UPSCALING METHOD OF RELATIVE PERMEABILITY FROM PLUG CORE TO WHOLE CORE

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ABSTRACT

This paper presents the results of the interpretation of several unsteady-state coreflood experiments and discusses a method to estimate the relative permeability of the whole core using the data of the smaller scale cores and their characteristics. A water displacement test was conducted on a heterogeneous carbonate whole core (target core), then a series of the same test followed on the several plug cores that were extracted from the target core. Each test on the plug cores was interpreted by 3D coreflood simulation model that was constructed based on the detailed core characterization data. A newly developed simulation matching program called GEMAP *[(1)] that adopted genetic algorithm was employed to derive a set of normalized kro/krw and Pc curves representing each pore-type as grid data. The relative permeability curves of the plug cores were computed by the two-phase upscaling in-house program called CAVLUP *[(2)] that was initially developed for reservoir-scale upscaling problem. Both capillary-limit and viscous-limit upscaled kro/krw curves were computed by the program. The kro/krw curves were also determined by different method i.e. steady-state coreflood simulation and compared with the upscaled curves. The result showed that the capillary-limit upscaling method could reasonably reproduce the kro/krw curve generated by steady-state coreflood simulation of the same displacement velocity to that of the actual experiment. Based on the statistical data of porosity, permeability and pore-type, 3D stochastic models were constructed for the target core. A total of 100 kro/krw curves were computed using CAVLUP. On the other hand, 3D deterministic model was constructed to re-optimize the kro/krw and Pc curves of each pore-type and compute kro/krw curve by simulation matching. The result showed that the average upscaled curve of the stochastic models was close to that of the optimized model. It was concluded that the kro/krw curve of the target core could be reasonably estimated from plug-core-scale data by the same upscaling method as applied to reservoir scale problem.

INTRODUCTION

Upscaling is one of such the techniques that assign representative properties to each simulation block of a coarse grid model using parameters of a fine grid model. In general, the objective of upscaling is to reduce the number of grid-blocks of a flow model so that a flow simulation can be conducted in a reasonable range of computation time retaining the characteristics of the heterogeneity and the multiphase flow in the resultant upscaled flow model. Although several techniques were reported to be effective in upscaling problem of reservoir-scale simulation, the aspect of upscaling of laboratory data has not been investigated in depth. Indeed, it is practically impossible to obtain a core plug that represents certain reservoir-scale simulation block, unless the reservoir is relatively homogeneous. The question is how we can upscale core-size data such as relative permeabilities and capillary pressures measured by laboratory experiments to utilize as input data of simulation model for heterogeneous reservoir. The motivation of the laboratory-based study described in this paper is to seek a possible approach to answer the question by solving core-scale problem i.e. how we can estimate the relative permeability of the whole core using the data of smaller scale cores. For this purpose we conducted many unsteady-state coreflood experiments on one heterogeneous carbonate core, first using as a whole core and afterwards as several small plug cores. These data were fully interpreted by the coreflood simulation-matching program. The in-house upscaling program was also utilized to compute the kro/krw curves of the cores.

LABORATORY EXPERIMENTS

OVERALL WORKFLOW

The overall workflow of the laboratory experiments is shown in Figure 1. In order to develop an upscaling method to estimate the relative permeability of certain target core samples using data of smaller scale cores, we selected one visually heterogeneous carbonate whole core as the target core and first conducted water displacement test on the core under X-ray CT scanner that has a resolution of 0.35mm span. After the test the core was cleaned and cut into two pieces. Then the total of six 1 inch-diameter plug samples were drilled out from the cut pieces. The remaining portion of the whole core was sliced into ten pieces of a half inch in thickness and forwarded to the detailed core characterization such as minipermeameter measurement, thin section, SEM, specific surface area, pore throat size distribution measurement etc. Then a series of water displacement test was carried out on the plug cores. They were also forwarded to the detailed core characterization similar to that of the target core. The coreflood simulation models of the plug cores were constructed based on such characterization data and each test was interpreted by simulation matching. The coreflood simulation model was also constructed for the target core to determine the kro/krw curve.

