BUOY RINA

B. ENG. (HONS) PETROLEUM ENGINEERING

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MULTI-WELL DRAINAGE AREA CALCULATION BASED ON DIFFUSIVE TIME OF FLIGHT: A NOVEL APPROACH FOR QUICK PRODUCTION FORECAST FOR CBM FIELDS

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Multi-Well Drainage Area Calculation Based On Diffusive Time Of Flight: A Novel Approach For Quick Production Forecast For CBM Fields

by

Buoy Rina

Dissertation submitted in partial fulfillment of
the requirements for the Bachelor of Engineering (Hons)
(Petroleum Engineering)

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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

MULTI-WELL DRAINAGE AREA CALCULATION BASED ON DIFFUSIVE TIME OF FLIGHT: A NOVEL APPROACH FOR QUICK PRODUCTION FORECAST FOR CBM FIELDS

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A project dissertation submitted to the
Petroleum Engineering Programme
Universiti Teknologi PETRONAS
in Partial Fulfillment of the requirement for the
Bachelor of Engineering (Hons)
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Approved by

…………………………….
(Mr. Ali F.Mangi Alta'ee)
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
JANUARY 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Buoy Rina

ABSTRACT

For coalbed methane fields, selection of dynamic simulation models, namely, 3D numerical or analytical material balance (MB) is based on the scale and timeframe. At field scale and under reasonable timeframe, MB model is preferred to 3D numerical model due to its shorter turn-around time for simulation and results extraction. Conventionally, well drainage as the inputs for MB model is inferred from well spacing, which is unrealistic in heterogeneous media. In this study, end-of-transient well drainage areas are determined by Diffusive Time of Flights (DTOF) by employing numerical fast marching method (FMM) with the fine gridded property maps. Property up-scaling is performed in each well drainage. With drainage and average property information, full field production forecast is performed with MB model. To validate the proposed approach, results are compared against those of numerical model and conventional practice in which well drainage area is inferred from well spacing

ACKNOWLEDGEMENT

First of all, I would like to express my grateful thank to Mr. Mr. Ali F.Mangi Alta'ee, the university project supervisor for his continuous support, valuable advice and excellent guide. He has spent his valuable time and effect checking the project progress and ensuring that everything is on the right track as planned.

Furthermore, I would like to take this chance to thank Ms. Archana Kumar, the industrial co-supervisor and senior reservoir engineer from Leap Energy Partners for spending her valuable time and effort in guiding, advising, and supervising the project.

Finally, I would like to thank the University for offering this final year project courses (FYP1 and FYP2) which allows me to grow my technical capacity, communication skills, and project management. Moreover, I would like to thank Leap Energy Partners for granting the access to use their developed DotCBM software (Development Optimization Toolkit of CBM) and commercial ECLIPSE package for CBM for this study.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Dynamic reservoir modeling is one of the most essential parts of field development planning for CBM fields. The choice of full field modeling approach lies on the modeling objectives. Generally, there are two options for full field modeling, namely: 3D numerical modeling and multi-well material balance modeling and each option has its own pros and corns. 3D numerical modeling which is based numerical discretization of the reservoir into small domain is able to capture complex behaviors of reservoir and unconventional well modeling; however, this option is quite computationally expensive for the case of large CBM fields with high population of wells. On the other hand, multi-well modeling which uses the average properties within the pre-defined areas does not allow well communication during calculation so that its computational speed is far better than numerical modeling.

Reference [4] proposed semi-analytical (i.e. multi-well material balance modeling) for full field modeling of large CBM fields in which the number of wells is up to 1000's of wells as full 3D modeling is time-inefficient. To allow such analytical simulation, fine gridded property maps must be up-scaled to the selected well spacing. Thus, each well has equal drainage area which is based on the selected spacing.

1.2 Problem Statement

1.2.1 Problem Identification

In multi-well material balance model, wells are conventionally assumed to drain equal part of the reservoir. Based on image well principle, production lost in some wells is gained in the others. This practice does not really represent the reservoir as in reality, wells do not drain equally. Some wells drain big portions and vice versa based on the heterogeneous property maps. Thus, with conventional practice, field rather than well scale is the main focus.

1.2.2 Significant Of the Project

The proposed workflow employs end-of-transient well drainage information in production forecasting; therefore, actual contribution of each well's production to the total field production is captured. Thus, quick production forecast can be achieved with multi-well material balance modeling approach while the accuracy of production profiles at both well and field level are improved.

1.3 Objectives

The objectives of this project are as follows:

- To propose the new workflow for better production forecast for large CBM fields at field and well scale with better drainage representation of the wells
- To illustrate the power and utility of and validate the proposed workflow through example case study
- To provide recommendations for future research and development.

1.4 Scope of Study

- Designing an integrated Excel Spreadsheet coupled with built-in VBA, which is able to perform the computation of DTOF and then, well drainage areas based on numerical FMM and heterogeneous property maps, and perform the average property up-scaling within each well drainage
- Running the simulations using material balance method (DotCBM Software) and numerical Method (ECLIPSE) for the example case study

1.5 The Relevancy of the Project

The project is mainly related to the engineering aspect of petroleum engineering. Specifically, this project contributes to the development and improvement of dynamic reservoir modeling of best practice field development workflow applied in unconventional reservoirs in which high population of wells is commonly found.

