

UDC 55:51-7; 622.24

## DEVELOPMENT OF METHODOLOGY FOR COMPUTER-ASSISTED HISTORY MATCHING OF FRACTURED BASEMENT RESERVOIRS

Phan Ngoc Trung, Nguyen The Duc  
(Vietnam Petroleum Institute)

To obtain better simulation model for fractured basement reservoirs, one of the important research trend is to improve of workflow and method for calibrating model parameters to dynamic data (history matching). Analyzing challenges and solutions in fractured reservoir simulation in general and basement fractured ones in particular, a workflow for calibrating model parameters to dynamic data has been proposed. At each step of the workflow, calibration routine is accomplished using Computer-Assisted History Matching techniques. To perform calibration workflow with five steps by using computer-assisted history matching techniques, three computer programs have been developed. This paper presents our study in developing methodology and accompanied computer tools

**Keywords:** history matching, fractured basement reservoir, pseudo relative permeability, parameterization, optimization.

**E-mail:** trungpn@vpi.pvn.vn

**DOI:** 10.5510/OGP20120100098

### 1. INTRODUCTION

In practice, most simulation models for fractured basement reservoir in Vietnam, although have been elaborately developed and well history matched, still give prediction results largely different from reality. This repeated issue leads to a speculation that the traditional history matching workflow and method (with conventional reservoirs) may have points incompatible with the fractured basement reservoirs. Therefore, it is necessary to study for improving methodology of history matching fractured basement reservoirs. The proposed workflow and method for history matching are presented in Section 2. The description of computer programs developed for assisting proposed methodology is presented in Section 3.

### 2. PROPOSAL OF WORKFLOW AND METHOD

#### 2.1. Selection of dynamic modeling method for fractured basement reservoirs

The descriptions of single-porosity and dual-porosity modeling methods in reservoir simulations can be found in many publications (e.g. [1], [2]). Although the application of dual-porosity models can reproduce some typical behaviors of fluid flow in the natural fractured reservoirs (e.g. [3]-[5]), this kind of modeling method is not selected for reservoir simulations of fractured granite basements in Vietnam due to main reasons as follows:

1. Too many parameters of dual-porosity model for our fractured granite basement reservoirs to be determined by using the two medium. In reality, it is very difficult to determine. The high uncertainty of these model parameters can lead to the loss of credibility of prediction results.
2. Nowadays computer capabilities are still difficult to meet for simulations of real large reservoirs by using dual-porosity model.
3. The dual-porosity model may not exactly

simulate the behaviors of fluid flow in the fractured granite basement reservoirs. As described by many authors (e.g. [6]), one of the most important properties of fractured granite basement in Vietnam is that in which the matrix rock itself have no storage capacity and no permeability for oil. Oil is often localized in vugs, micro channels especially in open fractures. Because of the absences of both matrix-to-fracture and matrix-to-matrix flows, it may not be appropriate to apply the dual-porosity model (both single-permeability and dual-permeability idealizations) to the fractured granite reservoirs.

With above-mentioned features, fractured granite basement reservoirs of Vietnam should be seen as a porous medium with high heterogeneity and single-porosity model is suitable option for fluid flow simulation at present.

#### 2.2. Calibration workflow

The parameters selected to be calibrated in the proposed history-matching workflow are aquifer properties, permeability distribution, relative permeability curves, porosity distribution and rock compressibility.

The proposal of the history-matching workflow is based on the following principles:

- The overall calibration stage is first performed, and then the detailed distributions of parameters are adjusted.
- In each stage, the parameters with higher uncertainty are adjusted firstly and then the parameters with lower uncertainty.

It is noted that when the single-porosity model is used for fractured basement reservoir, the pseudo relative permeability curves can not be built. Then these parameters can be considered as to be highest uncertainty.