EXPERIMENTAL PROCEDURE

The core was cleaned using toluene, methanol and methyl chloride/acetone mixture then dried in a humidity-controlled oven at 80°C. After the conventional core analysis, both side faces of the core were measured by minipermeameter with 5mm span to investigate the permeability distribution. The core was mounted on the coreflood apparatus under X-ray CT scanner and saturated by synthetic formation brine doped with 15% NaI. The un-doped brine was injected to monitor the frontal advancement that could be relating to the absolute permeability distribution [*(3)]. The core was again saturated with the doped brine and then displaced with dead oil till Swir. The oil was replaced with the recombined oil and aged under reservoir temperature of 100°C for 3 weeks. The recombined oil was replaced with dead oil and then unsteady-state water displacement test was carried out under X-ray CT scanning at 60°C. The fluids remaining in the core were extracted by

Soxhlet and then the core was dried. We applied the same procedure to both the target core and the plug cores. In the case of the plug cores, they were finally sliced into several disks of 1 cm in thickness and forwarded to the detailed core characterization.

CORE CHARACTERIZATION

One whole core sample that was recovered from a Cretaceous carbonate reservoir in Middle East was used for the study. The sample was mainly composed of algal bioclastic peloidal packstone/grainstone. The dimension of the sample was 3.5 inch in diameter and half foot in length. The average porosity and air permeability were 32.2% and 30.7mD respectively. After the drill-out of the plug cores, the sample was sliced into ten disks and more than fifty 10 mm diameter chips were also extracted from them for the detailed core characterization. Figure 2 shows the schematic of preparation/ analysis work on the target core.

Based on the detailed petrographical and petrophysical analysis, the sub-region pore-type composing the core was finally classified into three pore-types i.e. poorly to moderately sorted bioclastic-peloidal grainstone/packstone (Pore-type A), fine grained peloidal packstone (Pore-type B) and algal fragment (Pore-type C). Although we attempted to classify the pore-types into more number of groups based on, for example, cross-plot of porosity vs. permeability, no clear trend and relation with those three pore-types were found from the plot. Figure 3 shows the summary of the classification of pore-type that provided the basis of the construction of 3D coreflood simulation models. It is shown that the target core was moderately heterogeneous having the overall permeability range from 8mD to 228mD measured by minipermeameter.

INTERPRETATION OF WATER DISPLACEMENT TESTS ON PLUG CORES

The water displacement tests were interpreted by constructing 3D coreflood simulation models. In order to improve the accuracy and the efficiency of the interpretation process, an automated simulation-matching program called GEMAP was developed based on genetic algorithm. The next section briefly describes the program.

BRIEF DESCRIPTION OF GEMAP

There are many methods available to find some suitable solution for certain problem such as we find in history matching. If the search space spreads widely i.e. the problem is complicated, some methods show a local extreme, either minimum or maximum point as a result. Genetic algorithm that applies Darwin’s theory about evolution is one of the most suitable methods to solve such problems. It starts with a set of solutions called population that are represented by chromosomes. Solutions from one population are taken and used to form a new population that is more suitable to certain conditions by means of such as selection, crossover, and mutation.

In applying genetic algorithm to automated simulation-matching program for coreflood experiments, it is necessary to consider how to describe the problem and evaluate multiple solutions of equations. The objective of the program is that the unknown grid parameters i.e. kro/krw and Pc curves are to be optimized by reasonable matching with experimental data such as changes of grid water saturation and differential pressure during displacement test. In this program, normalized relative permeability and capillary pressure curves are defined by the following equations.

$$k_{ro}(S_w) = k_{ro\max} R_1^{\ no} \tag{1}$$

$$k_{rw}(S_w) = k_{rw\max} R_2^{\ nw} \tag{2}$$

$$P_c = P_{c\max}\left[(1-c+d)R_1^a + cR_2^b - dR_1 + c\right] \tag{3}$$

$$R_1 = \frac{1-S_w-S_{or}}{1-S_{wi}-S_{or}} \tag{4}$$

$$R_2 = \frac{S_w-S_{wi}}{1-S_{wi}-S_{or}} \tag{5}$$

Eq. (1) and (2) are "power-law" expressions and include 4 unknown parameters (*no, nw*, k_{romax}, k_{rwmax}). Eq. (3) is a newly defined equation with 5 unknown parameters (*a, b, c, d*, P_{cmax}) that enables to express oil-wet Pc curve

