

Assisted History Matching by Using Recursive Least Square and Discrete Cosine Transform

By

Muhammad Ashraf Bin Abu Talib

13671

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Petroleum)

MAY 2014

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Assisted History Matching By using Recursive Least Square and Discrete Cosine
Transform

by

Muhammad Ashraf Bin Abu Talib

13671

A project dissertation submitted to the
Petroleum Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(PETROLEUM)

Approved by,

(Mr. Berihun Mamo Negash)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2014

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.

MUHAMMAD ASHRAF BIN ABU TALIB

ABSTRACT

History matching is the act of adjusting a model of a reservoir until it closely reproduces the past behavior of a reservoir. Before the computer was invented, history matching is done manually by trial and error method and personal judgment which only can be done by experienced engineer. Because of these factors, manual history matching technique consume a lot of time. Thus, this project is carried to do assisted history matching and to determine whether Recursive least square as optimization method and Discrete cosine transform as parameter reduction method can be combined or not.

In order to achieve the objective, a number of steps have been done. First, a synthetic model has been built by modifying ODEH data. Two sets of permeability value have been selected to get two data which are historical and simulated data from the model. Then, the fluid flow equation is derived to get the forward model. Forward model is then used to design the objective function. After objective function has been designed, DCT is applied to the reservoir data in order to minimize the number of parameters. Next, RLS is applied to the parameter which has been reduced to optimize the data. These steps are repeated until the threshold value is lower than the set threshold. For this project, RLS and DCT methods are compared with the literature review to know the successfulness of this combination.

For the first part of final year project, the derivation of forward model has been done. For the second part of final year project, a synthetic model has been built and objective function has been design from the forward model. Before applying the RLS and DCT, the illustrations of these methods need to be done to see how it work and then RLS and DCT were applied to the reservoir data.

The outcomes at the end of this project are first two set of data is obtain from the synthetic model which are historical and simulated data. Then algorithms for DCT and

RLS are proposed which can be applied to the history matching problem. From the result, the combination of RLS and DCT are successful and can be used for history matching purpose.

ACKNOWLEDGEMENT

Alhamdullilah, praise be upon Allah, with His will and permission, this Final Year Project entitle Assisted history matching by using recursive least square and discrete cosine transform has been completed successfully. This project is in par with the requirements for graduate of Geosciences & Petroleum Engineering Department. The author truly feel it is a great learning and a gesture towards the success of the Department to produce well rounded and highly capable Petroleum Engineers.

The author would like to take this opportunity to convey their upmost gratitude to the following people.

Project Supervisor; Mr Berihun Mamo Negash for his constant and patient guidance since first day the project. His effort and time spent in supervise and giving his idea in the learning process are appreciated. His enthusiasm and dedication had inspired the author to strive harder in completing this project

The author also would like to thank to all project coordinators for time and willingness in assisting the project through seminars and discussion sessions.

Token of appreciation also goes to all the friends who have given motivation to the author during completing this project.

Thank you.

TABLE OF CONTENTS

CERTIFICATION OF ORIGINALITY	iii
ABSTRACT.....	iv
ACKNOWLEDGEMENT	vi
LIST OF FIGURES	x
LIST OF TABLE	xi
ABBREVIATIONS AND NOMENCLATURES	xii
CHAPTER 1: INTRODUCTION	1
1.1 Background	1
1.2 Problem Statement	3
1.3 Objective	4
1.4 Scope of Study	4
1.5 Relevancy of the Project	4
CHAPTER 2: SUMMARY OF THE STATE OF ART	5
2.1 Inverse problem.....	5
2.2 History Matching.....	6
2.3 Assisted History Matching	7
2.4 Flow in porous media.....	8
2.4.1 Basic Definition	8
2.5 Forward Model	9
2.5.1 Derivation of continuity equation.....	10
2.6 Objective Function	15
2.7 Optimization Method	18

2.8 Parameter Reduction Method.....	18
2.9 Synthetic Reservoir Model.....	19
CHAPTER 3: LITERATURE REVIEW	20
3.1 Introduction	20
3.2 Application of Recursive Least Square and Discrete Cosine Transform.....	20
3.2.1 Recursive Least Square.....	20
3.2.2 Discrete Cosine Transform	22
3.3 Demonstration of Recursive Least Square and Discrete Cosine Transform	23
3.3.1 Demonstration of RLS	23
3.3.2 Demonstration of DCT	26
3.4 Previous Study.....	28
3.4.1 Recursive Least Square.....	28
3.4.2 Discrete Cosine Transform	29
CHAPTER 4: METHODOLOGY/ PROJECT WORK.....	30
4.1 Research Methodology.....	30
4.2 Project activities:	30
4.4 Gantt Chart	32
4.5 Key milestone.....	33
CHAPTER 5: RESULT AND DISCUSSION	34
5.1 Synthetic Reservoir Model.....	35
5.1.1 Model Description	35
5.1.2 Sensitivity Analysis	36
5.1.2.1 Methodology.....	37

5.1.2.2 Result	37
5.1.3 Flow Distribution.....	38
5.3 Limitation	42
5.4 Algorithm for combination of RLS and DCT	43
CHAPTER 6: CONCLUSION AND RECOMMENDATION	45
REFERENCES	47
APPENDIX.....	51

LIST OF FIGURES

FIGURE 1: The different between Forward Model and Inverse model	6
FIGURE 2 : Mass balance illustration	10
FIGURE 3: History Matching Flow chart.....	17
FIGURE 4: Porosity versus Time Graph	26
FIGURE 5: History Matching flow process	30
FIGURE 6: Algorithm for DCT and RLS.....	34
FIGURE 7: Model configuration	36
FIGURE 8: Total production rate versus time(PERMEABILITY)	37
FIGURE 9: Total production rate versus time(POROSITY).....	38
FIGURE 10: Oil Saturation before the test.....	39
FIGURE 11 : Oil Saturation at the middle of the test.....	39
FIGURE 12: Oil saturation at the end of the test.....	40
FIGURE 13: Total Oil Production and Oil Production rate Versus Time	41
FIGURE 14: Algorithms for combination of RLS and DCT.....	43

LIST OF TABLE

TABLE 1: Result of the RLS iteration	25
TABLE 2 : Gantt Chart.....	32

ABBREVIATIONS AND NOMENCLATURES

P= Pressure

T= transmissibility

λ =mobility

Q= flow rate

A=area

K=permeability

K_{ro}=relative permeability to oil

μ =viscosity

Φ =porosity

B=formation volume factor

C= compressibility

T=time

P_{cow}=capillary pressure of oil to water

CHAPTER 1

INTRODUCTION

1.1 Background

In oil and gas industry, performance of a reservoir plays an important role in ensuring the continuity of oil and gas production which contribute income to a company. Thus, reservoir management is very important to make sure that the reservoir performance is taking care of. Among the reservoir management activities is forecasting of the reservoir production. This is very important to the engineers because from the forecasting activity, the engineers can plan methods to handle all the possibilities which will occur to the reservoir. Before History matching was invented, scientist forecast the future production of a reservoir by building a reservoir model [1]. “Basically, the common models used can roughly be divided in two groups, deterministic models and stochastic models. Natural systems can be modeled as deterministic systems, by claiming all processes, parameters, boundary and initial conditions to be known. As a result, deterministic models claim their results to be true, or assume that a single best prediction is sufficient. Stochastic models, in contrast, admit the inherent uncertainty, and hence provide a range of possible predictions, with probabilities assigned to them. Uncertain parameters are not assumed to be known, but probability functions are used to handle them. Often deterministic models are good enough for making basic predictions or to provide fundamental system and process understanding” [1].

There are many disadvantages of using a model such as model is not reliable for complex, dynamic system and uncertainty quantifications. History matching was invented to replace the modeling method. Even the modeling a reservoir is not so accurate for history matching purpose, this history matching was carried out more than

three iterations and each iteration the model were updated and thus at the same time reduce the error by using model [2].

History matching is a process of finding the best combination of reservoir parameters which produce observed data from simulated model and this method consists of inverse problem [3]. The aim of history matching is to build a model which has minimum difference between the model and the history of the reservoir. Other than that, it also used to build a model which matches the historical data to forecast the reservoir performance.

Traditionally, history matching is done manually by hand. But the disadvantages of doing this method manually is it consume a lot of time because of the number of parameters which need to deal with in order to get accurate result. The steps to do manual history matching are first, the geologist collected the data of the reservoir such as permeability, pressure and porosity. Then all the data which has been interpreted was used by reservoir engineers to build the fluid flow model. From the fluid flow model the engineers built the history matching curve and if there is data mismatch, the parameters of the fluid flow model were changed without changing the geological model.

Nowadays, history matching can be done assisted by the computer based on the several methods which has been invented by the engineers. This method is called assisted history matching. Assisted history matching techniques can be combined with parameter reduction methods to ease the calculation process by eliminating some parameters which is not important. Assisted history matching technique is widely used nowadays because it can save time and money which need to be used for history matching.

There are several assisted history matching methods which can be used in building a reservoir model such as genetic algorithm and Kalman Filter. These methods were used repeatedly to calculate and optimize all the parameter in order to minimize the different between reservoir model and the history data of the reservoir. Meanwhile, these methods can be combined with parameter reduction methods such as zonation, principle component analysis and discrete cosine transform. Parameter reduction methods are very important to eliminate unnecessary parameters and prioritize the parameters. In this

paper, the methods used to build the reservoir model are Recursive Least Square method which is combined with discrete cosine transform.

1.2 Problem Statement

Manual history matching has been invented by Kruger in 1961[4]. For this method, the reservoir engineers need to play and change the reservoir parameters to minimize the difference between simulated and observed value by trial and error method and this method is done by personal judgment[4]. This method need to be done by experienced reservoir engineers and large amount of budget need to be invested to do this method. Other than that, this method consumed a lot of time because the engineers need to deal with thousands of grid blocks to estimate reservoir parameter to build the model[4]. Thus, the accuracy of manual history matching can be questioned because it always comes with uncertainties.

Engineers have invented a new way to overcome manual history matching problems which is assisted history matching. It is computer based method which can vary the reservoir parameters automatically[2]. This method is define as building of initial model by using approximation of the reservoir parameters which then undergo a parameter reduction process of an objective function which represents the different between calculated response and observation[4]. Assisted history matching can shorten the process of calculation by reducing the number of parameters and optimize all the parameters.

For this project, methods used are Recursive Least Square (RLS) and Discrete Cosine Transformation. From the literature review, RLS cannot handle large number of parameters [5]. For parameter reduction methods, Discrete Cosine Transformation is widely used in reducing the number of parameters in history matching process. It used pixel and color distribution pattern to determine which block is not affect the model performance and eliminate them. Thus, combinations of these methods were used to minimize the error between simulated and historical data.

1.3 Objective

The objective of this project is to determine whether the combination recursive least square (RLS) method for optimization purpose and Discrete Cosine Transformation (DCT) which is used to minimize the number of parameters from the conceptual model can be used in assisted history matching or not.

1.4 Scope of Study

This project is limited to development of synthetic reservoir and proposing algorithms for RLS and DCT which can be used for history matching purpose.

1.5 Relevancy of the Project

This project is very relevant to the history matching problems nowadays. This is because manual history matching consumed a lot of time and only experienced engineers can perform. For assisted history matching, there are a lot of software and methods to do history matching but there will be significant different in term of computational time. RLS is used for this project because it is the simplest algorithms as compared to other algorithms such as Kalman Filter and Genetic Algorithms. Meanwhile, DCT is used for parameterization technique because RLS cannot handle large amount of dat

CHAPTER 2

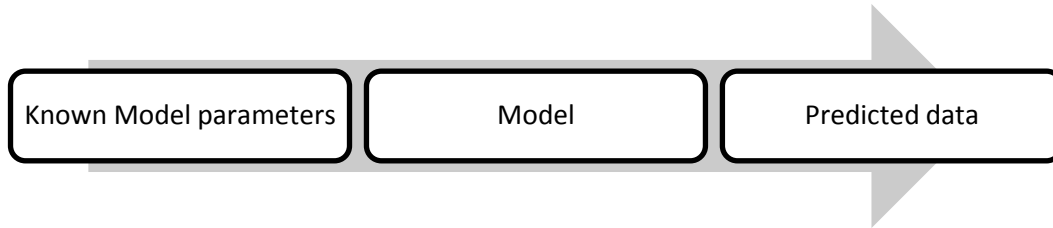
SUMMARY OF THE STATE OF ART

2.1 Inverse problem

“Inverse theory is concerned with problem of making inferences about a physical system from data and is a set of mathematical techniques for reducing data in order to obtain useful information concerning about the physical world on the basis of inferences drawn from observation” [6]. In other word, an inversed problem is a problem in which the answer is known but the question for the answer is not known. The theory of inverse problem was invented by Laplace and it is widely used by Gauss in 1809. Gauss is the one who made this theory become famous. Most history matching problems were nonlinear problem [7].