1.6 Feasibility of the Project

This project is fully based on computer programing and commercial software packages. This project is actually completed within the given time frame as the Gantt chart and plan are strictly followed.

CHAPTER 2

LITERATURE REVIEW

2.1 Diffusive Time of Flight (DTOF)

Diffusive time of flight (DTOF) can be derived by applying asymptotic approach to transient pressure response equation and the derivation work can be found in ref.[3] and ref.[4]. According to ref. [3], [4] and [1], Transient pressure front propagation can be described by the following eikonal equation:

$$|\nabla \tau(x)|\sqrt{\alpha(x)} = 1 \tag{1}$$

Where $\alpha(x)$ is diffusivity and given by:

$$\alpha(x) = \frac{k(x)}{\phi(x)\mu c_t} \tag{2}$$

Equation (1) is eikonal equation which describes transient pressure propagation. τ(x) is the propagation time of pressure front (also known as 'diffusive time of flight'). According to [3], the propagation time of pressure front is associated with maximum buildup or drawdown at a particular location and can be related with physical time in 2-D domain (i.e. constant thickness) as:

$$t(x) = \frac{\tau^2(x)}{4} \tag{3}$$

For the case of 3-D media, equation (19) is modified as:

$$t(x) = \frac{\tau^2(x)}{6} \tag{4}$$

$t(x)$ is the peak arrival time.

Equation (1) can be solved by using Fast Marching Method (FMM) as suggested by ref. [1]. FMM will be presented in the next part.

2.2 Fast Marching Method (FMM)

Reference [6] proposed a numerical solution to eikonal equation of equation (5) which is called Fast Marching Method (FMM) for monotonically advancing front. For form of eikonal equation given by Eq. (1), ref. [6] suggested the following discretization for the above eikonal equation:

$$\begin{pmatrix} \max(D_{ijk}^{-x}\tau, -D_{ijk}^{+x}\tau, 0)^2 \\ \max(D_{ijk}^{-y}\tau, -D_{ijk}^{+y}\tau, 0)^2 \\ \max(D_{ijk}^{-z}\tau, -D_{ijk}^{+z}\tau, 0)^2 \end{pmatrix} = \frac{1}{\alpha(x)} \tag{5}$$

D is the notation for backward (negative) and forward (positive) finite difference of τ with respect to location (x,y,z).Equation (5) is further simplified to the following form:

$$\max(\frac{\tau-\tau_1}{\Delta x},0)^2 + \max(\frac{\tau-\tau_2}{\Delta y},0)^2 + \max(\frac{\tau-\tau_3}{\Delta x},0)^2 = \frac{1}{\alpha(x)} \tag{6}$$

After expansion, equation (6) becomes a normal quadric equation with two values of roots. Only the root of higher value is chosen. Also, τ 1, τ 2 and τ 3 are frozen if any of them is not frozen, its value is set to be zero.

Fast Marching Method can be summarized as follows:

1. Tag the initial boundary points as frozen and find the nearest neighbors of the frozen
2. Solve eikonal equation for all the neighbors and put them into narrow band
3. Pick up a point in narrow band with the smallest value of τ , tag it as frozen and remove from narrow band
4. Find the neighbors of the chosen point which are unknown, solve eikonal equation for all these new points, and add into narrow band
5. If the neighbors of the chosen point is already in the narrow band, re-compute their values of τ
6. Loop Step 3, 4 and 5

2.3 Properties Up-scaling

As discussed about, only diffusivity at each grid block is needed to compute DTOF and then well drainage areas. Permeability and porosity are the most common varying properties within the reservoir while viscosity and compressibility does not vary much with location. Therefore, once each well's drainage is defined, property up-scaling must be performed in the respective drainage area.

Porosity can be averaged based on simple arithmetic averaging method.

Unlike porosity, there is no single formula for permeability averaging as averaging must consider the direction of the flow. Arithmetic averaging method is applied for parallel flow while harmonic method is applied for series flow. For the case of randomized permeability field, geometric averaging is considered. However, all the above averaging schemes do not include the impact of well. As well is placed on each drainage to be up-scaled, a well-based up-scaling scheme is derived based on the assumption that well is located in multi-composite system with radially changing permeability and the flow is under pseudo-steady state condition. Average permeability is expressed as:

$$k_{eff} = \frac{\ln \frac{r_e}{r_w} - \frac{1}{2}}{\sum_{p=0}^{n} \frac{1}{k_{p+1}} [\ln(\frac{r_{p+1}}{r_p}) - \frac{{r_{p+1}}^2 - {r_p}^2}{2{r_e}^2}]} \tag{7}$$

n+1 is total number of composites. The first radius (r0) is wellbore radius and the last radius (rn+1) is external drainage radius (re). The permeability lies with wellbore radius and r1 is labeled as k1 of layer 1.

From Eq. (7), it can be seen that permeability at the first few composites close to the well has great impact on the average permeability. It should be noticed that Eq. (7) is derived for radial system; however, it still can be used in Cartesian system by assuming grid block system as pseudo-radial one. That means layers of cells around the well block are considered as composites. The validity of the scheme will be presented through example case.