In this program, population consists of n pieces of chromosomes (solutions). Each chromosome contains information of 9 coefficients that are shown in Eq. (1)-(5) as unknown parameters. Each parameter is encoded to one binary string. All parameters are joined together and show one chromosome.

In order to evaluate matching degree of accuracy, a fitness function was defined as follows.

$$F_{obj} = W_{sw}\frac{\sum_{ijkt=1}^{ijkt\max}\left(W1_t W_{ijkt} A_{ijk}\left|Sw_{ijkt}^{sim} - Sw_{ijkt}^{\exp}\right|\right)}{\sum_{ijkt=1}^{ijk(\max)}\left(W1_t W_{ijkt} A_{ijk}\right)} + W_{dp}\frac{\sum_{t=1}^{t\max}\left(W2_t\left|dP_t^{sim} - dP_t^{\exp}\right|\right)}{\sum_{t=1}^{t\max} W2_t} \tag{6}$$

The fitness function is calculated by comparing difference between experiments results and simulation results for every time step. Water saturations are compared for every grid in Eq. (6), because water saturation data are taken for each grid location in experiments under X-ray CT scanning. On the other hand, only one differential pressure is taken in each time step. In order to meditate the difference of the dimensions between water saturation and differential pressure, there are lot of weighting factors i.e. W defined in the fitness function.

KRO/KRW AND PC CURVES FOR EACH PORE-TYPE

A total of eight water displacement tests were carried out on the six 1 inch-diameter plug samples. Due to the experimental problems e.g. permeability deterioration during oil drainage or core breaking/ crushing before and after flooding tests, only three tests i.e. 77DL, 79UU and 80DU were subjected to the detailed interpretation by 3D coreflood simulation model. Each model was composed of 5mm length cubes taking into account of the measurement density by minipermeameter and constructed from available data such as X-ray CT porosity/ S_{wi}/ S_{or}, minipermeameter permeability and distribution of pore-types. The unknown parameters of kro/krw and Pc curves of each pore-type were derived from the matching of these three tests with the experimental data such as changes of water saturation of each grid-cell and differential pressure during the test. We first optimized the unknown parameter of Pore-type A by simulation matching on 77DL because the core was composed of 98% of the pore-type. Then the optimization of Pore-type B and C were carried out mainly by simulation matching on 79UU and 80DU respectively. As a result, a unique set of kro/krw and Pc curves was derived for the three pore-types. Figure 4 presents the denormalized curves using the average end point data of all the grids.

Figure 5 shows the example of the result of the matching of the water displacement test conducted on the core 79UU in terms of the average water saturation, the differential pressure and the water-cut. Figure 6 also shows the result of the matching with the average water saturation changes in the positions of every 5mm distance from the inlet. The degree of the matching of this test as well as the other two tests, though they were not shown in this paper, was quite acceptable from our experience.

KRO/KRW CURVE FOR EACH PLUG SAMPLE

The relative permeability representing each plug sample was evaluated by steady-state coreflood simulation under two different displacement velocities i.e. low velocity of 0.05cc/min, the same velocity to that of the experiment, and high velocity of 5cc/min, hypothetical experimental velocity for comparison purpose. On the other hand, we applied the two-phase upscaling program called CAVLUP to compute the kro/krw curve for both capillary-limit and viscous-limit cases. The two-phase upscaling method is an extension of the following single-phase upscaling correlation (Eq. (7)) that was derived from an intensive numerical experiment.

$$\log(\overline{k_h}) = 0.3634\log(k_h^+) + 0.6318\log(k_h^-) + 0.0156 \tag{7}$$

As shown in Figure 7, it was found that the capillary-limit upscaling could reasonably reproduce the kro/krw curve generated by the steady-state coreflood simulation of the same displacement velocity to that of experiment. This result agrees to the study carried out by S. Ekrann et al. [*(4)]. It was also shown that the kro/krw curve of the viscous-limit upscaling was close to that of the hypothetical simulation result. Figure 8 shows the upscaled kro/krw curves of the three plug samples computed by the program.