In this project, forward model was introduced first before using inverse theory to determine a new model parameter. Forward problem is used to generate theoretical data for a model by choosing a set of model parameter and calculates the predicted value. For this project, the forward problem can be illustrated in flow in a porous medium part. The forward problem includes calculating the predicted pressure at certain time step from a given parameter. Meanwhile, inverse problem relates the data to the predicted model and uses alteration to estimate the model parameter. Figure 1 presented the meaning steps of forward model and inverse model:

Forward Model



Inverse Model

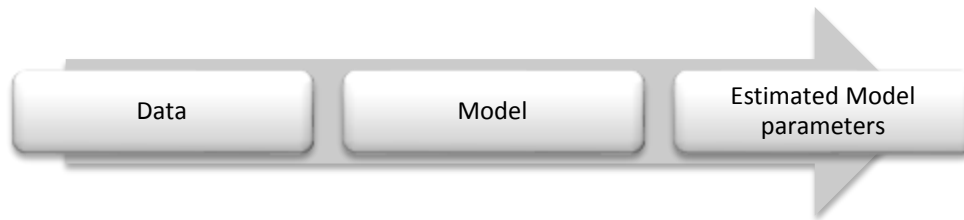


FIGURE 1: The different between Forward Model and Inverse model

2.2 History Matching

The economic growth of a reservoir in term of a petroleum recovery project is effected by the reservoir performance in term of production under current and future operating conditions[4]. At this point, history matching plays an important role in reservoir management process to evaluate the history and the present reservoir performance. History matching is building an integrated model from the available data to get an accurate production forecast[8]. In addition, “history matching is the act of adjusting a model of a reservoir until it closely reproduces the past behavior of a reservoir” [4]. Other than that, history matching is a method to produce and accurate prediction of the future production of the reservoir [9]. Meanwhile, researchers said that history matching is building a dynamic model which can be updated in term of model and parameters which will reproduce the well histories and the reservoir itself [2]. History matching is also defined as a process which the reservoir parameters are undergo alteration until it closely reproduces past behavior of a reservoir with the objective to update the reservoir model in order to have a confident tool to forecast future [10]. The first studies on history matching were in 1961 by Kruger which is done manually by trial and error method [4]. History matching is done to the geologic model and it is very important for

the development of a field operation strategies and to forecast the production of the field [11].

From all the definition from different researchers, history matching can be define as a technique which include building of a model which can be updated in term of the parameters value in order to get the least different between the model and the historical data. This technique is very important for reservoir management.

2.3 Assisted History Matching

For this project, assisted history matching was used instead of doing it manually. “Assisted history matching or semiautomatic history matching is defined as building of an initial model with an initial approximation of the reservoir parameters which then goes through a systematic process reduction of an objective function that represents the mismatch between observation and calculated response”[4]. The engineers who were responsible in inventing assisted history matching were Jacquard and Jain in 1965[4]. History matching was assisted by computer which eases the history matching process and save a lot of time and cost. Traditional history matching is time consuming, expensive and often frustrating [12]. Other that, to predict reservoir performance, it can be very complex and difficult to comprehend and as the consequence, there are a lot of researches done on assisted or automatic history matching technique.

Assisted history matching has been proven to converge quickly in terms of the number of reservoir simulations or iteration[13]. The steps to do assist history matching are first, the geologist provide the reservoir engineer with the geological data of the reservoir. From the geological data, a fluid flow model was built by reservoir engineers before performing assisted history matching. If there is data miss match during the process of history matching, the reservoir engineer would refer back to the geological data and make some modification before using it to build a new fluid flow model.

One example of automatic history matching technique has been published by using synthetic two- or three-phase reservoir data [14]. The model is made up of 450 grid-cells. 450 parameters were used, 1413 observed pressure data values and 785 water cut

and rate data values to reduce the squared data mismatch function. 10 years has been used as the simulation history period. In total, 11 cpu-hours were necessary for reducing the squared data mismatch function by a factor of 200. “A model of History Matching in 2009 includes production data at 30 wells, 20 production and 10 injection wells, and time-lapse seismic data for estimating approximately 270 000 parameters. The used coarse grid which consists of 540 000 cells was obtained by upscaling a high-resolution model with 20 million cells. The latter include horizontal and vertical permeability, porosities, net-to-gross ratio of each grid block, fluid contacts, fault transmissibility and relative permeability parameters” [14].

Based on the example, it is possible nowadays to do history matching technique to a quite large scaled reservoir model with a large number of parameters which is uncertain. History matching cannot be considered a truly practical yet and a compatible method need to be choose based on the data and the problem because there is no generally best method for history matching[15].

From the perspective of different researchers, assisted history matching is the best technique nowadays to build the model which can be used to predict future production of the reservoir as compared to manual history matching and at the same time minimize the time taken to do the history matching.

2.4 Flow in porous media

This chapter discuss on the theoretical background of multiphase flow system which include the derivation of equation, and basic definition of the term which were used in this project.

2.4.1 Basic Definition

This part discuss on the basic definition of term which were used throughout the report and the project.

2.4.1.1 Porosity

According to Schlumberger oilfield glossary, porosity is defined as the fraction or the volume of void spaces which can contain fluids. Porosity is formed between rock a particle which is not compacted together and it also can be formed through alteration of the rock. Other than that, porosity can be generated from the fractures. Porosity can be calculated by this formula:

$$\text{Porosity} = \text{volume of void space} / \text{total volume of the solid} = \frac{V_v}{V_t}$$

2.4.1.2 Saturation

Saturation is defined as the amount of oil, gas or water in a rock pores and it can be calculated by:

$$S_\alpha = \frac{V_\alpha}{V_v} = \frac{V_\alpha}{V_T \cdot \phi}$$

The summation of the saturation of fluid inside a pore volume is equal to 1.

$$\sum_{\alpha=1}^n S_n = 1$$

2.4.1.3 Capillary Pressure:

Capillary pressure is the discontinuity in fluid pressure between any two immiscible fluid[1]. Laplace's equation is used to calculate the capillary pressure, P_{cow} between adjacent oil and water phases and it can be related to the principal radius of curvature R_1 and R_2 of the shared medium and the interfacial tension σ_{ow} for the oil/water interface. The equation to calculate the capillary pressure is:

$$P_{cow} = p_o - p_w = \sigma_{ow} \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$$

2.5 Forward Model

Before these methods are applied, forward model must be build. Forward model is a mathematical model which is build based on fundamental physical laws and depends on

certain parameters[4]. “The components of forward model are used to calculate the required sensitivity of the observed quantities to the unknown parameters of the inverse problem”[16]. There are two components which are required for the forward model to estimate the unknown parameters[4]:

- A reservoir simulator to model the flow of fluid through porous media
- A rock physics model to calculate seismic response.

Forward model are built by deriving the fluid flow equation, mass balance equation and Darcy equation. After forward model is built, the objective function was designed based on the pattern of the forward model.

2.5.1 Derivation of continuity equation

Figure 2 shows the mass balance illustration.



FIGURE 2 : Mass balance illustration

Conservation of mass equation

$\dot{m}_{in} - \dot{m}_{out} = \text{rate of change of mass}$

$$-\frac{d}{dx}(\rho_l u_l) = \frac{d}{dt}(\Phi \rho_l S_l), \quad l = o, w$$

Darcy equation

$$u_l = -\frac{kk_{rl}}{\mu l} \frac{dP_l}{dx}, \quad l = o, w$$

Darcy equation is substitute into mass balance equation and the fluids which were taken into consideration were oil and water.

$$\frac{d}{dx} \left(\frac{kk_{ro}}{\mu_o B_o} \frac{dP_o}{dx} \right) - q_o = \frac{d}{dt} \left(\frac{\Phi S_o}{B_o} \right) \text{ for oil}$$

$$\frac{d}{dx} \left(\frac{kk_{rw}}{\mu_w B_w} \frac{dP_w}{dx} \right) - q_o = \frac{d}{dt} \left(\frac{\Phi S_w}{B_w} \right) \text{ for water}$$

$$P_{cow} = P_o - P_w$$

$$S_o + S_w = 1$$

Then, expand the left side of the equation

Left side flow term

$$\left(\frac{dP_l}{dx} \right)_{i+1/2} = \frac{P_{l_{i+1}} - P_{l_i}}{\Delta x} - \dots - 1 \quad l = o, w$$

$$\left(\frac{dP_l}{dx} \right)_{i-1/2} = \frac{P_{l_i} - P_{l_{i-1}}}{\Delta x} - \dots - 2 \quad l = o, w$$

Next, discretization of flow equation which include backward and forward.

Forward

$$\left[f(x) \frac{dP_l}{dx} \right]_{i+1/2} = \left[f(x) \frac{dP_l}{dx} \right]_i + \frac{\Delta x_{i/2}}{1!} \frac{d}{dx} \left[f(x) \frac{dP_l}{dx} \right]_i + \frac{\left(\frac{\Delta x_i}{2} \right)^2}{2!} \frac{d^2}{dx^2} \left[f(x) \frac{dP_l}{dx} \right]_i + \dots \quad l = o, w$$

Backward

$$\left[f(x) \frac{dP_l}{dx} \right]_{i-1/2} = \left[f(x) \frac{dP_l}{dx} \right]_i - \frac{\Delta x_{i/2}}{1!} \frac{d}{dx} \left[f(x) \frac{dP_l}{dx} \right]_i + \frac{\left(-\frac{\Delta x_i}{2} \right)^2}{2!} \frac{d^2}{dx^2} \left[f(x) \frac{dP_l}{dx} \right]_i + \dots \quad l = o, w$$

The forward –backward equation is substitute into equation 1 and 2

$$\frac{d}{dx} \left[f(x) \frac{dP_l}{dx} \right] = \frac{f(x)_{i+1/2} \frac{P_{i+1} - P_i}{\Delta x} - f(x)_{i-1/2} \frac{P_i - P_{i-1}}{\Delta x}}{\Delta x} \quad l = o, w$$

For oil

$$\frac{d}{dx} \left(\frac{kk_{ro}}{\mu_o B_o} \frac{dP_o}{dx} \right)_i \approx T_{xoi+\frac{1}{2}} (P_{oi+1} - P_{oi}) + T_{xoi-\frac{1}{2}} (P_{oi-1} - P_{oi})$$

For water

$$\frac{d}{dx} \left(\frac{kk_{rw}}{\mu_w B_w} \frac{dP_w}{dx} \right)_i \approx T_{xwi+\frac{1}{2}} (P_{wi+1} - P_{wi}) + T_{xwi-\frac{1}{2}} (P_{wi-1} - P_{wi})$$

$$T_{xoi+\frac{1}{2}} = \frac{2\lambda_{oi+1/2}}{\Delta x \left(\frac{\Delta x}{k_{i+1}} + \frac{\Delta x}{k_i} \right)} \quad \lambda_o = \frac{k_{ro}}{\mu_o B_o}$$

Upstream mobility is defined as:

$$\lambda_{oi+\frac{1}{2}} = \lambda_{oi+1} \text{ if } P_{oi+1} \geq P_{oi} \text{ or } \lambda_{oi} \text{ if } P_{oi+1} < P_{oi}$$

$$\lambda_{wi+\frac{1}{2}} = \lambda_{wi+1} \text{ if } P_{wi+1} \geq P_{wi} \text{ or } \lambda_{wi} \text{ if } P_{wi+1} < P_{wi}$$