CHAPTER 3

METHODOLOGY

3.1 RESEARCH METHODOLOGY

A. Description of The Proposed Workflow

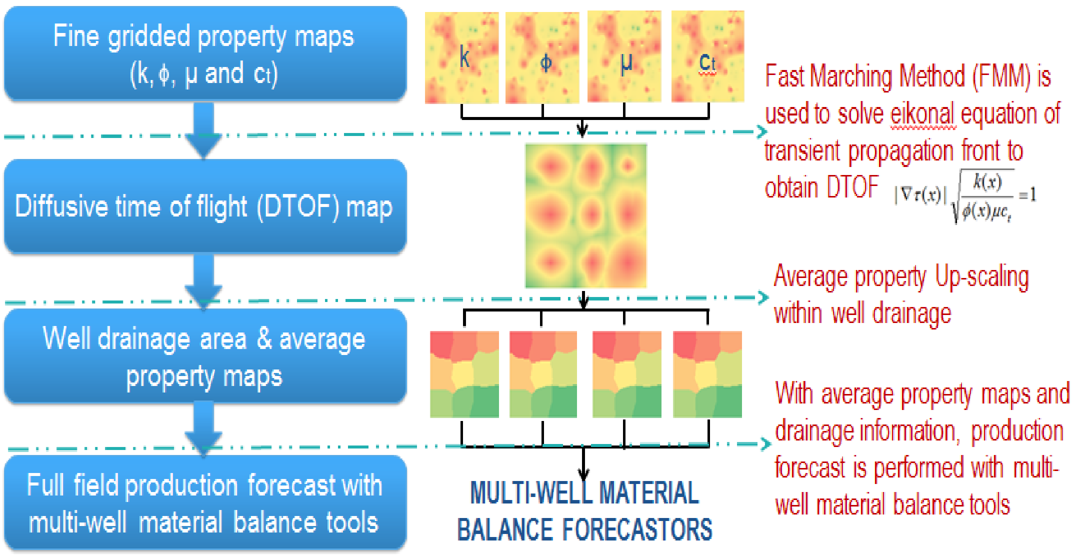

Figure 1: Illustration of the proposed work

B. Description of Example Case Study Outline

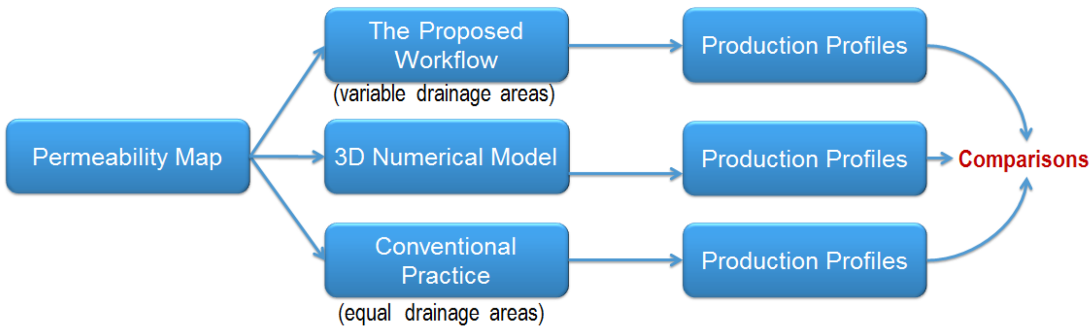

Figure 2: Example case study outline used to validate the proposed workflow

The proposed workflow is the general workflow designed to allow better production forecast for large CBM fields at field and well scale with better drainage representation of the wells. In order to validate the proposed workflow, the example case study outline is followed.