ESTIMATION OF KRO/KRW CURVE OF TARGET CORE

Based on the statistical data of porosity, permeability and pore-type as well as the kro/krw and Pc curves of three pore-types derived in the previous section, 3D stochastic models were constructed for the target core. The variations of the grid parameters such as porosity and permeability were within the range of the actual measurement data obtained from X-ray CT and minipermeameter. The percentage of the three pore-types was assumed to be constant. These statistical data are shown in Figure 9. A total of 100 upscaled kro/krw curves were generated using CAVLUP and the result was that all the kro/krw curves almost converged into one curve as shown in Figure 10(a). To assess this trend the percentage of Pore-type B and C were exchanged and another set of kro/krw curves were generated. The result is presented in Figure 10(b) that shows the similar trend to Figure 10(a), although the average curves of both cases are different. This means that the kro/krw curve is not affected by the variation of the permeability distribution but the percentage of pore-types. Naji Saad et al. [*(5)] also reported the independence of the upscaled kro/krw curve on the permeability distribution.

To compare the average kro/krw curve of Figure 10(a) with that of the target core, 3D deterministic model was constructed. The kro/krw curve was determined by CAVLUP after re-optimization of the parameters of kro/krw and Pc curves of each pore-type by simulation matching with GEMAP. The result showed that the upscaled average kro/krw curve of stochastic models was close to that of the 3D deterministic model as shown in Figure 11. Thus, it was concluded that the kro/krw curve of the target core could be reasonably estimated by applying the procedure as follows:

Step 1: Conduct water displacement tests on plug cores.
Step 2: Conduct detailed core characterization
Step 3: Construct 3D coreflood simulation model
Step 4: Conduct simulation matching and derive representative kro/krw and Pc curves for each pore-type using GEMAP
Step 5: Estimate percentage of pore-types of target core and construct stochastic models
Step 6: Predict kro/krw curve of the target core using CAVLUP

DISCUSSIONS

The approach seeking the kro/krw curve of certain part of the core through the process of the matching with the data of the coreflood experiment is seen in the work by C. Dabbouk et al. [*(6)]. Their concern was to estimate the kro/krw and Pc curves for some vuggy high permeable layer that was partially included in the core. Although the approach is similar, our process of interpretation is more rigorous in terms of the method of matching and the number of experiments.

The upscaling method described in this paper has also a potential to extend from core-scale to the size of a geological fine cell when sufficient numbers of the upscaled kro/krw curves are generated in the core-scale. The upscaled curve of the fine cell can be obtained by means of stochastic modeling if the statistical data, especially the percentage of the core-scale rock-type composing of the cell are provided. A. Kumar et al. [*(7)] proposed a hierarchical upscaling because different upscaling techniques are required at each scale for process-dependent reasons and also different correlation of physical properties are required in some regions or at some scales. The biggest advantage of our method is that it is process-independent and thus can be commonly used for multi-step upscaling from pore-scale to core-scale, and further to reservoir simulation-scale in a consistent manner.

CONCLUSIONS

The CAVLUP program that was initially developed for upscaling of reservoir-scale simulation study was demonstrated to be an effective tool to compute whole-core-scale kro/krw curves from plug-core-scale data. The following procedure is proposed to predict the kro/krw curve of the target core.