Considering the above principles, the proposed history matching workflow consists of the following

steps:

- Step 1:** Simultaneously calibrating the pseudo relative permeability curves and the overall degree of permeability anisotropy.
- Step 2:** Simultaneously calibrating the net pore volume, rock compressibility and aquifer parameters.
- Step 3:** Calibrating vertical permeability distribution.
- Step 4:** Calibrating horizontal permeability distributions.
- Step 5:** Calibrating porosity distribution.

### 2.3. Proposed Calibration method

The calibration method in each step is developed using computer-assisted history matching techniques. In this approach, the optimization algorithms are used to find the location corresponding to minima of the objective function which quantify the mismatch between measurement and calculation of the two types of well data: water cut and shut-in pressure. Value of the objective function is calculated as the combination of two overall standard deviations (root-mean-square deviations) between measurement and calculation of water rate and shut-in pressure in all wells and at all times that have measured data:

$$E = \left( \alpha_R^2 \cdot E_R^2 + \alpha_P^2 \cdot E_P^2 \right)^{\frac{1}{2}} \quad (1)$$

Where:

- $E_R$  is the overall standard deviation of water rate (Equation (2)).
- $E_P$  is the overall standard deviation of pressure (Equation (4)).
- $\alpha_R$  and  $\alpha_P$  are the weighted factors.

The overall standard deviation of the water rate is determined from the mismatches between the measurement and calculation of all the wells and at all measuring times:

$$E_R = \left( \frac{\sum_{j=1}^{NW} \sum_{i=1}^{NO_j} (qw_{j,i}^{obs} - qw_{j,i}^{sim})^2}{\sum_{j=1}^{NW} NO_j} \right)^{\frac{1}{2}} \quad (2)$$

where  $j$  is the index of the well,  $NW$  is the number of the wells,  $i$  is the index of the measurement times,  $NO_j$  the number of measurement times of the  $j$  th well,  $qw_{j,i}^{obs}$  is the measured water rate of the well and  $qw_{j,i}^{sim}$  is the calculated water rate of the  $j$  th well at the  $i$  th measurement time. The denominator in Equation (2),  $\sum_{j=1}^{NW} NO_j$ , represents the number of the water rate measurement data of all wells.

The degree of water rate matching at  $j$ -th well is evaluated as follows:

$$E_{R,j} = \left( \frac{\sum_{i=1}^{NO_j} (qw_{j,i}^{obs} - qw_{j,i}^{sim})^2}{NO_j} \right)^{\frac{1}{2}} \quad (3)$$

Similarly, the overall standard deviation of the well pressure between measurement and calculation is calculated according to expression:

$$E_P = \left( \frac{\sum_{j=1}^{NW} \sum_{i=1}^{NO_j} (p_{j,i}^{obs} - p_{j,i}^{sim})^2}{\sum_{j=1}^{NW} NO_j} \right)^{\frac{1}{2}} \quad (4)$$

Where  $p_{j,i}^{obs}$  is the measured pressure and  $p_{j,i}^{sim}$  is the calculated pressure at the  $i$ -th measurement time of the  $j$ -th well; other symbols have the same meaning as in Equation (2).

The degree of pressure matching at  $j$ -th well is evaluated as follows:

$$E_{P,j} = \left( \frac{\sum_{i=1}^{NO_j} (p_{j,i}^{obs} - p_{j,i}^{sim})^2}{NO_j} \right)^{\frac{1}{2}} \quad (5)$$

Minimizing the objective function calculated by Equations (1)-(5) means to minimize the mismatches between measurement and calculation of all the wells and at all measurement times. In some cases, to avoid the big difference between modified and initial porosity distributions obtained from geological model, the regularization method is employed with the objective function (1) has the following form:

$$E = \left( \alpha_R^2 \cdot E_R^2 + \alpha_P^2 \cdot E_P^2 \right)^{\frac{1}{2}} + \sigma_r \left[ \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} \sum_{k=1}^{N_z} (\phi_{ijk}^{new} - \phi_{ijk}^{prior})^2 \right]^{\frac{1}{2}} \quad (6)$$

where  $N_x$ ,  $N_y$ ,  $N_z$  are the number of grid cells in the  $x$ ,  $y$ ,  $z$  directions,  $\phi_{ijk}^{prior}$  and  $\phi_{ijk}^{new}$  are the initial and modified value of cell porosity,  $\sigma_r$  is the regularization factor.