3.2 OVERALL PROJECT ACTIVITIES

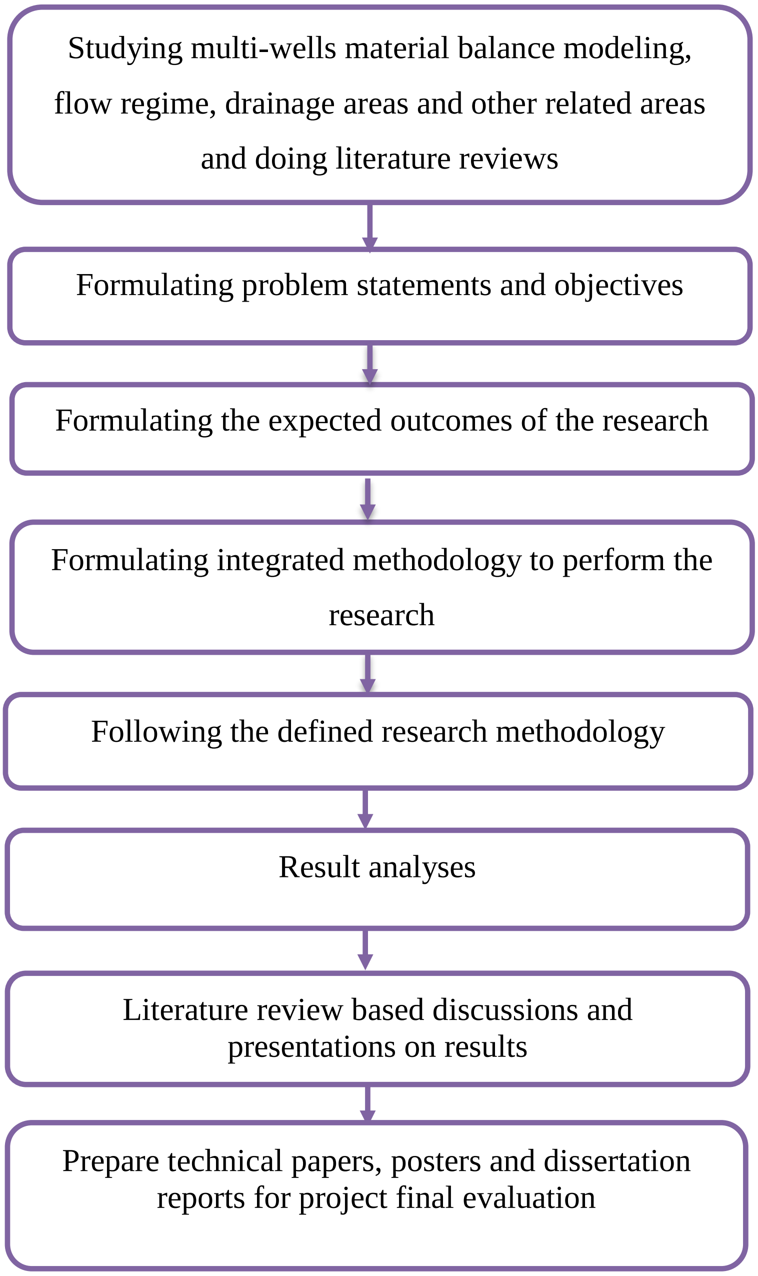

Figure 3: Overall project activities (including FYP1 and FYP2)

3.3 GANTT CHART AND KEY MILESTONES

Final Year Project I															
Details/Week	**1**	**2**	**3**	**4**	**5**	**6**		**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Topic Selection & Confirmation							**Mid Semester Break**								
Preliminary Research Work															
Preliminary Report submission															
Proposal Defense (Oral Presentation)															
Project Work Continues															
Interim Draft Report submission															
Submission of Interim Report															

Figure 4: Gantt chart and key milestone for FYP1

Final Year Project II															
Details/Week	**1**	**2**	**3**	**4**	**5**	**6**		**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Materials Preparation & Lab Booking							**Mid Semester Break**								
Pre-test Analysis															
1st Project Run															
Progress Report Submission															
2nd Project Run															
Post-test Analysis															
Pre-EDX															
Draft Report Submission															
Dissertation Submission (Softbound)															
Technical Paper Submission															
Oral Presentation															
Dissertation Submission (Hardbound)															

Figure 5: Gantt chart and key milestone for FYP2

3.4 TOOLS AND SOFTWARE NEEDED

Excel and VBA: Microsoft Office

ECLISPE: 3-D numerical modeling simulator developed by Schlumberger

DotCBM: Development Optimization Toolkit for CBM developed by Leap Energy

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 EXAMPLE CASE STUDY OF CBM FIELD

The proposed approach is illustrated by using an example case of CBM field with 9 producing wells and each well is producing at the same time and conditions. The reservoir dimension is 90 x 90 x 1 cells and a grid block is equation to 100 ft x 100 ft x 13.28 ft. The heterogeneous permeability map is given by Fig. 6 while porosity, compressibility, viscosity, Langmuir isotherm etc. are considered unchanged with location.

Based on the proposed workflow, first, property maps are used as the inputs for FMM and then, DTOF map is generated along with the identification of well drainage areas. To validate DTOF-based drainage area method, numerical simulation by ECLIPSE is run to obtain early-time transient pressure information and maximum pressure contours. The DTOF-based drainage areas and maximum pressure contour-based drainage areas are compared. Once well drainage areas are determined, permeability must be up-scaled within the drainage of each well. A well-based up-scaling scheme is proposed and it is validated by numerical simulation. Within a given drainage area, numerical simulation is set up and run by using permeability field (heterogeneous) and the average permeability computed by the proposed scheme and the production performances are compared. With the computed drainage area and average permeability of each well, full field production forecast can be performed by using multi-well material balance model. Development Optimization Toolkit for CBM (DotCBM) developed by Leap Energy Partners is employed. To validate the results, numerical simulation by ECLIPSE is set up and run with the fine gridded permeability map.

4.2 DTOF WELL BOUNDARIES VS. PRESSURE BOUNDARIES

Once DTOF map is created, it is possible to identify each well's drainage area. These well drainage areas form during transient pressure propagation caused by the impulse source at wells. To validate DTOF drainage map, ECLIPSE simulation is run to obtain the maximum pressure contour map at early producing time such that the flow is at the end of transient regime. It is worth mentioning that the maximum pressure contour between wells is the well boundaries. The comparison between DTOF based drainage map and maximum pressure contour drainage map is shown in Fig. 7. It is observed that there exists good agreement in well boundaries between two methods. However, the drainage map from DTOF shows better resolution. This observation is consistent with ref. [1].

4.3 PERMEABILITY UP-SCALING

Eq. (7) is used to perform the permeability up-scaling within drainage areas obtained above. Strong correlation between the average permeability and permeability at the well block is seen as expected. This is shown in Fig. 8. For most of the cases, average permeability clusters closely around the permeability at the well block if permeability field does not change sharply from well block to the surrounding blocks.

To validate the proposed up-scaling scheme, the two following scenarios are run in ECLIPSE by using the example case study.