Step 1: Conduct water displacement tests on plug cores.
Step 2: Conduct detailed core characterization
Step 3: Construct 3D coreflood simulation model
Step 4: Conduct simulation matching and derive representative kro/krw and Pc curves for each pore-type using GEMAP
Step 5: Estimate percentage of pore-types of target core and construct stochastic models
Step 6: Predict kro/krw curve of the target core using CAVLUP

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(6) Chawki Dabbouk, Liaqat Ali, Glyn Williams and Garry Beattie, “SPE 78530 Waterflood in Vuggy Layer of Middle East Reservoir - Displacement Physics Understood” presented at the 10th Abu Dhabi International Petroleum Exhibition and Conference, 13-16 October 2002

(7) A. Kumar. C.L. Farmer, G.R. Jerauld and D. Li, “SPE 38744 Efficient Upscaling from Cores to Simulation Models” presented at the 1997 SPE Annual Technical Conference and Exhibition held in San Antonio, 5-8 October 1997

Nomenclature

A_{ijkt} = Flag for active cell @(i, j, k, t)

a = Unknown parameter for capillary pressure

b = Unknown parameter for capillary pressure

c = Unknown parameter for capillary pressure

d = Unknown parameter for capillary pressure

$dp_t^{\exp}$ = Differential pressure of experiment @(t)

dp_t^{sim} = Differential pressure of simulation @(t)

k_{ro} = Oil phase relative permeability

$k_{ro\max}$ = Oil phase relative permeability @ S_{wi} (unknown parameter)

k_{rw} = Water phase relative permeability

$k_{rw\max}$ = Water phase relative permeability @ S_{or} (unknown parameter)

no = Unknown parameter for oil phase relative permeability

nw = Unknown parameter for water phase relative permeability

P_c = Capillary pressure

PV = Pore volume

S_w = Water saturation

S_{wi} = Initial water saturation

S_{or} = Critical oil saturation

S_{ijkt}^{sim} = Grid water saturation of simulation @(i, j, k, t)

S_{ijkt}^{sim} = Grid water saturation of experiment @(i, j, k, t)