After done with the left side, move on to the right side term

For oil

$$\frac{d}{dt} \left(\frac{\Phi S_o}{B_o} \right) = \frac{\Phi}{B_o} \frac{dS_o}{dt} + S_o \frac{d}{dt} \left(\frac{\Phi}{B_o} \right)$$

$$\frac{d}{dt} \left(\frac{\Phi}{B_o} \right)_i \approx - \frac{\Phi_i}{\Delta t_{oi}} \left[\frac{c_r}{B_o} + \frac{d \left(\frac{1}{B_o} \right)}{dP_o} \right]_i (P_o^{t+\Delta t} - P_{oi}^t)$$

The right side of the equation include Standard backward approximation of time derivative

$$\left(\frac{\Phi}{B_o} \frac{dS_o}{dt} \right)_i \approx - \frac{\Phi_i}{B_{oi} \Delta t_i} (S_{wi}^{t+\Delta t} - S_{wi}^t)$$

$$\frac{d}{dt} \left(\frac{\Phi S_o}{B_{oi}} \right)_i \approx C_{poq} (P_{oi}^{t+\Delta t} - P_{oi}^t) + C_{swoi} (S_{wi}^{t+\Delta t} - S_{wi}^t)$$

$$C_{poq} = \frac{\Phi(1 - S_{wi})}{\Delta t} \left[\frac{c_r}{B_o} + \frac{d \left(\frac{1}{B_o} \right)}{dP_o} \right]_i$$

$$C_{swoi} = -\frac{\Phi_i}{B_{oi}\Delta t_i}$$

For water

$$\frac{d}{dt}\left(\frac{\Phi S_w}{B_w}\right) = \frac{\Phi}{B_w} \frac{dS_w}{dt} + S_w \frac{d}{dt}\left(\frac{\Phi}{B_w}\right)$$

$$\frac{d}{dt}\left(\frac{\Phi}{B_w}\right) = \frac{d}{dP_w}\left(\frac{\Phi}{B_w}\right) \frac{dP_w}{dt} = \frac{d}{dP_w}\left(\frac{\Phi}{B_w}\right) \left(\frac{dP_o}{dt} - \frac{dP_{cow}}{dt}\right)$$

$$\frac{d}{dt}\left(\frac{\Phi S_w}{B_w}\right)_i \approx C_{powi}(P_{oi}^{t+\Delta t} - P_{oi}^t) + C_{swwi}(S_{wi}^{t+\Delta t} - S_{wi}^t)$$

$$C_{powi} = \frac{\Phi_i S_{wi}}{\Delta t} \left[\frac{c_r}{B_o} + \frac{d\left(\frac{1}{B_w}\right)}{dP_w} \right]_i$$

$$C_{swwi} = \frac{\Phi_i}{B_{wi}\Delta t_i} - \left(\frac{dP_{cow}}{dS_w}\right)_i C_{powi}$$

Same as the left side term, the right side term also undergo discrete form of oil and water

For oil

$$T_{xoi+\frac{1}{2}}(P_{oi+1} - P_{oi}) + T_{xoi-\frac{1}{2}}(P_{oi-1} - P_{oi}) - \dot{q}_{oi} = C_{poq}(P_{oi}^{t+\Delta t} - P_{oi}^t) + C_{swoi}(S_{wi}^{t+\Delta t} - S_{wi}^t)$$

For water

$$T_{xwi+\frac{1}{2}}[(P_{wi+1} - P_{wi}) - (P_{cowi+1} - P_{cowi})] + T_{xwi-\frac{1}{2}}[(P_{wi-1} - P_{wi}) - (P_{cowi-1} - P_{cowi})] - \dot{q}_{wi} = C_{powi}(P_{oi}^{t+\Delta t} - P_{oi}^t) + C_{swwi}(S_{wi}^{t+\Delta t} - S_{wi}^t)$$

$$T_{xoi+\frac{1}{2}} = \frac{2\lambda_{oi+1/2}}{\Delta x \left(\frac{\Delta x}{k_{i+1}} + \frac{\Delta x}{k_i} \right)} \quad T_{xoi-\frac{1}{2}} = \frac{2\lambda_{oi-1/2}}{\Delta x \left(\frac{\Delta x}{k_{i-1}} + \frac{\Delta x}{k_i} \right)}$$

$$T_{xwi+\frac{1}{2}} = \frac{2\lambda_{wi+1/2}}{\Delta x \left(\frac{\Delta x}{k_{i+1}} + \frac{\Delta x}{k_i} \right)} \quad T_{xwi-\frac{1}{2}} = \frac{2\lambda_{wi-1/2}}{\Delta x \left(\frac{\Delta x}{k_{i+1}} + \frac{\Delta x}{k_i} \right)}$$

Combine the discrete form of oil and water by eliminating the saturation of water terms and arrange the equations

$$\begin{aligned}
& P_{oi-1} \left(T_{xoi-\frac{1}{2}}^t + \alpha_i T_{xoi-\frac{1}{2}}^t \right) \\
& + P_{oi} \left(- \left(T_{xoi+\frac{1}{2}}^t + T_{xoi-\frac{1}{2}}^t + C_{poq}^t \right) - \alpha_i \left(T_{xwi+\frac{1}{2}}^t + T_{xwi-\frac{1}{2}}^t + C_{powi}^t \right) \right) \\
& + P_{oi+1} \left(T_{xoi+\frac{1}{2}}^t + \alpha_i T_{xwi+\frac{1}{2}}^t \right) \\
& = - (C_{pooi}^t + \alpha_i C_{powi}^t) P_{oi}^t + \dot{q}_{oi} + \alpha_i \dot{q}_{wi} + \alpha_i T_{xwi+\frac{1}{2}}^t (P_{cowi+1} - P_{cowi})^t \\
& + \alpha_i T_{xwi-\frac{1}{2}}^t (P_{cowi-1} - P_{cowi})^t
\end{aligned}$$

$$a_i P_{oi-1} + b_i P_{oi} + c_i P_{oi+1} = d_i$$

$$a_i = T_{xoi-\frac{1}{2}}^t + \alpha_i T_{xoi-\frac{1}{2}}^t$$

$$b_i = - \left(T_{xoi+\frac{1}{2}}^t + T_{xoi-\frac{1}{2}}^t + C_{poq}^t \right) - \alpha_i \left(T_{xwi+\frac{1}{2}}^t + T_{xwi-\frac{1}{2}}^t + C_{powi}^t \right)$$

$$c_i = T_{xoi+\frac{1}{2}}^t + \alpha_i T_{xwi+\frac{1}{2}}^t$$

$$\begin{aligned}
d_i = & - (C_{pooi}^t + \alpha_i C_{powi}^t) P_{oi}^t + \dot{q}_{oi} + \alpha_i \dot{q}_{wi} + \alpha_i T_{xwi+\frac{1}{2}}^t (P_{cowi+1} - P_{cowi})^t \\
& + \alpha_i T_{xwi-\frac{1}{2}}^t (P_{cowi-1} - P_{cowi})^t
\end{aligned}$$

$$\alpha = - \frac{C_{swwi}^t}{C_{swoi}^t}$$

Apply Boundary condition to the final equation for production at bottom hole pressure specified well condition

$$q_{oi} = \frac{WC_l}{A\Delta x} \lambda_{oi} (P_{oi} - P_{bhl})$$

$$q_{wi} = \frac{WC_l}{A\Delta x} \lambda_{wi} (P_{wi} - P_{bhl})$$

Substitute boundary condition to the equation and the equation below is the final equation of the forward model

$$\begin{aligned}
& P_{oi-1} \left(T_{xoi-\frac{1}{2}}^t + \alpha_i T_{xoi-\frac{1}{2}}^t \right) \\
& + P_{oi} \left(- \left(T_{xoi+\frac{1}{2}}^t + T_{xoi-\frac{1}{2}}^t + C_{poq}^t + \frac{WC_i}{A\Delta x} \lambda_{oi} \right) \right. \\
& \left. - \alpha_i \left(T_{xwi+\frac{1}{2}}^t + T_{xwi-\frac{1}{2}}^t + C_{powi}^t + \frac{WC_i}{A\Delta x} \lambda_{wi} \right) \right) + P_{oi+1} \left(T_{xoi+\frac{1}{2}}^t + \alpha_i T_{xwi+\frac{1}{2}}^t \right) \\
& = - (C_{pooi}^t + \alpha_i C_{powi}^t) P_{oi}^t - \frac{WC_i}{A\Delta x} \lambda_{oi} P_{bhi} - \alpha_i \frac{WC_i}{A\Delta x} \lambda_{wi} P_{bhi} \\
& + \alpha_i T_{xwi+\frac{1}{2}}^t (P_{cowi+1} - P_{cowi})^t + \alpha_i T_{xwi-\frac{1}{2}}^t (P_{cowi-1} - P_{cowi})^t
\end{aligned}$$

$$a_i = T_{xoi-\frac{1}{2}}^t + \alpha_i T_{xoi-\frac{1}{2}}^t$$

$$b_i = - \left(T_{xoi+\frac{1}{2}}^t + T_{xoi-\frac{1}{2}}^t + C_{poq}^t + \frac{WC_i}{A\Delta x} \lambda_{oi} \right) - \alpha_i \left(T_{xwi+\frac{1}{2}}^t + T_{xwi-\frac{1}{2}}^t + C_{powi}^t + \frac{WC_i}{A\Delta x} \lambda_{wi} \right)$$

$$c_i = T_{xoi+\frac{1}{2}}^t + \alpha_i T_{xwi+\frac{1}{2}}^t$$

$$\begin{aligned}
d_i = & - (C_{pooi}^t + \alpha_i C_{powi}^t) P_{oi}^t - \frac{WC_i}{A\Delta x} \lambda_{oi} P_{bhi} - \alpha_i \frac{WC_i}{A\Delta x} \lambda_{wi} P_{bhi} + \alpha_i T_{xwi+\frac{1}{2}}^t (P_{cowi+1} - P_{cowi})^t \\
& + \alpha_i T_{xwi-\frac{1}{2}}^t (P_{cowi-1} - P_{cowi})^t
\end{aligned}$$

2.6 Objective Function

The second step is applying objective function to the forward model. Objective function as the amount of differences between observation data and simulator response for a given set of data [4]. Objective function is used to compute the difference between simulated and measured seismic or production data and it can be separated as the total amount of local parameter related to wells or seismic zones[16]. Objective function is also defined as the different between simulated and observed data [6].

Objective function is used to represent error between simulated and history data and it need to undergo modification on each iteration so that it produce the least error [17]. Other than that, Objective function also was evaluated at each iteration [18]. “Objective function quantifies the mismatch between the model response and measured prediction data by using the sum of the squared residuals” [19].

There are three type of objective function which is widely used to build an objective function [4].

1. Least square formulation

$$F = (d^{obs} - d^{cal})^T (d^{obs} - d^{cal})$$

2. Weighted least square formulation

$$F = (d^{obs} - d^{cal})^T w (d^{obs} - d^{cal})$$

3. Generalized least square formulation

$$F = \frac{1}{2}(1 - \beta)\{(d^{obs} - d^{cal})^T C_d^{-1}(d^{obs} - d^{cal})\} + \frac{1}{2}\beta\{(\alpha - \alpha_{prior})^T C_\alpha^{-1}(\alpha - \alpha_{prior})\} \setminus$$

Where d^{obs} represent the observed data, d^{cal} is the response of the system as predicted by the forward modeling and w is a diagonal matrix that assigns individual weights to each measurement. The objective function was optimized several times until the best fit is obtained between the calculated data and the observed data. The flow of the alteration of the objective function is shown Figure 3.