- Once well drainage areas are determined, it is assumed that each well's drainage is stationary (i.e. no well interaction) and full field simulation is performed with heterogeneous permeability map.
- Once well drainage areas are determined, it is assumed that each well's drainage is stationary (i.e. no well interaction) and full field simulation is performed with average permeability values for each drainage.

The idea of making well's drainages stationary is to remove interference effect so that apple-to-apple comparison basis is obtained.

Full field production performances from the above scenarios are compared as shown in Fig.9 and 10. It can be clearly seen that the proposed up-scaling scheme can compute the well average permeability which well represents the permeability field of the well.

4.4 MULTI-WELL MATERIAL BALANCE VS. 3D NUMERICAL MODELING

Once each well's drainage and average properties are obtained, production forecast simulation is performed by DotCBM. The skin factor of -1 is used here for all wells to reconcile the differences between analytical material balance model vs.

numerical model. Those differences will be elaborated later. The study on computational performance of analytical material balance model vs. numerical model is also available in ref. [5]. It takes DotCBM around 3s to complete the simulation for 4000-day simulation time (calculation mood: daily). To validate the new workflow, ECIPSE simulation is set up for the example case study. Heterogeneous permeability field in Fig. 6 is used in ECLIPSE. It takes around 52s to complete the simulation with the same simulation (time step: roughly 4 days). The production profile comparison between DotCBM vs. ECLIPSE is shown in Fig. 11 and 12. Good match between the analytical material balance model with new workflow vs. numerical model is clearly seen.

When comparing the production performance analytical material balance model vs. numerical model, one should be aware of several main factors contributing to the difference between two modeling approaches as follow:

- Transient effect at early production and near-wellbore desorption are captured in numerical modeling while material balance modeling starts with boundary-dominated flow. These two effect can be mitigated by adding negative skin to material balance model
- Inference effect is not accounted in material balance model while it is captured in numerical.
- In material balance modeling, well is assumed to be in the center of the drainage and this is actually not true as most of DTOF-based drainage areas have irregular shapes as shown in Fig. 7.

However, the results show pretty close match between 3D numerical modeling and multi-well material balance modeling and computational time (CPU time) is greatly reduced with multi-well material balance approach. Therefore, in the development of a large CBM field in which the number of well is up to 1000 wells, multi-well material balance modeling is quite commended for the purpose of identifying the possible range of project values and costs, screening the projects and sectorizing the fields before any serious numerical simulation attempt is made.

4.5 THE PROPOSED WORKFLOW VS. CONVENTIONAL PRACTICE

Conventionally, well drainage area is inferred from well spacing and the property maps created in the course of reservoir characterization must be up-scaled to the spacing as suggested by ref. [4]. Such practice relies on the principle of image wells. That means whatever production is lost in some wells is gained in others. Thus, the conventional practice concerns only production forecast at field level.

The proposed workflow employs end-of-transient well drainage information in production forecasting; therefore, actual contribution of each well‘s production to the total field production is captured. To demonstrate this, two simulation scenarios are set up for both conventional practice and proposed workflow. Gas rate comparison at well and field level between the two scenarios and numerical simulation is shown in Fig. 13 through 16. At field level, only slight improvement is observed while clear improvement is seen at well level. Well 5 and 6 are cases in which wells' drainages are overestimated and underestimated, respectively with the conventional practice. However, the problem is removed with the new workflow if the well interference effect is not the dominant effect.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

A systematic, novel workflow is presented to enable quick production forecast via multi-well material balance modeling for any given fine, gridded, heterogeneous CBM field. The power and utility of the proposed workflow have been demonstrated through an example case study. Several specific conclusions and recommendations are as follows:

- In heterogeneous multi-well system, DTOF-based drainage method which is based on Fast Marching Method (FMM) is able to determine each well's drainage area in system which forms during transient flow with high resolution in short time as FMM algorithm perform very fast. This has been validated by comparing DTOF-based drainage map and transient pressure-based map generated by numerical simulation and good agreement between the two methods is obtained.
- Well-based up-scaling scheme works very well in continuous, correlated permeability field created by Source Point Method (SPM) for the example case study. Accurate determination of well's average permeability is very important to ensure quick yet accurate enough full field production forecast
- Due to some factors as described earlier, slight difference in production profiles generated by multi-well material balance modeling and 3D numerical modeling is seen in the example case study and such difference is also observed in literature. Thus, it is recommended that research effort should be focus on reconciling the production profiles generated by the two modeling approaches.
- Actual contribution of each well to full field production can be captured with the proposed workflow rather than conventional approach which is based on the principle of image wells. This illustrates importance of accurate well drainage determination and up-scaling within the right drainage.