$W1$ = Weight of time for dp

$W2$ = Weight of time for S_w

W_{dp} = Weight of dp

W_{sw} = Weight of S_w

W_{ijkt} = Weight of cell *@(i, j, k, t)*

$\overline{k_h}$ = Upscaled absolute permeability of horizontal direction

k_h^+ = Upper bound average permeability defined by Li et al. in SPERE 2001

k_h^- = Lower bound average permeability

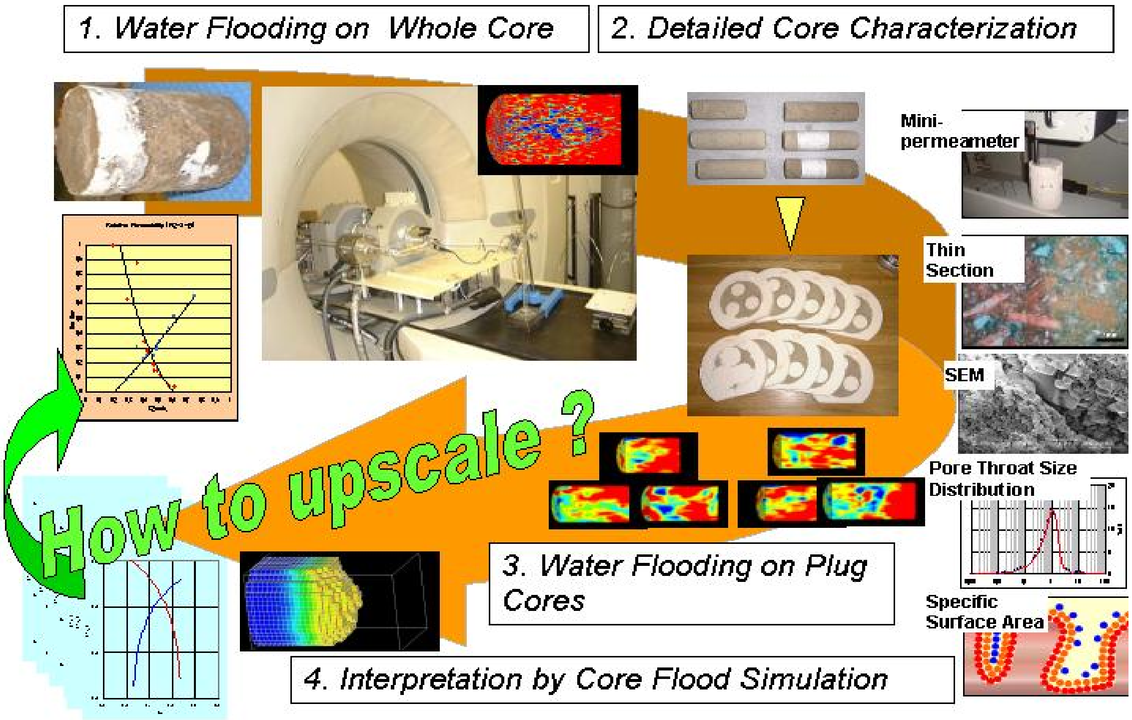


Figure 1. The overall workflow of the laboratory experiments

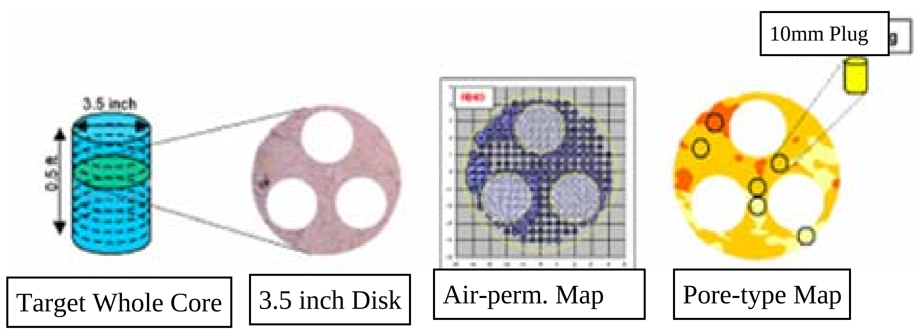


Figure 2. The schematic of preparation/ analysis work on the target core

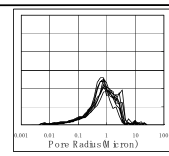
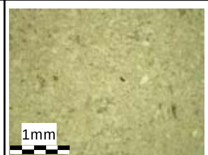
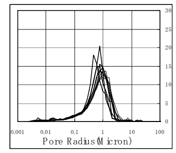
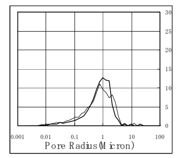
Pore-type (Properties)	Photomicrograph	Air-permeability (md)	Porosity (%)	Pore Throat Size Distribution
Pore-type A **Coarse PK/GRst** (Burrow fill Intergranular Pore, Micro Pore)		23 - 228	28 - 32	
Pore-type B **Fine WK/PKst** (Micrite, Matrix Micro Pore)		8 - 35	22 - 32	
Pore-type C **Algal Fragment** (Intragranular Pore, Vug)		24 - 40	28 - 30	

Figure 3. The summary of the classification of pore-type

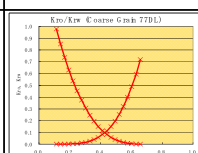
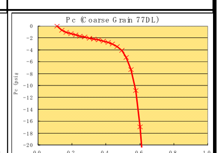
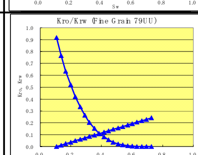
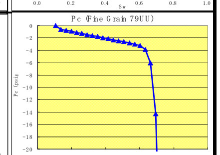
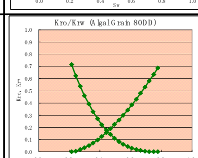
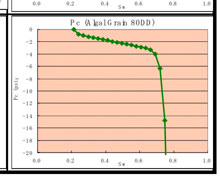
Pore-type (Properties)	Pore - Kro/Krw	Pore - Pc
Pore-type A **(Coarse PK/GRst)**		
Pore-type B **(Fine WK/PKst)**		
Pore-type C **(Algal Fragment)**		