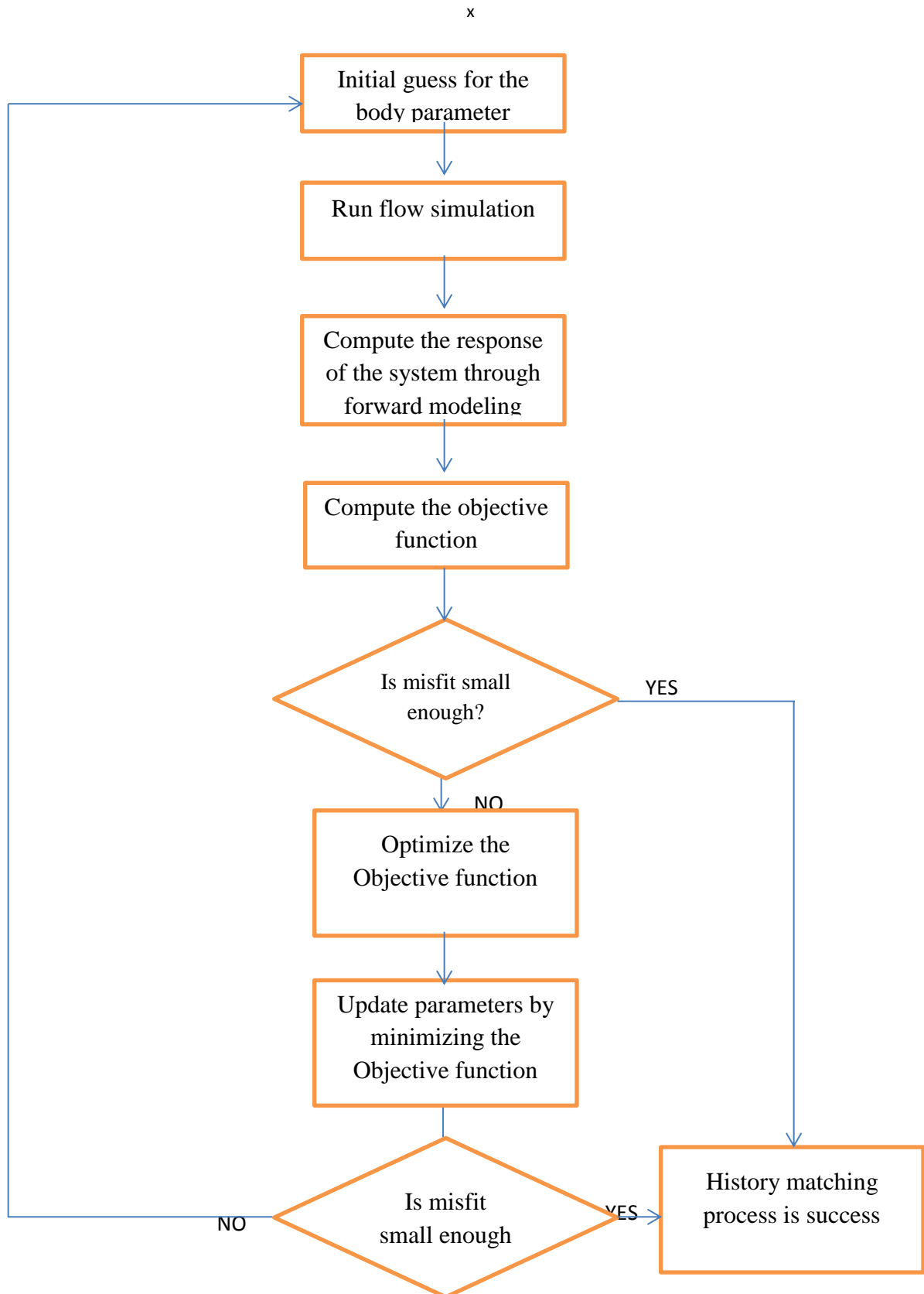


FIGURE 3: History Matching Flow chart

2.7 Optimization Method

History matching is basically a minimization process [20]. In order to do the minimization process, optimization algorithm is needed. It is important to select an optimization algorithms so that, less iteration is needed to match the data [20]. The best optimization algorithms are the one which can converge quickly. Inverse algorithms which can converge solution faster must be utilized in optimization stage so that the time for history matching activities can be reduce [21].

Optimization algorithm for history matching are divided into three; gradient based optimization, non-gradient based optimization and global minima [22]. For gradient based optimization methods, it is used to estimate optimal parameters by using gradient of the objective function. Meanwhile for non-gradient based method used only objective function to do the evaluation to find the optimum point without using gradient and Hessian matrix [23]. For global minima optimization, it is a branch of applied mathematics and numerical analysis.

Examples of gradient based method are steepest decent, conjugate algorithms and Gauss newton method. For non-gradient methods the example are Nelder-Mead, Mesh adaptive direct search and general pattern search[24].

2.8 Parameter Reduction Method

For a real case, history matching was applied on a real reservoir which has thousands of grid blocks and parameters. History matching a large number of parameters in a real reservoir is a challenge because of computational effort required for a large reservoir and the need of insure that solutions are geologically realistic [22]. All of these challenges can be helped by using algorithms which can reduced the number of parameters[22].

To reduce the number of parameters, parameterization technique must be applied first. There are several parameter reduction method which can be used for history matching purpose such as pilot point method, gradual deformation, zonation and discrete cosine transform [25]. Parameter reduction method must reduce the number of parameter

without defect the reservoir model. In other word, parameter reduction method cannot eliminate a parameter value which can affect the reservoir [26].

2.9 Synthetic Reservoir Model

Synthetic reservoir model is making a new reservoir field by making another field as a reference [11]. Synthetic reservoir model is also define as an artificial model which is built by creating the reservoir data [27]. A synthetic reservoir model is used to mimics certain reservoir with certain condition such as synthetic reservoir model which mimics a deep water deposit of amalgamated channel complexes [28].

Synthetic reservoir model is widely used by engineers to do the experiment for history matching because it is easy to create data. If the test is successful, the method can be applied to the real reservoir.

Approach and Benefit

The previous section clearly describes the definition of the terms which were used in this report. A three phase reservoir model will be described later in this report. The approach of this report is to use RLS as filtering method and the first step is to reduce the initial model parameter. The combination of RLS filtering and model reduction method seems to be promising in term of accuracy.

As the goal of this report is just the fundamental method, it does not required real data but this project worked with generated synthetic data. The explanation on the methods used will be elaborate more in chapter 3 and 4.

CHAPTER 3

LITERATURE REVIEW

3.1 Introduction

Reservoir history matching is basically a difficult inverse problem arising in the oil and gas industry and it is very crucial to have parameter reduction and optimization methods in the process [22]. Both of the methods are very important to reduce the uncertainties in history matching process.

This chapter discuss on the application of recursive least square and discrete cosine transform, demonstration of the methods and discussion on previous work which has been done by using these methods.

3.2 Application of Recursive Least Square and Discrete Cosine Transform

3.2.1 Recursive Least Square

In this modern world, various parameter estimation algorithms have been studied by researchers in order to improvise the parameter estimation process which is widely needed to forecast the performance of a system. Recursive least square is defined as an iterative estimation algorithms used to optimize a system [29]. RLS is widely used for nonlinear problems to analyze the signal pattern and it is used for signal processing[30]. RLS is known as an ‘online’ estimation algorithm. Online algorithms required to update the solution as new data become available. It means that, RLS is an iterative method which updates the parameter values as the new data of parameter available. Other than that, RLS also being used in estimating parameter in DC motor system [31].

There are many methods which can be used to do the history matching technique such as Ensemble Kalman Filter, Genetic Algorithms, and Evolutionary Algorithms. The main purpose of all these algorithms is to minimize the objective function. The initial guess of body parameters is the starting point of this algorithm and the process is iteratively advanced until the best fit is obtained between the calculated and observed data. Several optimization algorithms are developed for this purpose.

The methods which are applied for this project is recursive least square (RLS). RLS is not widely used in history matching. Thus, the references for this project are also limited. RLS is used basically for optimization purpose for problems such as radio signal problems and frequency of sound waves problems. RLS is basically used to model an effective physical system and parameter estimation [32]. Recursive least square also is an algorithm which is able to detect nonlinear and the relationship of time varying data [30]. Usually, RLS is adapted from Bayesian perspective.

RLS is a famous algorithm which is used in adaptive filtering, adaptive control and system identification [14]. One study has been carried out at past by researcher to compare between Kalman filter and RLS for flow in open channels. It is used to study the effect of the random disturbances on the system variables in the depths of flow used in the closed loop [33]. The result was RLS provides good stability and performance and it is much simpler than Kalman Filter method.

There are many applications of RLS algorithms in estimation problem and RLS is widely used in adaptive control and signal processing [32, 34]. Thus RLS is very suitable to be used to an electrical problem. RLS is basically the modification of Least Square method [5]. Least square method is defined as a batch processing method because the initial measurement needs to be taken before making any estimation of the best parameter coefficients and least square method used inverse matrix to be solved [35]. From this statement, matrix inverse is hard to solve and required a lot of calculation. Thus RLS is invented and it does not include matrix inverse. This is because, by using RLS method, estimate values of parameters are available as soon as measurements are taken [35].

3.2.2 Discrete Cosine Transform

A real reservoir has thousands of grid blocks which need to be optimized in order to match the simulated data with historical data. Thus, it is a must to have parameter reduction method in order to minimize the number of unnecessary parameters [22].

Among parameter reduction methods are Gradzone method, Zonation method, Principle Component Analysis and Discrete Cosine Transform (DCT). For this project, parameter reduction method used is discrete cosine Transform (DCT). Discrete Cosine Transform is defined as a Fourier based transform [4] and it was introduced for signal decorrelation which is widely used for image compression [36].

DCT is also define as a Fourier based transform which is designated for signal decorrelation and usually used to minimized the amount of data [11] by using orthonormal cosine transform [37]. Other than that, DCT is also used for parameterization of spatially-distributed reservoir properties and it can be applied to integrate production data [36]. DCT also provides an attractive alternative with fewer assumptions [38].

DCT is used widely in image compression because this method provides efficient ways of storing large amounts of data. In image compression, DCT works by separating images into parts of differing frequencies. Then quantization step is carried out and during this step the less important frequencies are discarded. For this project, DCT is used as parameter reducing method. The DCT equation below computes the i, j entry of the DCT of an image:

$$D(i, j) = \frac{1}{\sqrt{2N}} C(i)C(j) \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} p(x, y) \cos \left[\frac{(2x+1)i\pi}{2N} \right] \cos \left[\frac{(2y+1)j\pi}{2N} \right]$$
$$C(u) = \begin{cases} \frac{1}{\sqrt{2}} & \text{if } u = 0 \\ 1 & \text{if } u > 0 \end{cases}$$

3.3 Demonstration of Recursive Least Square and Discrete Cosine Transform

3.3.1 Demonstration of RLS

In this part, a simple demonstration was shown in order to give a clear view to the readers on how RLS work. The example below is the simple example of RLS for linear system [35].

The basic idea behind a RLS algorithm is to compute the parameter update at time instant k by adding a correction term to the previous parameter estimate $\hat{\theta}(k-1)$ once the new information becomes available [39].

First let consider a discrete dynamic system which is described by the equations below:

$$y(k) = \varphi^T(k-1)\theta$$

$$z(k) = y(k) + v(k)$$

$$\varphi^T(k-1) = [-z(k-1), \dots, -z(k-n), u(k-1), \dots, u(k-m)]$$

$$\theta^T = [a_1, \dots, a_n, b_1, \dots, b_m]$$

$U(k)$ is the system input while $y(k)$ is the system output. For $z(k)$ is the measured system output and $v(k)$ is a zero mean white Gaussian noise term which is used for measurement of noise and modeling uncertainties. $\varphi^T(k-1)$ and θ are the information vector and the unknown vector respectively. The number of parameters to be estimated is denoted as $N = n+m$.

A typical RLS algorithm which is widely used is as below:

$$\hat{\theta} = \hat{\theta}(k-1) + P(k)\varphi(k-1)\varepsilon(k)$$

$$\varepsilon(k) = z(k) - \varphi^T(k-1)\hat{\theta}(k-1)$$

$$P(k) = P(k-1) - \frac{P(k-1)\varphi(k-1)\varphi^T(k-1)P(k-1)}{1 + \varphi^T(k-1)P(k-1)\varphi(k-1)}$$

Where $\hat{\theta}$ is known as the least square estimate of θ . $\varepsilon(k)$ is the one step ahead prediction error. The amount of correction is directly proportional to the prediction error.