The next contents of the paper presents the technical basis of the computer program is designed to support implementation of the proposed workflow and method.

### 3. TECHNICAL DESCRIPTION OF COMPUTER PROGRAMS FOR ASSISTED HISTORY MATCHING

To perform calibration workflow with five steps as suggested above by using computer-assisted history matching techniques, three computer programs have been developed, including:

1. *Program calibrating pseudo relative permeability curves and overall permeability anisotropy* (Program 1). This computer program is used in Step 1.
2. *Program calibrating reservoir pore volume, rock compressibility and aquifer parameters* (Program 2). This computer program is used in Step 2.
3. *Program calibrating permeability and porosity distributions* (Program 3). This program is used in Step 3, Step 4 and Step 5.

The most important part in the developed computer

programs uses optimization algorithms for minimizing objective function. The parameterization techniques are developed and used in the computer program to reduce the number of variables of optimization problems. Detailed descriptions of parameterization techniques, optimization problems, optimization algorithms and geologically consistent method are presented in the following sections.

### 3.1. Parameterization technique and optimization problem in Computer Program 1

Program 1 is developed to assist in calibrating pseudo relative permeability curves and overall permeability anisotropy (Step 1). Due to importance and high uncertainty of these reservoir attributes, they are selected to adjust first in proposed history matching workflow.

The relative permeability curves show the dependence of the relative permeability on phase saturation. In order to calibrate relative permeability curves, it is necessary to represent these curves by a number of parameters (parameterization). Then the calibration of relative permeability will be performed by adjusting the parameter values.

One of the simplest approaches for parameterization of relative permeability curves is to employ Corey type curves [7]. Using Corey function, the relative permeability of oil and water are presented as follows:

$$k_{ro}(S_w) = \left( \frac{1 - S_w - S_{or}}{1 - S_{wc} - S_{or}} \right)^a$$

$$k_{rw}(S_w) = \left( \frac{S_w - S_{ow}}{1 - S_{wc} - S_{or}} \right)^b * k_{rwmax}$$
(7)

In general, three parameters (a, b) and the water relative permeability at maximum water saturation ( $k_{rwmax}$ ) are adjusted in history matching for conventional reservoirs. However, for fractured basement reservoir, because of high uncertainty of irreducible water saturation  $S_{wc}$  and residual oil saturation  $S_{or}$  these two parameters should be also adjusted. Therefore, five parameters need to be adjusted for calibration of oil and water relative permeability curves in Corey type for fractured basement reservoirs.

Another approach for parameterization of relative permeability curves has been proposed by Chierci [8]. The Chierici function presents the dependence of relative permeability on saturation in the following form:

$$k_{ro}(S_w) = \exp \left[ -a \left( \frac{S_w - S_{wc}}{1 - S_w - S_{or}} \right)^b \right]$$

$$k_{rw}(S_w) = \exp \left[ -c \left( \frac{S_w - S_{wc}}{1 - S_w - S_{or}} \right)^{-d} \right] * k_{rwmax}$$
(8)

Chierici function has two parameters more than Corey function. There are 7 parameters for calibration of pseudo relative permeability curves for oil and water in fractured basement reservoirs.

Besides these two mentioned types, other function types can be also used for parameterization of relative permeability curves in history matching reservoir model. In the work presented in the paper, approximation

of relative permeability curves in Corey function is employed.