Figure 4. The denormalized curves of each pore-type

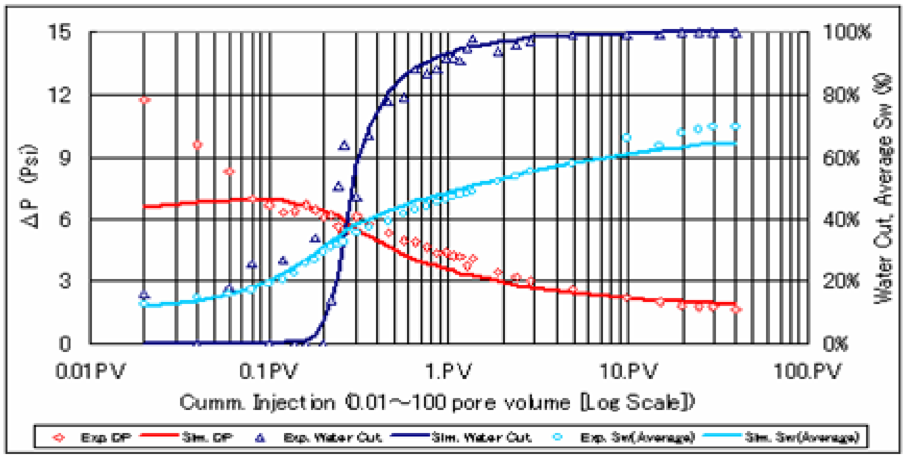


Figure 5. Example of core 79UU: matching of average water saturation, differential pressure and water-cut

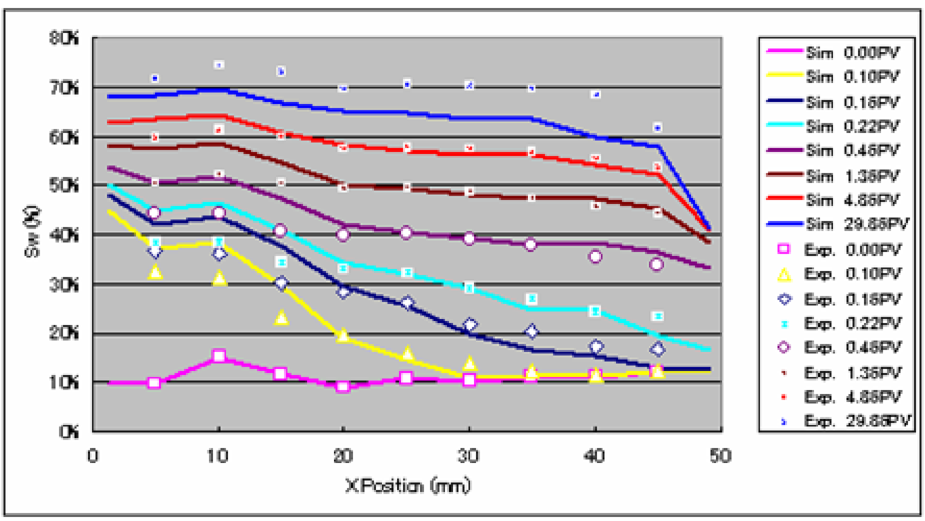


Figure 6. Example of core 79UU: matching of average water saturation profile changes

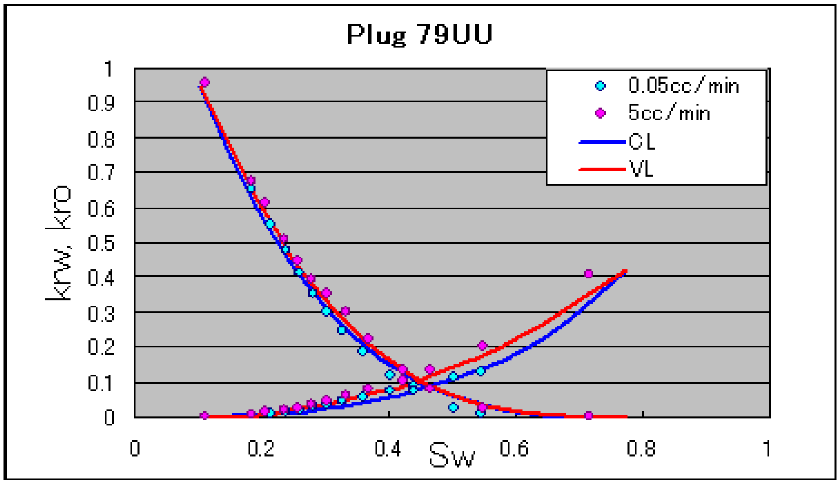


Figure 7. Comparison of kro/krw curves: steady-state coreflood simulation vs. upscaling by CAVLUP