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APPENDIXES

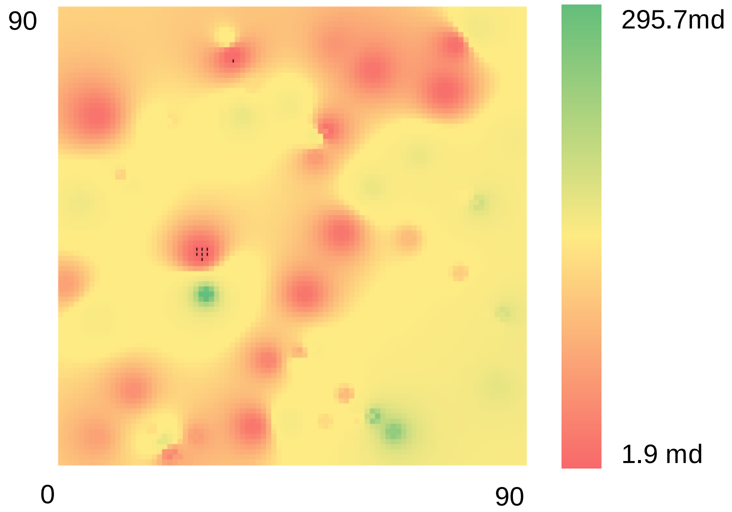


Figure 6: Continuous correlated permeability field used in the example case

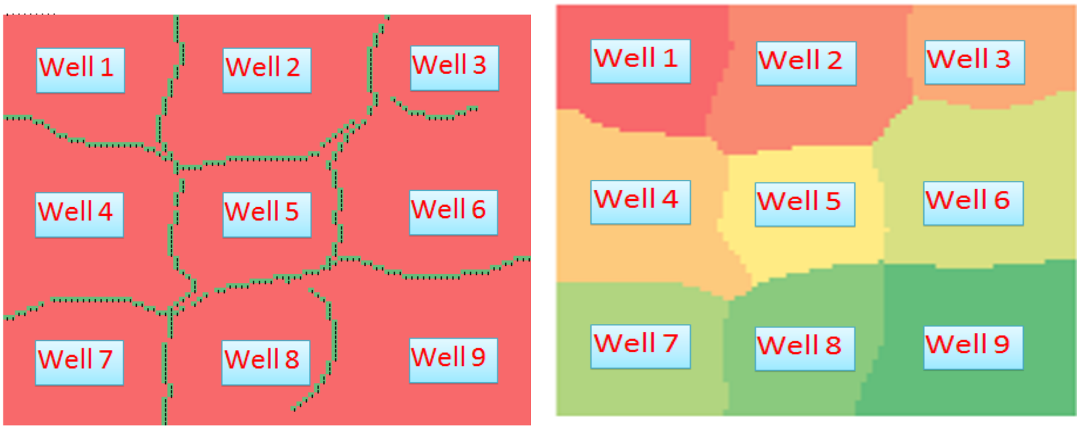


Figure 7: DTOF-based well drainage map (right) and maximum pressure contour–based well drainage map (left)

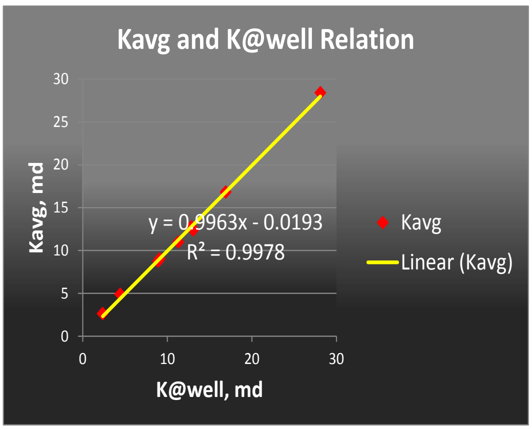


Figure 8: The strong relation between the up-scaled permeability vs. the permeability at the well block

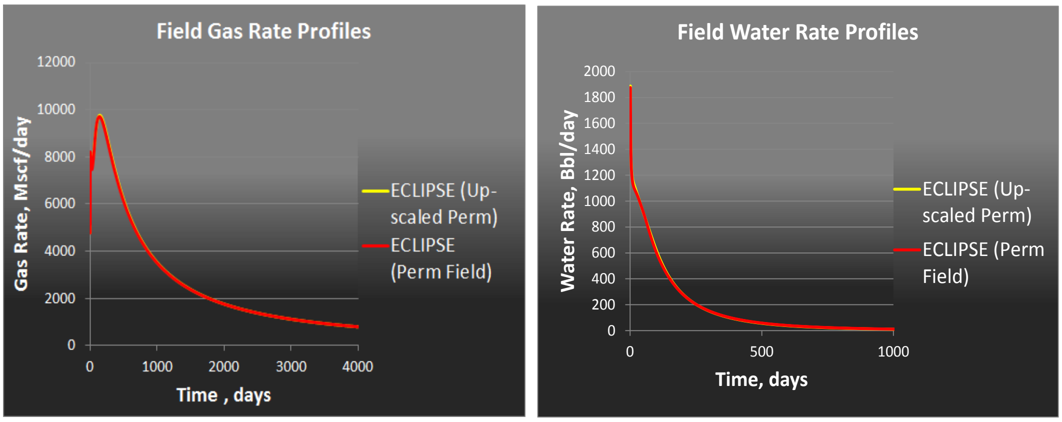


Figure 9: Validating the used up-scaling scheme based on field rate profile comparison