Overall calibration of permeability anisotropy is performed by adjusting three multiplying factors for three directional permeability values:

$$k_x(i, j, k) = \lambda_{per,x} k^0(i, j, k)$$

$$k_y(i, j, k) = \lambda_{per,y} k^0(i, j, k)$$

$$k_z(i, j, k) = \lambda_{per,z} k^0(i, j, k)$$
(9)

Where (i, j, k) is the index of grid cells;  $k_x$ ,  $k_y$  and  $k_z$  are the permeability values in x, y, z directions respectively;  $k^0$  is initial permeability obtained from geological model.

Using above parameterization techniques, simultaneous calibrations of pseudo relative permeability curves and overall permeability anisotropy can be performed by solving the following optimization problem:

Determine the values of 8 parameters: a, b,  $k_{rwmax}$ ,  $S_{WC}$ ,  $S_{orr}$ ,  $\lambda_{per,x}$ ,  $\lambda_{per,y}$  and  $\lambda_{per,z}$  in order to minimize:

$$E = E(a, b, k_{rwmax}, S_{WC}, S_{orr}, \lambda_{per,x}, \lambda_{per,y} \text{ and } \lambda_{per,z})$$
(10)

with E is calculated from Equation (1)

The optimization algorithms (presented in Section 2.5) are used to find the best parameter values (a, b,  $k_{rwmax}$ ,  $S_{WC}$ ,  $S_{orr}$ ,  $\lambda_{per,x}$ ,  $\lambda_{per,y}$  and  $\lambda_{per,z}$ ) and then determine the pseudo relative permeability curves and the permeability anisotropy factors which give the best agreement between measurement and simulation.

### 3.2. Parameterization technique and optimization problem in Computer Program 2

The values of reservoir pore volume, rock compressibility and aquifer parameters have strong effects on simulated pressure of all well in the reservoir. Therefore, they are simultaneously adjusted in the proposed history matching workflow.

Calibration of the reservoir pore volume is carried out by adjusting a multiplying factor  $\lambda_{por}$  for all grid cell porosity values  $\varphi(i, j, k)$ :

$$\varphi(i, j, k) = \lambda_{por} \varphi^0(i, j, k)$$
(11)

where  $\varphi^0(i, j, k)$  are the initial porosity values of grid cells (i, j, k).

The rock compressibility factor ( $c_{por}$ ) can be adjusted without parameterization or using a multiplying factor. In general, reservoir simulators use a value of rock compressibility for a reservoir.

For aquifer parameters, it is assumed that the aquifer position has been determined and the calibrations are only performed for aquifer properties such as thickness, porosity, permeability, angle of influence ... The specific parameters may vary depending on aquifer type used in the simulation model. Assuming the aquifer parameters need to be adjusted are  $\lambda_{aq,1}$ ,  $\lambda_{aq,2}, \dots, \lambda_{aq,N}$ , simultaneous calibration of reservoir pore volume, rock compressibility and aquifer parameters can be performed by solving the following optimization problem:

Determine the values of parameters:  $\lambda_{por}$ ,  $c_{por}$ ,  $\lambda_{aq,1}$ ,  $\lambda_{aq,2}, \dots, \lambda_{aq,N}$  in order to minimize:

$$E = E(\lambda_{por}, c_{por}, \lambda_{aq,1}, \lambda_{aq,2}, \dots, \lambda_{aq,N})$$
(12)

with  $E$  is calculated from Equation (1)

### 3.3. Parameterization technique and optimization problem in Computer Program 3

The parameterization techniques in program 3 are developed by using the pilot point method. The basis of pilot points as a method of spatial parameter definition is that parameter values are assigned to a set of points distributed throughout the model domain rather the directly to every grid cells of a numerical model. Parameter values are then assigned to the grid cells through spatial interpolation from pilot points to the grid. If we select  $n$  pilot points which are centers of grid cells  $(i_p, j_p, k_p)$   $p = 1, \dots, n$  and use  $n$  multiplying factors  $X_p$  for calibrating the values of permeability (or porosity) for these grid cells:

$$\psi(i_p, j_p, k_p) = X_p \psi^0(i_p, j_p, k_p) \quad \text{with } p = 1, \dots, n \quad (13)$$

Then the permeability (or porosity) values of all grid cells in the model domain will be adjusted as follows:

$$\psi(i, j, k) = X(i, j, k) \psi^0(i, j, k) \quad \text{with } \forall i, j, k \quad (14)$$

where  $X(i, j, k)$  is calculated by spatial interpolation from the factors  $X_p$ .

