, when oil viscosity is constant, with the increase of oil volume ratio, the difference of oil recovery is smaller. When oil volume ratio is high, most oil distributed in fracture, and the flow in fracture is occupying the predominant position, therefore flow in matrix can be ignored, and ESF can represent...
DPSP. When oil volume ratio is constant, the influence of viscosity is very complicated, and when oil viscosity is from 25 cp to 50 cp, the two recovery curves are very similar no matter what the oil volume ratio is.

![Figure 8. DPDP and ESF comparison under different Nf/N when μo=25cp and 100cp.](image)

Table 3 shows oil recovery errors of ESF under different oil volume ratio and oil viscosity. As can be seen from the table, when oil volume ratio is higher than 0.9, or when oil viscosity is from 25 to 50 cp, DPDP can be equivalent to ESF.

| Table 3. Oil recovery errors of ESF. |
|----------------------------------------|
|                                   | Nf/N=0.3 | Nf/N=0.5 | Nf/N=0.7 | Nf/N=0.9 |
| μo=1cp                              | -14.81%  | -9.56%   | -4.39%   | -2.15%   |
| μo=5cp                              | 10.98%   | 5.71%    | 1.84%    | -1.03%   |
| μo=25cp                             | 0.00%    | 0.00%    | 0.00%    | 0.00%    |
| μo=50cp                             | 1.85%    | 2.38%    | 0.00%    | 0.49%    |
| μo=100cp                            | 10.11%   | 8.09%    | 4.24%    | -1.16%   |
| μo=150cp                            | 16.97%   | 15.00%   | 8.78%    | 0.00%    |

3.3. DPDP and ESM comparison

Figure 9 and Figure 10 show some simulation results of oil recovery comparison in DPDP and ESF under different permeability difference and oil viscosity. As can be seen from Figure 5, when oil viscosity is constant, with increase of permeability difference, the difference of the two recovery curves is bigger. When the permeability difference is constant, with the increase of viscosity, the difference of the two curves is smaller. ESM ignore the flow in fracture, the higher the permeability difference, the fluid flow in fracture is stronger, and the higher the oil viscosity the flow exchange between matrix and fracture is weaker. Therefore, ESM can equivalent to DPDP at high oil viscosity and low permeability difference.
Table 4 shows oil recovery errors of ESM under different permeability difference and oil viscosity. As can be seen from the table, when permeability difference is lower than 5, or when oil viscosity is higher than 50 cp, the oil recovery errors are less than 3%, and DPDP can be equivalent to EFM.

|     | R=1  | R=5  | R=8  | R=10 |
|-----|------|------|------|------|
| $\mu_o=1$cp | 0.12%| 0.32%| -11.11%| -12.64%|
| $\mu_o=5$cp | 0.43%| 2.88%| 9.64% | 11.49% |
| $\mu_o=25$cp | 0.00%| 0.54%| 6.12% | 7.61% |
| $\mu_o=50$cp | 0.00%| 0.75%| 1.11% | 2.67% |
| $\mu_o=100$cp | 0.00%| 0.71%| 1.33% | 2.05% |
| $\mu_o=150$cp | 0.00%| 0.66%| 0.71% | 1.53% |

3.4. Equivalence criterion of various models

From the simulation results, equivalence criterion of DPSP, ESF and ESM to DSDP has been established, as can be seen Table 5. When DPSP, ESF or ESM meet the criteria in Table 5, DPDP model can be replaced by the corresponding model. The equivalence criterion is able to overcome the blindness of model selection, and make it much faster and much easier for historical matching and scheme prediction of complex fractured reservoirs.
### Table 5. Equivalence criterion to DPDP of various models.

| Model | Equivalence criterion                        |
|-------|---------------------------------------------|
| DPSP  | $R > 15$                                    |
| ESF   | $R > 500$ & $(N_f/N > 0.9$ or $25 \text{cp} < \mu_o < 50 \text{cp}$) |
| ESM   | $R < 5$ or $\mu_o > 50 \text{cp}$          |

### 4. Field application

The K oil field is an offshore fractured carbonate reservoir with 4 platforms and 32 wells, the oil field was developed with early depletion then converted to water flooding. Take platform A as an example, the average permeability of the matrix is $100 \times 10^{-3} \mu m^2$ and average permeability of the fracture is $250 \times 10^{-3} \mu m^2$, the oil viscosity is 1.3 cp. There are 10 producers on-line for 6 years developed with natural energy, then two wells KE-06 and KA-08 converted to injection wells and continuing produced for 7 years. The geological model of the field was first built to DPSP, but history matching of the field is very difficult and time consuming due to weak convergence and long production history.

According to Table 5, this DPDP can be equivalent to ESM, as shown in Figure 11. The history matching results of the two models has been compared, as shown in Figure 12. From Figure 12, it can be seen, the history matching result of ESP (blue line) is acceptable, although not so good as DPDP (red line). The matching results in the late production period of ESP is excellent, and can be applied to carry out the development plan prediction. In addition, the running time of ESP model is only 100
minutes at 32 cores CPU, and that of DPDP is 400 minutes, which means that 70% times has been saved after equivalence. Therefore, lots of manpower and computer resources can be saved and simulation cost can be reduced greatly.

5. Conclusions
(1) There are four common reservoir models for fractured reservoir: DPDP, DPSP, ESF and ESM. DPDP is the primary choice for fractured reservoir simulation, but facing with problems of poor convergence and longtime of running period. Other three models can be equivalent to DPDP model under certain conditions.
(2) The equivalence criterion for different models has been studied. Permeability difference and viscosity are major parameters influencing equivalence criterion. When permeability difference is higher than 15, DPDP can be equivalent to DPSP. When oil volume ratio is higher than 0.9 or when oil viscosity is from 25 to 50 cp, DPDP can be equivalent to EFM. When permeability difference is lower than 5 or when oil viscosity is higher than 50 cp, DPDP can be equivalent to EFM.
(3) The study results have been applied in a fractured reservoir of K oilfield. Based on the equivalence criterion, the DPDP of this oilfield can be equivalent to EFM. After equivalence, 70% model running period has been saved, and the history matching result is good.

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