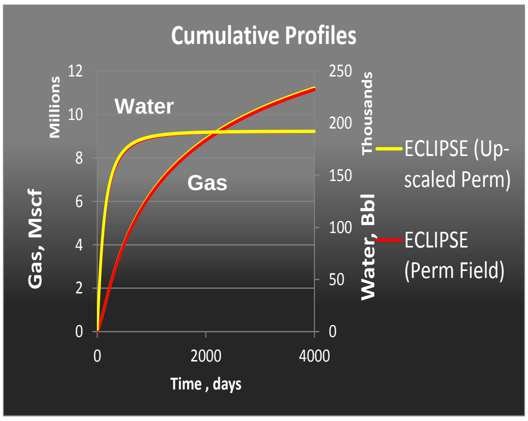


Figure 10: Validating the used up-scaling scheme based on field production profile comparison

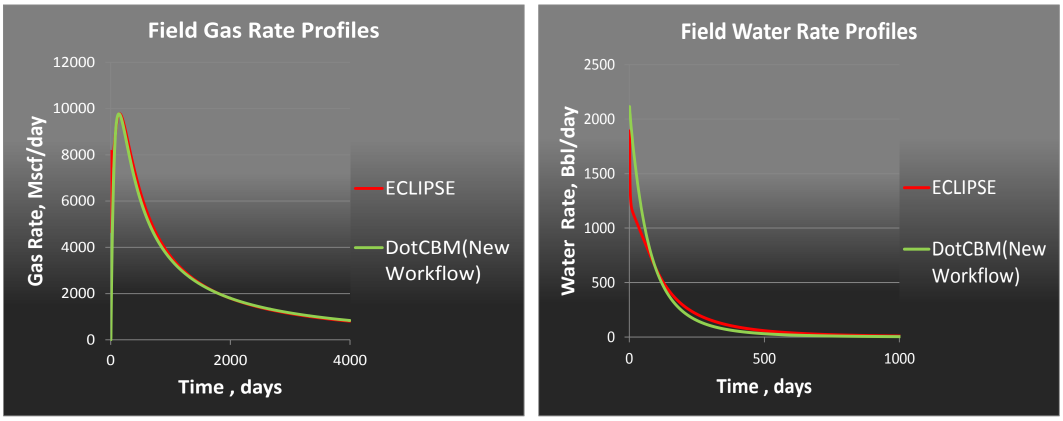


Figure 11: Field production rate profile comparison between DotCBM (new workflow) vs. ECLIPSE (numerical)

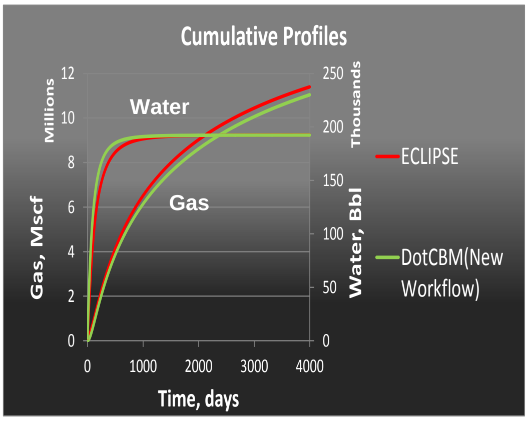
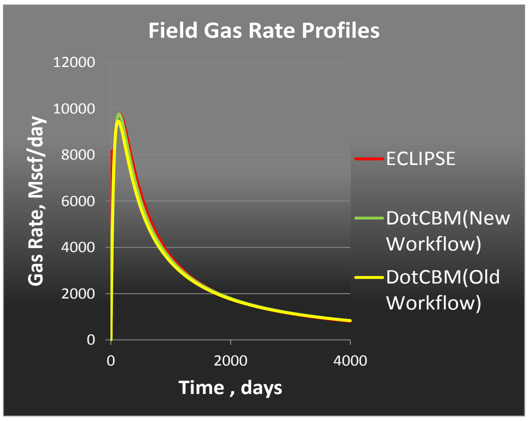


Figure 12: Field production profile comparison between DotCBM (new workflow) vs. ECLIPSE (numerical)



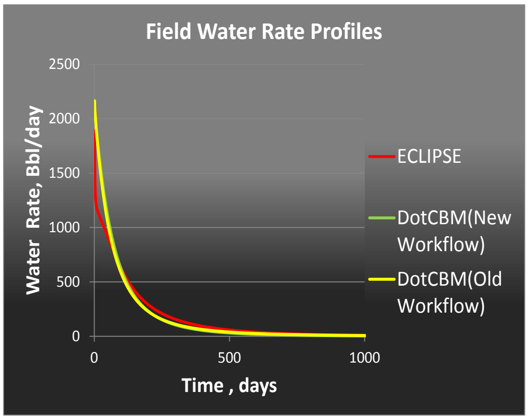


Figure 13: Field production rate profile comparison among DotCBM (new workflow), DotCBM (old workflow) and ECLIPSE (numerical)

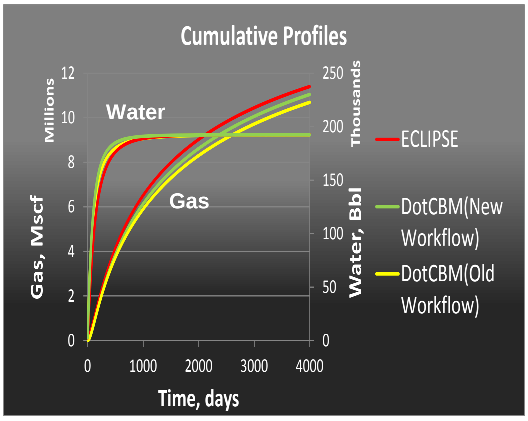


Figure 14: Field production profile comparison among DotCBM (new workflow), DotCBM (old workflow) and ECLIPSE (numerical)