Example of RLS: Parameter Estimation of a time-invariant system

Example of simple linear first order of RLS in history matching problem to estimate the value of permeability and compare it with historical data [35]:

$$K_{1_k} = \frac{2(2k-1)}{k(k+1)} \quad k = 1, 2, \dots, n$$

$$K_{2_k} = \frac{6}{k(k+1)T_s}$$

The residual equation is given by:

$$Res_k = x_k^* - \widehat{x_{k-1}} - \dot{x_{k-1}} T_s$$

Combining the top equation with residual equation:

$$\widehat{x_k} = \widehat{x_{k-1}} + \dot{x_{k-1}} T_s + K_{1_k} Res_k$$

$$\dot{x_k} = \dot{x_{k-1}} + K_{2_k} Res_k$$

The data given is:

$$x_1^* = 1.2$$

$$x_2^* = 0.2$$

$$x_3^* = 2.9$$

$$x_4^* = 2.1$$

TABLE 1: Result of the RLS iteration

Value of K	Calculation
k=1	$K_{1_1} = \frac{2(2k-1)}{k(k+1)} = \frac{2(2*1-1)}{1(1+1)} = 1$ $K_{2_1} = \frac{6}{k(k+1)T_s} = \frac{6}{1(1+1)1} = 3$ $Res_1 = x_1^* - \widehat{x}_0 - x_0 T_s = 1.2 - 0 - 0 * 1 = 1.2$ $\widehat{x}_1 = \widehat{x}_0 + \widehat{x}_0 T_s + K_{1_1} Res_1 = 0 + 1 * 1.2 = 1.2$ $\widehat{\dot{x}}_1 = \widehat{x}_0 + K_{2_1} Res_1 = 0 + 3 * 1.2 = 3.6$
k=2	$K_{1_2} = 1$ $K_{2_2} = 1$ $Res_2 = -4.6$ $\widehat{x}_2 = 0.2$ $\widehat{\dot{x}}_2 = -1$
k=3	$K_{1_3} = \frac{5}{6}$ $K_{2_3} = 0.5$ $Res_3 = 3.7$ $\widehat{x}_3 = 2.28$ $\widehat{\dot{x}}_3 = 0.85$
k=4	$K_{1_4} = 0.7$ $K_{2_4} = 0.3$ $Res_4 = -1.03$ $\widehat{x}_4 = 2.41$ $\widehat{\dot{x}}_4 = 0.54$

From the calculation that has been done, the graph (Figure 4) has been produce:

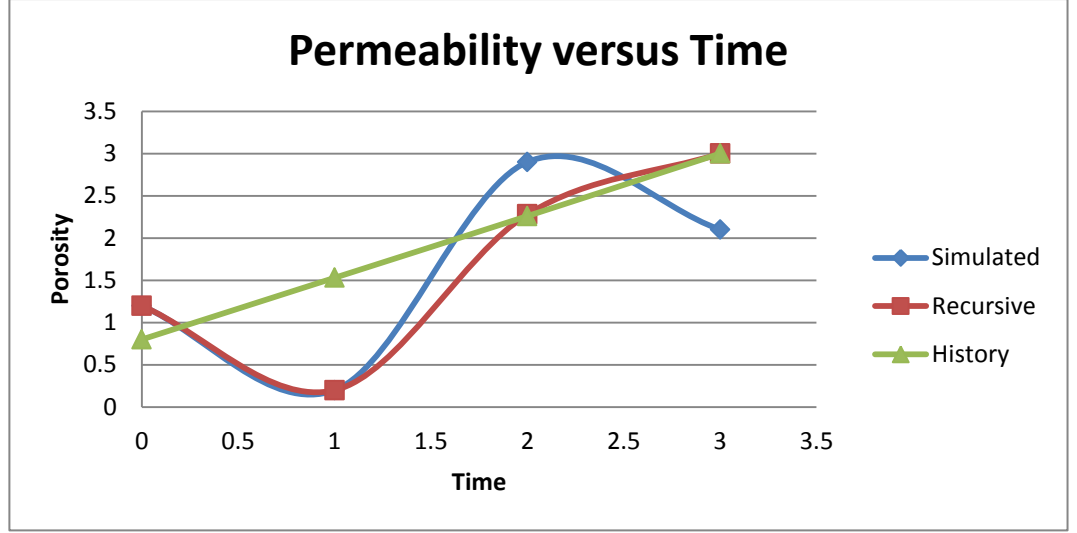


FIGURE 4: Porosity versus Time Graph

From the graph (Figure 4), the green line is the permeability historical data. The blue line is the simulated porosity data and the red one is the data after undergo one iteration. From the graph, the red line is moving toward the historical data. Thus, the red line can match the historical data if more iteration is carried out.

3.3.2 Demonstration of DCT

DCT is widely used in image compression. DCT was demonstrated by using an example on image compression[40].

1. The image is broken into 8x8 blocks of pixels
2. Working from left to right, top to bottom, the DCT is applied to each block
3. Quantization is used to compressed the image on each zone
4. The array of compressed blocks that constitute the image is stored in a drastically reduced amount of space

For the standard 8x8 block, the equation of the DCT is like this[40]:

$$D(i, j) = \frac{1}{\sqrt{2N}} C(i)C(j) \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} p(x, y) \cos\left[\frac{(2x+1)i\pi}{16}\right] \cos\left[\frac{(2y+1)j\pi}{16}\right]$$

$$C(u) = \begin{cases} \frac{1}{\sqrt{2}} & \text{if } u = 0 \\ 1 & \text{if } u > 0 \end{cases}$$

To get the matrix form, this equation is used[40]:

$$T_{i,j} = \begin{cases} \frac{1}{\sqrt{N}} & \text{if } i = 0 \\ \sqrt{\frac{2}{N}} \cos \left[\frac{(2j+1)i\pi}{2N} \right] & \text{if } i > 0 \end{cases}$$

This equation can be used in this project during the process of reducing the number of parameters. The concept is just the same. So after finding T matrix, the original value of parameter at each block is leveled off by subtracting the value with the optimum DCT value which is then name as M matrix[41].

After finding T and M matrix, DCT can be performed by using this formula:

$$D = T \times M \times T^T$$

Next D matrix is multiplied by the quantization unit (Q) which determine the type of data that we need. For example, large number of quantization is used to get large value of the block and eliminate the lower number in the block. Usually, quantization of 50 is used to get more compression and lower data quality.

The final step is after the quantization step, the data is reconstructed back by multiplying the quantization matrix with the compressed matrix(C). And then the reconstructed data (R) is added with the optimum DCT value which has been subtracted at the beginning of the calculation[42].

$$R = (C \times Q) + \text{DCT optimum value}$$

3.4 Previous Study

In this part, the discussion on previous study of RLS and DCT in history matching process is explained in detail.

3.4.1 Recursive Least Square

RLS is not widely used in history matching purpose. Thus it is not much reference for recursive least square method. One of the study used RLS to identify reservoir parameter from the South Belridge Diatomite reservoir [39]. This project is a pilot project and it has steam injected into low permeability diatomite through two vertical hydrofractures. In this problem, the reseacher tried to match the temperature and pressure profiles in order to estimate reservoir permeability.

The researcher chooses RLS as optimization method because the problem includes the uses of discrete time model parameter. The researcher made an assumption that permeability is constant and then come out with this objective function:

$$\alpha(t+1) = \alpha(t) + F^{-1}(t+1)(P_{j+1}^t - 2P_j^t + P_{j-1}^t)\varepsilon(t+1)$$

From their experiment, the result showed that RLS converged was extremely rapid and it was quite accurate to the tenth decimal places. The only problem was RLS is unstable for large number of parameter problem and more stable with small number of parameter [39]. Thus, parameter reduction method needs to be combined with RLS method to make it accurate.

In addition, one of the study carried out by a researcher to determine the efficiency of updating technique by using RLS to an electrical problem [5]. The objective of the study is to estimate the performance of DC motor in a circuit. The result was RLS produced large value of errors in each iteration. Thus, RLS must be carried out for a problem with least amount of unknown parameters to reduce the error [5].

From the previous study, RLS is a good estimator because it converge rapidly thus less alterations are needed [34]. To use RLS in history matching, there are some limitations in applying this method in the problem which need to be followed to get accurate estimation [32]:

1. RLS must be used to estimate small scale of reservoir or it need to be combine with parameter reduction method to make it more accurate and stable
2. To estimate a reservoir parameter, number of unknown parameters for the reservoir must be small so that less value of error will be produced.
3. Δt and Δx of the model must be increase monotonically (increasing without decrease or vice versa) or have a fix value in order to make RLS more stable and accurate.

3.4.2 Discrete Cosine Transform

DCT is widely used in image compression and pattern recognition [38]. Previous study had been done to know the effectiveness of DCT as parameterization method[38]. The researcher used 64 x64 blocks to test DCT. The grid blocks were used to compare the DCT method with Karhunen-Loeve Transform (KLT) method. The objective of this test was to determine which method is the best to parameterize the reservoir block in term of permeability. One grid block this had been fully parameterized (clean) as the reference.

From this test, the result found that DCT was most effective to parameterize vertical permeability. In this test different modes were also used for the permeability image to increase the effectiveness of DCT [37]. DCT offer the best parameterization option for reservoir history matching application where flexible, robustness, computational efficiency and the ability to properly capture facies structure and connectivity are all important.

The other example is done which combine ensemble kalman filter with Discrete Cosine transform [37]. The objective of the study is to use DCT to provide low dimensional parameterization for history matching purpose and to reduce the values of permeability, pressure and saturation of the field for each individual block. From the experiment, the result stated that DCT is a good parameterization for permeability values and poor for saturation value [37].From this chapter, DCT can be used with RLS by following the RLS assumption and modified the DCT algorithms to make it suitable to be used with RLS. The modification must be done to the objective function.

CHAPTER 4

METHODOLOGY/ PROJECT WORK

4.1 Research Methodology

The research methodology of this project is focusing on applying Discrete Cosine Transform for parameter reduction method and Recursive least Square for optimization method. Thus, the methods were planned based on the process flow to achieve the objective of this project which is to minimize time taken to do history matching by using RLS and DCT.

4.2 Project activities:

Figure 5 shows the process flow of the project. In this part, all the activities which need to be done under each of the main method for this project were listed down.

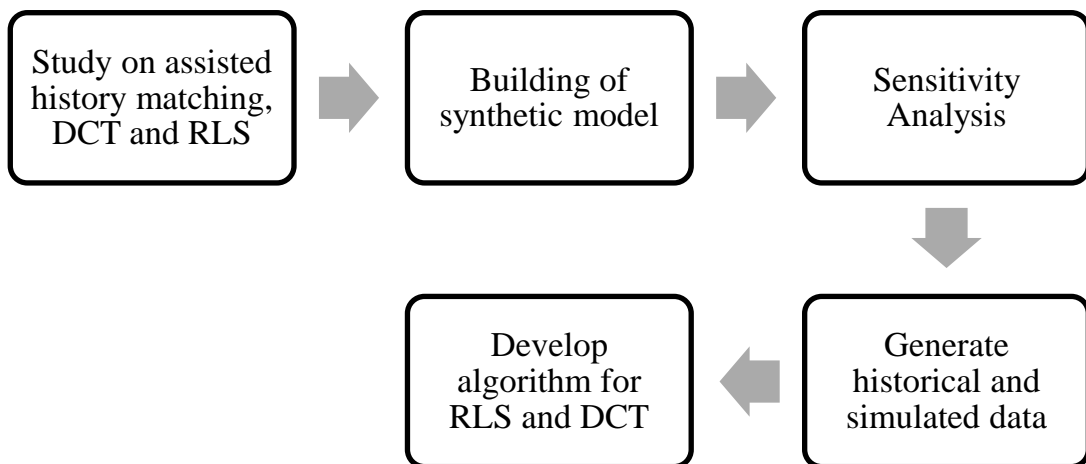


FIGURE 5: History Matching flow process

- 1) Research on assisted history matching, DCT and RLS
 - Find all the papers which is related to the project which can be used as references
 - Critically analyzed all the papers and summarize the paper
- 2) Building of synthetic reservoir model
 - Modified ODEH reservoir data to be used in the project
 - The derived equation is shown in summary of project progress
- 3) Sensitivity analysis
 - Do the sensitivity analysis by changing the value of permeability and porosity
- 4) Generate Historical and Simulated data
 - Used the reservoir model to generate two data which are historical and simulated data
- 5) Develop algorithm for RLS and DCT
 - From the two data, algorithm for RLS and DCT were develop
- 6) Apply Recursive least square
 - After reduce the number of parameter(permeability), a graph is generated by using the reduced number of parameter
 - Apply RLS to optimize the parameters
- 7) Calculate the threshold
 - Set the threshold value
 - The model parameters such as flow rate is compared with the historical data



4.4 Gantt Chart


TABLE 2 : Gantt Chart

Gantt Chart	Period (Weeks)													
Description of planning	1	2	3	4	5	6	7	8	9	10	11	12	13	14
FYP 1 (January 14 – April 14)														
Doing research on the project - search journal - summarize the journal														○
Proposal Defense presentation									○					
Develop Forward model														○
Design Objective Function														○
Report the result to supervisor														○


FYP 2 (May 14 – September 14)														
Description of planning	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Build the synthetic reservoir						●								
Demonstrate RLS and DCT							●							
Generate history and simulated data										●				
Develop algorithm for RLS and DCT													●	
Submit the result to SV														●

4.5 Key milestone

Based on the gantt chart (Table 2), the key milestone is denoted as the symbol  for FYP 1 and  for FYP 2.