By using the parameterization technique described by Equations (13)-(14), calibrations of permeability or

porosity distributions can be performed by minimizing the function:

$$E = E(X_1, X_2, \dots, X_n) \quad (15)$$

### 3.4. Optimization algorithms in 3 computer programs

Seven conventional optimization algorithms can be selected to be used in three developed computer programs, namely:

1. Steepest descent method ([9]-[11]).
2. Gauss-Newton method ([12]-[13]).
3. Simultaneous Perturbation Stochastic Approximation Method-SPSA method ([15]-[17]).
4. SIMPLEX method ([11], [14]).
5. Direction Set Methods ([13], [18]).
6. Conjugate Gradient Method ([9]-[11]).
7. Variable metric methods ([11], [19]).

The detailed descriptions of the listed algorithms can be found in the references.

## 4. CONCLUSION

A workflow for history matching of fractured basement reservoir simulation models has been proposed. The method adjusting parameters is developed based on computer-assisted history matching techniques.

Three computer programs have been built to perform the proposed history matching workflow and method.

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## Разработка методологии компьютеризированной настройки модели коллекторов с трещиноватыми геологическими фундаментами

Фан Нгок Чунг, Нгуен Че Дук  
(Вьетнамский Институт Нефти)

### Реферат

Одной из важных тенденций исследования для получения лучшей имитационной модели коллекторов с трещиноватым фундаментом, является совершенствование технологического процесса и метода калибровки параметров моделей с использованием динамических данных (восстановление истории). На основе анализа проблем и решений при моделировании трещиноватых коллекторов в целом и коллекторов с трещиноватым геологическим фундаментом в частности, была предложена технология калибровки параметров модели с использованием динамических данных. На каждом этапе рабочего процесса, калибровка выполняется с помощью Метода Компьютеризированной Настройки Модели. Для выполнения процесса калибровки в пять этапов, используя метод автоматизированной настройки модели, разработаны три компьютерные программы. Данная статья представляет наше исследование в области разработки этой методологии и соответствующих вычислительных средств.

## Çatlı geoloji fundamentli kollektorların modelinin kompyüter sazlanması metodologiyasının işlənilib hazırlanması

Fan Nqok Çunq, Nquyen Çe Duk  
(Vyetnam Neft Institutu)

### Xülasə

Çatlı fundamentli kollektorların ən yaxşı imitasiyamodelinin alınması üçün tədqiqatın ən vacib tendensiyalarından biri texnoloji proseslərin və dinamik məlumatlardan (tarixi bərpa etmək) istifadə etməklə modellərin parametrlərinin kalibrlənməsi üsulunun təkmilləşdirilməsidir. Bütövlükdə çatlı fundamentli kollektorların və xüsusilə çatlı geoloji fundamentli kollektorların modelləşdirilməsində, problem və qərarların təhlilinə əsaslanan dinamik məlumatlardan istifadə etməklə modelin parametrlərinin kalibrlənməsi texnologiyası təklif edilmişdir. İş prosesinin hər bir mərhələsində kalibrlənmə, Modelin Sazlanmasının Avtomatlaşdırılması Üsulunun köməyi ilə yerinə yetirilir. Modelin Sazlanmasının Avtomatlaşdırılması Üsulundan istifadə etməklə kalibrlənmə prosesinin beş mərhələdə yerinə yetirilməsi üçün 3 (üç) kompyüter proqramı işlənilib hazırlanmışdır. Məqalə, bu metodologiyanın işlənilib hazırlanması və uyğun hesablaşma vasitələri sahəsində bizim tədqiqatları təqdim edir.