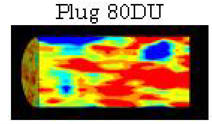
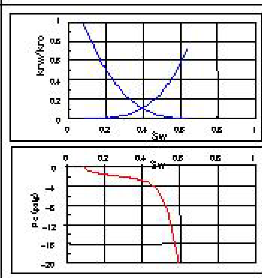
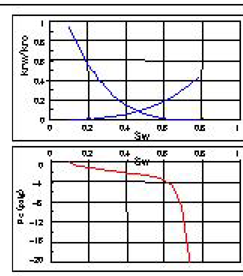
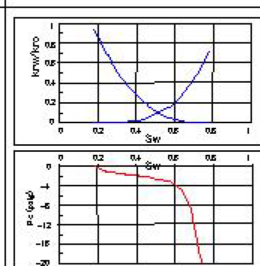
	Plug 77DL	Plug 79UU	Plug 80DU
			
Pore-type A	98.0%	53.1%	78.9%
Pore-type B	1.2%	46.5%	0.6%
Pore-type C	0.8%	0.4%	20.6%
kro/krw & Pc of Plug Core			

Figure 8. kro/krw curves of plug cores

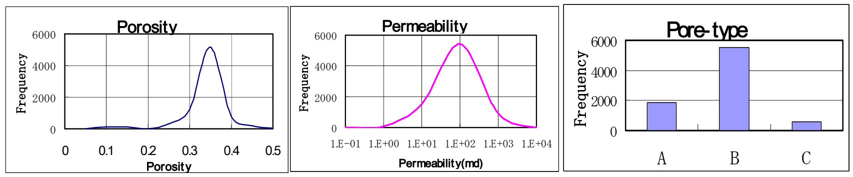
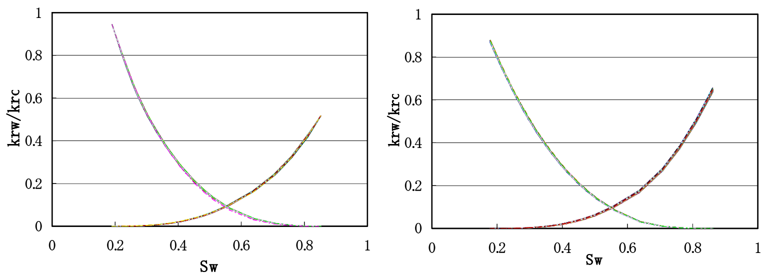


Figure 9. Variations of porosity, permeability and Pore-type



(a) **(b)**

Figure 10. Upscaled kro/krw curves from stochastic modeling

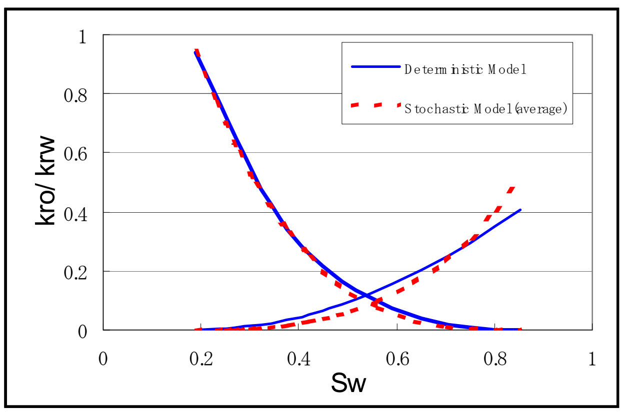


Figure 11. Comparison of kro/krw curves of deterministic model and stochastic models