Key milestone for FYP 1 

- Research study on the project title and summarize journal which related to the to the title
- Proposal Defense presentation
- Develop forward Model and design Objective Function
- Report the result to supervisor

Key milestone for FYP 2 

- Build synthetic reservoir model
- Demonstrate RLS and DCT
- Generate history and simulated data
- Develop algorithm for RLS and DCT
- Submit the result to SV

CHAPTER 5

RESULT AND DISCUSSION

An algorithm has been develop as shown below. For the first part is building the synthetic reservoir model and get historical and simulated data from the model by modified the value of permeability.

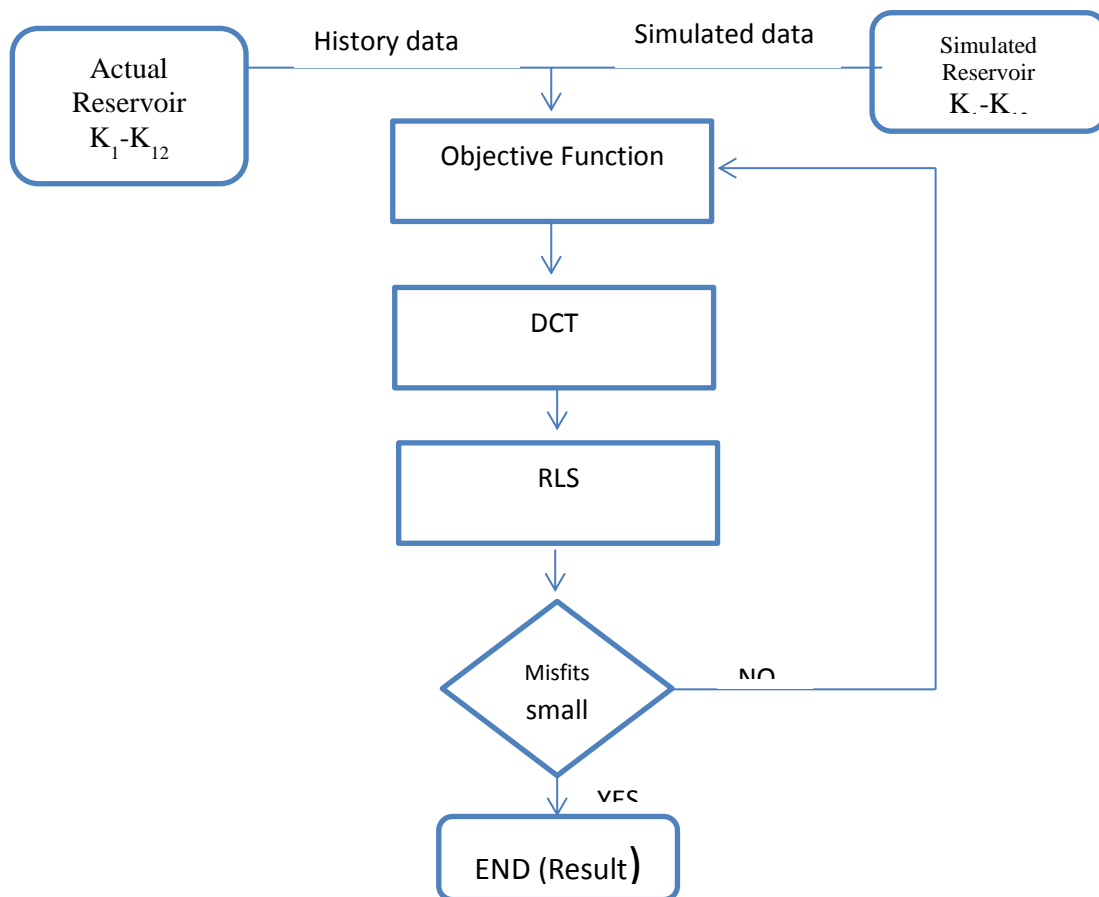


FIGURE 6: Algorithm for DCT and RLS

5.1 Synthetic Reservoir Model

5.1.1 Model Description

A synthetic model of a reservoir has been built by doing some modification to the ODEH data. The original ODEH data had 2 wells; (one producer and one injector) and it is tested for 1200 days. The configuration of the modified ODEH data model is as follow (Figure 7):

Dimension: 10 X 10 x 3 grid blocks

Location (coordinate; i j k1 k2):

- Producer : 5 5 3 3
- Injector 1 : 1 1 3 3
- Injector 2 : 10 1 3 3
- Injector 3 : 1 10 3 3
- Injector 4 : 10 10 3 3

Size: DX= 300 x 1000 ; DY= 300 x 1000 ; DZ= 100 x 20 (first layer); 100 x 20 (second layer); 100 x 80 (third layer)

Porosity, Φ = 0.3

Fluid present: Oil, water, gas and dissolve gas

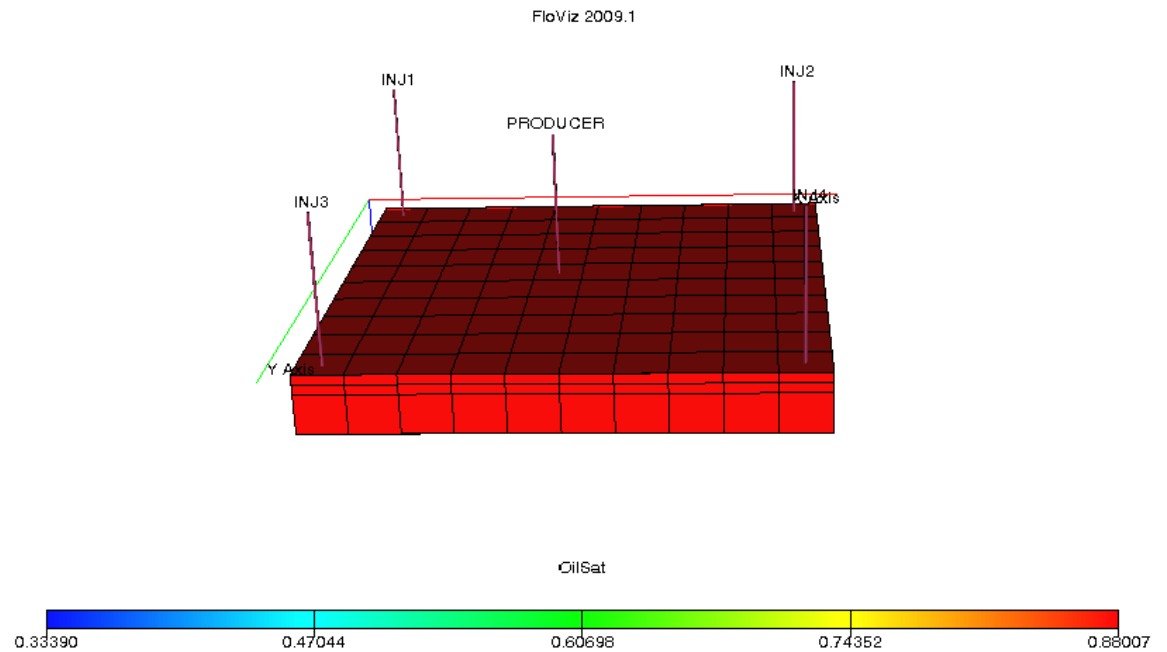


FIGURE 7: Model configuration

This model consist of one production well and four injection wells. The permeability is different for each layer. Each layer was divided into four zones and each zone is consisted of 25 grid blocks. One permeability value is assigned on each zone. Coding for this model can be referred in Appendix section. After the model is build, sensitivity analysis is carried out in order to test the capabilities of the model to detect any changes happen to any of the reservoir parameters.

5.1.2 Sensitivity Analysis

Sensitivity analysis is done to determine either any change made to the reservoir parameters affect the result gets from the model or not. For this model, the analysis was carried out by changing the permeability of each zone and recorded its effect to the reservoir total oil production. If there is changes occur, it means that the model is actively detect changes and can be used for this project. So this analysis is carried out to detect the effectiveness of the model to detect the changes.

5.1.2.1 Methodology

1. Change the permeability in DX direction of each zone at every layer. This process was repeated five times. Ranges of the permeability are as follow:
 - a. 100- 400 mD
 - b. 500 – 800 mD
 - c. 900 – 1200 mD
 - d. 1300 – 1600 mD
 - e. 1700- 2000 mD
2. Change the value of porosity
 - a. 10
 - b. 30
 - c. 80
3. Build a graph according to the recorded data.

5.1.2.2 Result

By using Office software in Eclipse, the graph of total oil production data from the analysis is obtained as follow:

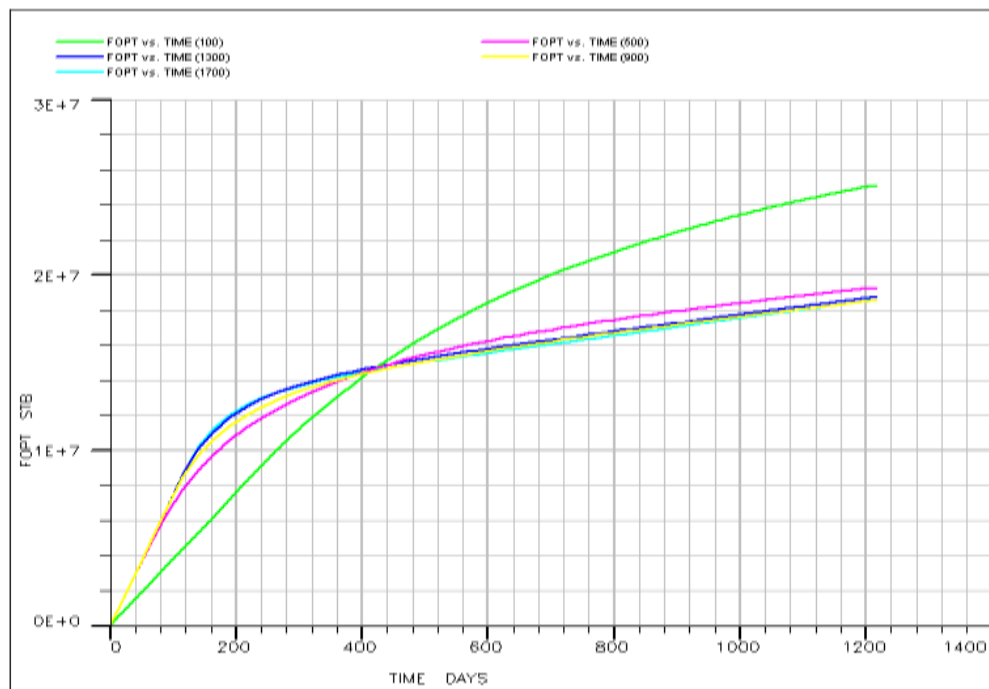


FIGURE 8: Total production rate versus time(PERMEABILTY)