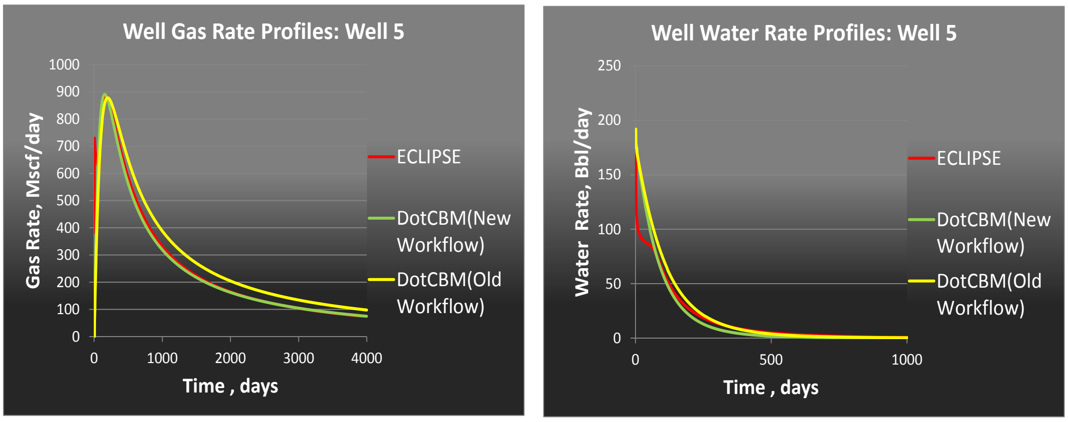


Figure 15: Well 5 production rate profile comparison among DotCBM (new workflow), DotCBM (old workflow) and ECLIPSE (numerical)

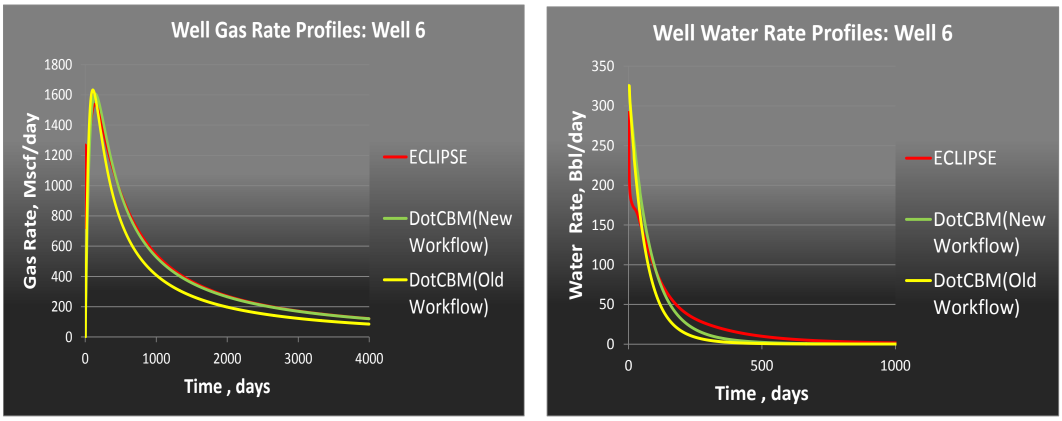


Figure 16: Well 6 production rate profile comparison among DotCBM (new workflow), DotCBM (old workflow) and ECLIPSE (numerical)

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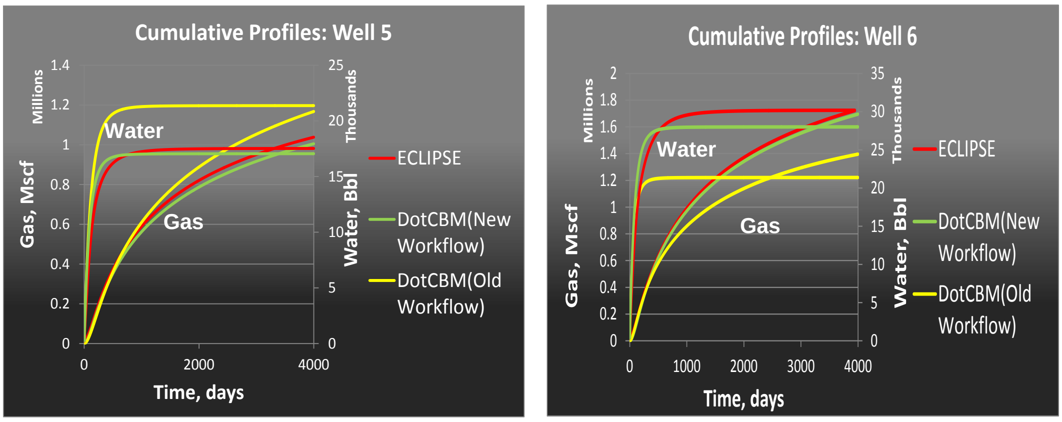

Figure 17: Well 5 & 6 production profile comparison among DotCBM (new workflow), DotCBM (old workflow) and ECLIPSE (numerical)