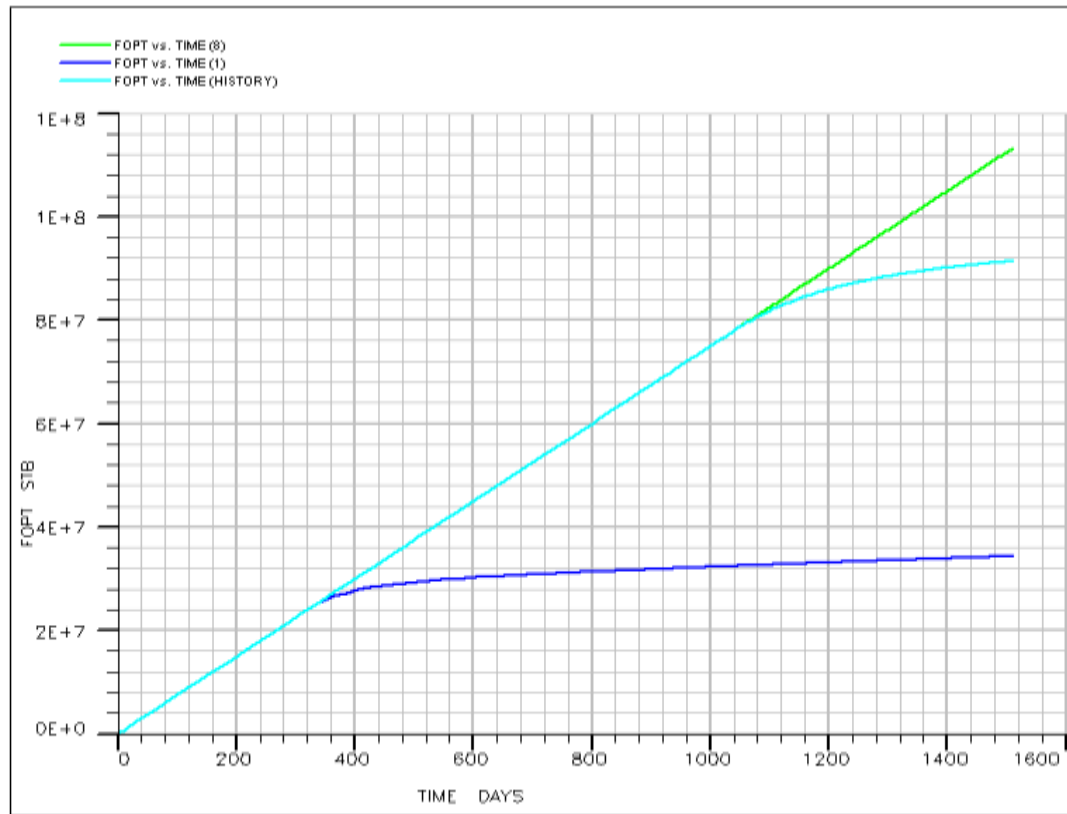


FIGURE 9: Total production rate versus time(POROSITY)

From the graph (Figure 8 and Figure 9), the total oil production changed when the permeability and porosity value changed. As a conclusion, the model is an active model and it can be used for this project because it can detect the changes of the permeability by showing different total oil production line for every permeability.

5.1.3 Flow Distribution

Flow test is carried out to find out either oil in the reservoir is being produced from the model or not. This section is divided into three sections; before the oil being produce, during the oil being produce and after the oil is mostly being produced.

Before the test:

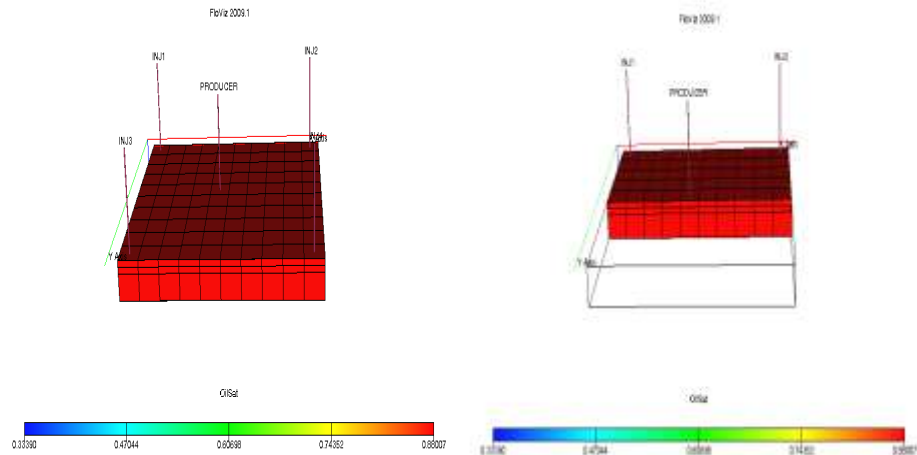


FIGURE 10: Oil Saturation before the test

The first picture (Figure 10) is the full picture of the reservoir model while the second picture is the cross section of the reservoir model. From the picture, before the oil is being produced, the reservoir is 100% saturated with oil.

Middle of the test:

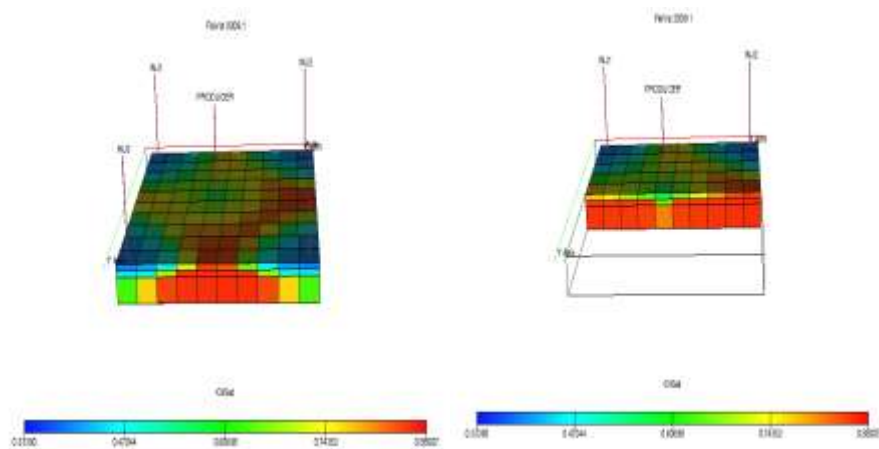


FIGURE 11 : Oil Saturation at the middle of the test

Figure 11 shows the condition of the reservoir at the middle of the producing time. The top layer of the reservoir is almost completely saturated with water. And the second

layer, the water start to saturate the injector area. From the cross section, the saturation of oil at the PRODUCER well starts to decrease.

End of test:

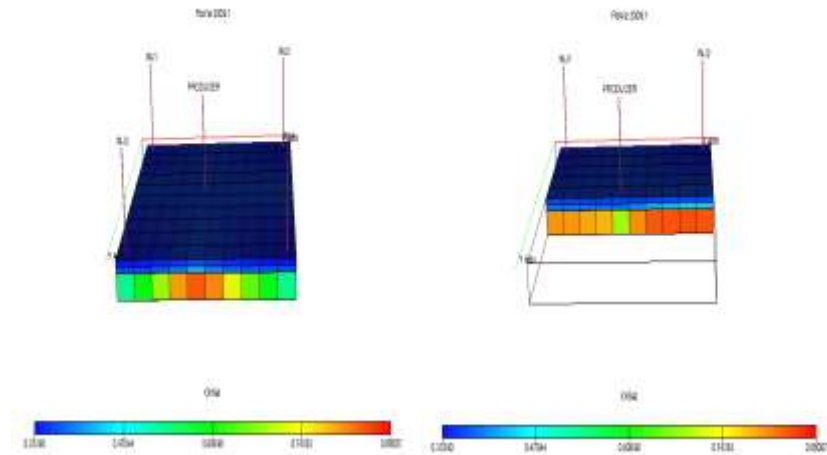


FIGURE 12: Oil saturation at the end of the test

At the end of the test, (Figure 12) the first and the second layer of the reservoir were 100% filled with water. At the third layer, oil saturation only decrease at the injector are and at the PRODUCER area.

5.1.4 History Data versus Simulated Data

The base data is set as the History data. There are three cases for this part. First the permeability value was changed. Second, the porosity value was changed followed by changed the porosity and permeability value. After run the simulation, the total oil production rate and production rate graph for the three cases were produced. From these two data; simulated and history data; four lines were produced on a graph. The graphs were shown below:

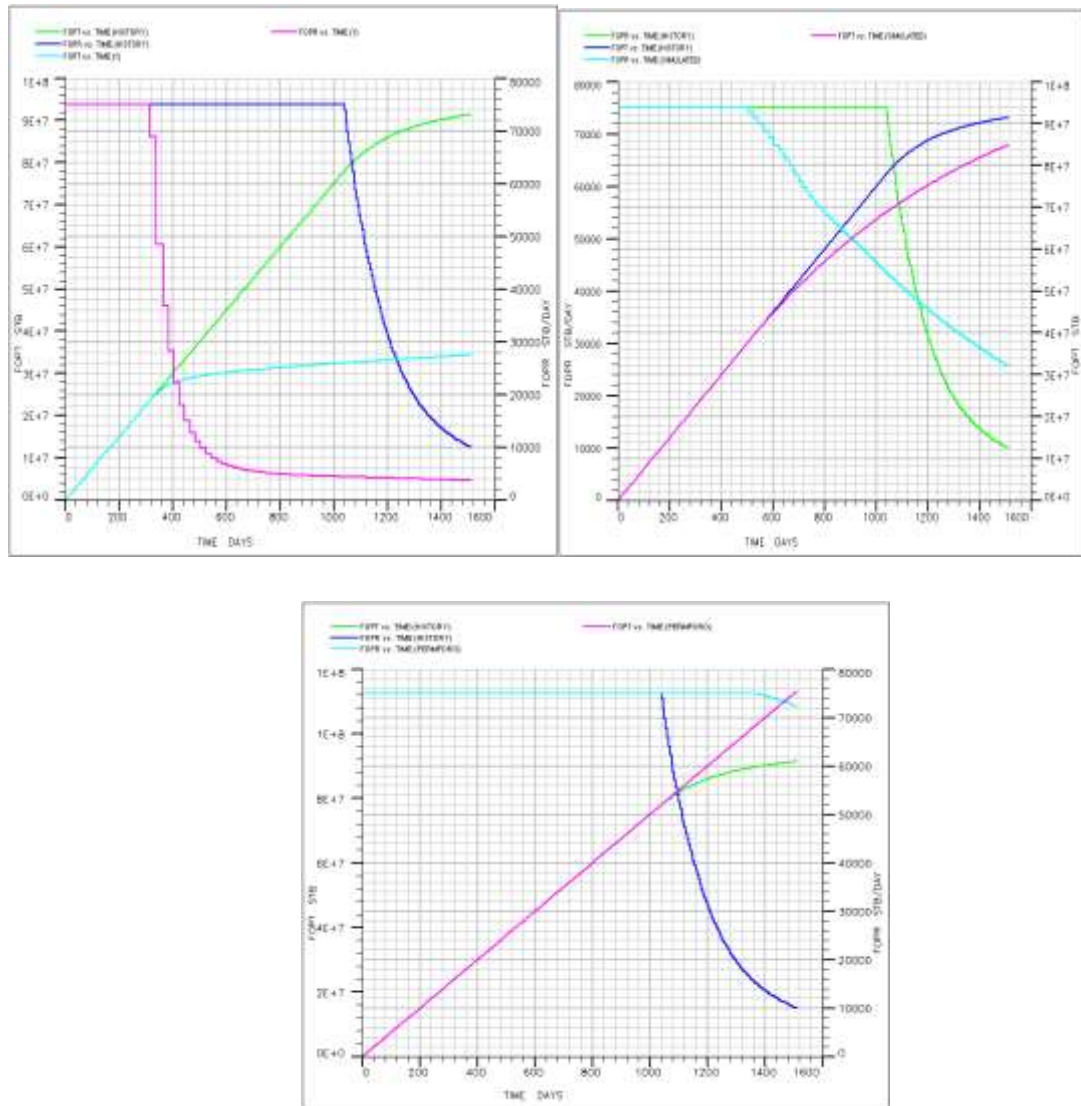


FIGURE 13: Total Oil Production and Oil Production rate Versus Time

From the graph, there is a difference or gap between the total oil production line of history data and simulated data. After obtaining this data, this project is aimed on matching the oil production data get from the simulated data to the history data.

This can be done by using RLS for optimization purpose and DCT as parameter reduction purpose aided by computer by using software like MatLab. The next step for this project is to come out with RLS and DCT coding to be used to match the data.

5.2 Objective Function

This part discuss on the objective function. Objective function used for this project was weighted Least Square. This type of objective function is used because most of the paper used this type of objective function thus the a lot of reference can be found by using this objective function.

$$Q = \sum_{n=1}^t w \{P_j^{\text{obs},n} - P_j^{\text{calc},n}\}^2$$

α is assumed to be constant and it is a function of location x and time t and is parameterized by permeability k [39].

$$P_j^{n+1} = P_j^n + \alpha \frac{\Delta t}{\Delta x^2} \{P_{j+1}^n - 2P_j^n + P_{j-1}^n\}$$

For a uniform time and space grid, the objective function used is weighted least square type and it is as below:

$$Q = \sum_{n=1}^t w \{P_j^{\text{obs},n} - P_j^{\text{calc},n}\}^2$$

5.3 Limitation

This project is a mathematical based project which is aided by computer to do the calculation. The software used is Matlab. Because of lack of knowledge in writing the coding for the algorithms, the result is presented as propose algorithms for both of the method (DCT and RLS) in form of flowchart. Other than that the result is also compared with the literature review. Usually, in a real problem, the coding for the calculation aided by the computer will be written by someone who is expert in this programming language by referring to the data given to them.

5.4 Algorithm for combination of RLS and DCT

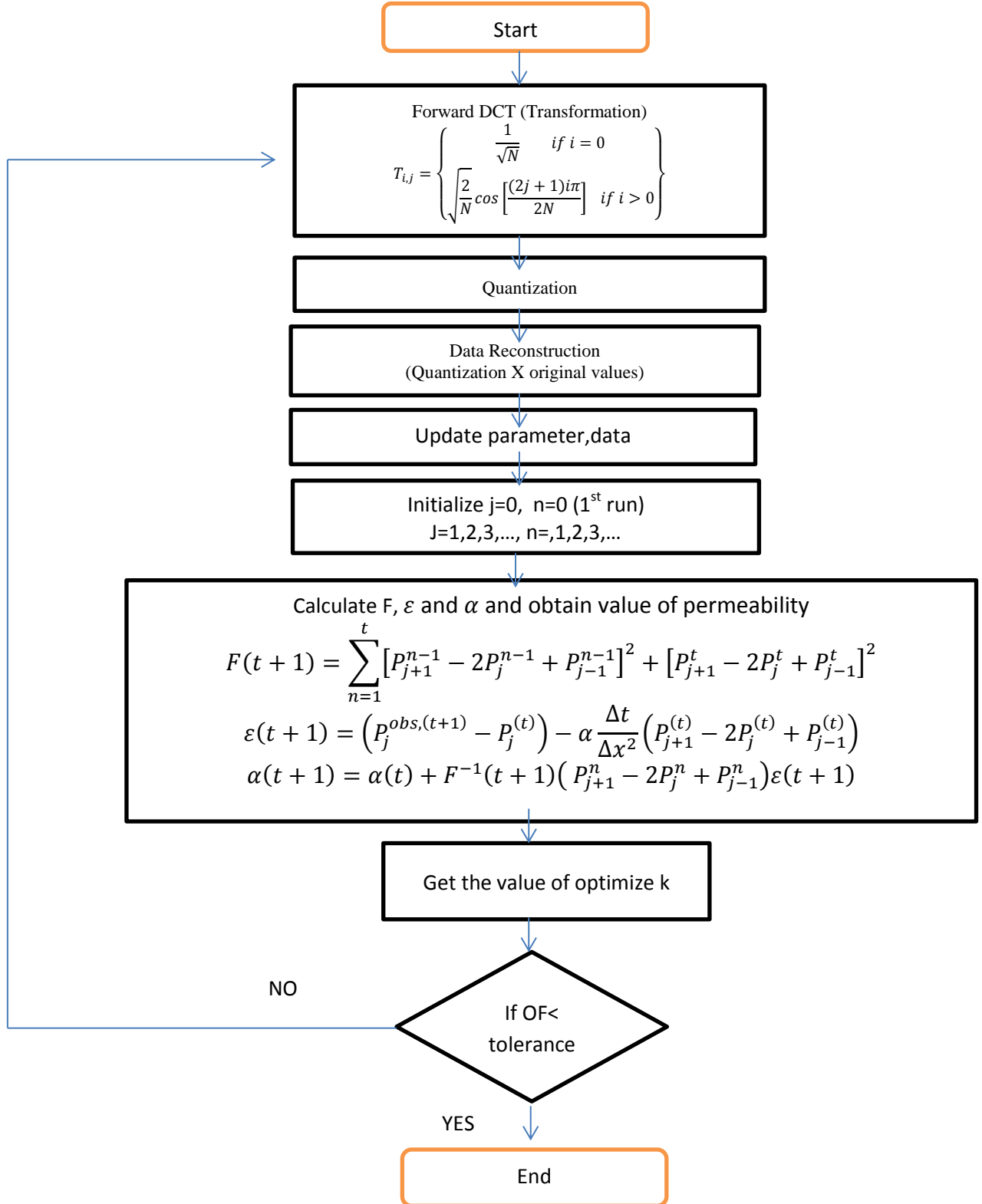


FIGURE 14: Algorithms for combination of RLS and DCT

First, the reservoir parameters from simulated data were inserted into the DCT forward transformation. By using this formula, a matrix was form. Then the matrix was multiplied with quantization number to decrease the number of parameter. Quantization number was ranging from 1 to 100. The higher the number of quantization, the lower the number of parameter eliminated. Then the data was reconstructed back by multiply it by original value.

Then after the number of parameter was reduced, the parameter undergo optimization process by using RLS. First the value of j and n were initialized to zero. Then the value of F , ε and α were calculated. The values of optimized permeability were obtained and then the objective function was calculated. If the objectives function value is lower than the tolerance, then the process end. If not, the calculation need to repeat back from step one.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

To conclude, one reservoir model is successfully being created by modifying ODEH data and from the sensitivity analysis, it can be proved that this model is applicable for history matching purpose because it can detect changes happen to the reservoir. Other than that, algorithms for both of the recursive least square and discrete cosine transform method is successfully being proposed. The proposed algorithms can be used by expert in coding to integrate the calculation of the parameters into the computer language to aid the calculation part.

The proposed algorithms also can be used as a reference for further studies. This project also successfully achieves its objective because it manages to prove that DCT and RLS can be combined to be used for history matching purpose. From the literature review, RLS is considered as a good optimization tools because it converge rapidly but these method must follow the condition to get accurate result. These conditions can help other researcher for further studies to increase the accuracy of the project. The conditions are:

1. RLS must be used to estimate small scale of reservoir or it need to be combine with parameter reduction method to make it more accurate and stable
2. To estimate a reservoir parameter, number of unknown parameters for the reservoir must be small so that less value of error will be produced.

3. Δt and Δx of the model must be increase monotonically (increasing without decrease or vice versa) or have a fix value in order to make RLS more stable and accurate.

Meanwhile, for DCT, it is a good parameterization tool which can be used to reduce the number of parameter by eliminate the parameter which will not affected the reservoir performance based on image compression method.

As recommendation to this project, the list below can be applied to the project for futher studies:

1. Both of the method can be used to estimate other parameter such as saturation, porosity and pressure
2. Apply these methods to the local reservoir available in Malaysia so that it can be used and give benefits to the oil and gas company.
3. Someone needs to apply and test the algorithms to a real reservoir

REFERENCES

1. Heimhuber, R., *Efficient History Matching for Reduced reservoir Models with PCE based Bootstrap Filters*, in *Institute for modelling hydraulic and environmental systems* 2012, University Of Stuttgart: Sonthofen.
2. Abrahem, F.S., Z.E. Heinemann, and G.M. Abrahem, *A New Computer Assisted History Matching Method*, 2010, Society of Petroleum Engineers.
3. Maschio, C. and D.J. Schiozer, *Development and Application of Methodology for Assisted History Matching*, 2005, Society of Petroleum Engineers.
4. Rwechungura, R.W., M. Dadashpour, and J. Kleppe, *Advanced History Matching Techniques Reviewed*, 2011.
5. Sjo, A., *Updating Techniques in Recursive Least Square*. 1992.
6. Dadashpour, M., *Reservoir Characterization using Production Data and time Lapse Seismic Data*, in *Department of Petroleum Engineering and Applied Geophysics* 2009, Norwegian University of Science and Technology: Trondheim.
7. Dean S. Oliver, A.C.R., Ning Liu, *Inverse Theory for Petroleum Reservoir Characterization and History Matching*. 2008, United State Of America: Cambridge University Press.
8. Yadav, S., *History Matching Using Face-Recognition Technique Based on Principal Component Analysis*, 2010, Society of Petroleum Engineers.
9. Walker, G.J., et al., *Assisted History Matching as a Useful Business Tool: An Example from Trinidad*, Society of Petroleum Engineers.
10. Arash Mirzabozorg, L.N., Zhangxin Chen, Chaodong Yang, *Differential Evolution for Assisted History Matching Process: SAGD Case Study*. 2013.
11. Eric Bhark, B.J., Akhil Datta Gupta, *A New Adaptively Scaled Production Data Integration approach using the Discrete Cosine Parameterization*. 2010.
12. P. Ferraro, F.V., *Use of Evolutionary algorithms in Single and Multiobjective Optimization Techniques for Assisted History Matching* 2009.
13. Chen, C., et al., *Assisted History Matching Using Three Derivative-Free Optimization Algorithms*, 2012, Society of Petroleum Engineers.

14. Xin xu, H.-g.H., Dewen Hu, *Efficient Reinforcement Learning Using Recursive Least Squares Methods* 2002.
15. Tavassoli, Z., J.N. Carter, and P.R. King, *Errors in History Matching*.
16. Cardoso, M.A., *Data_partitioning Technique for Gradient Based Optimization Methods in History Matching*. History Matching and Forecasting, 2011.
17. Cheng, H., K. Dehghani, and T.C. Billiter, *A Structured Approach for Probabilistic-Assisted History Matching Using Evolutionary Algorithms: Tengiz Field Applications*, Society of Petroleum Engineers.
18. H. Cheng, K.D., T. Biliter, *A structured Approach for Probabilistic Assisted History Matching Using Evolutionary Algorithms : tengiz Field Application*. 2008.
19. Friedel, T. and S.V. Taware, *Fast and Efficient Assisted History Matching for Large-Scale Applications*, 2012.
20. Sarma, P., et al., *A New Approach to Automatic History Matching Using Kernel PCA*.
21. Biswas, D., *Assisted History Matching for Surface Coupled Gas Reservoir Simulation*. SPE, 2006.
22. Salem Al-Akhdar, D.Y.D., Marc Dambrine, Astrid Jourdan, *An Integrated Parameterization and Optimization Methodology for Assisted History Matching: Application to a Libyan Field Case*. 2012.
23. Ding D. Y. , R.F., *Local Parameterization of Geostatistical realizations for History Matching*. 2009.
24. Dadashpour, M., R.W. Rwechungura, and J. Kleppe, *Fast Reservoir Parameter Estimation By Using Effect Of Principal Components Sensitivities And Discrete Cosine Transform*, Society of Petroleum Engineers.
25. L.Y., H., *Gradual Deformation of Non Gaussian Stochastic Models*. 2000.
26. Marsily de G., L.G., Boucher M., Fasanino G., *Interpretation of Interference Tests in a Well Field using Geostatistics Techniques to fit the Permeability Distribution in a Reservoir Model*. Geostatistics for natural resources charactheristic 1984.

27. George E trimble Chair, j.H.a.k., Gregory R King, *Basic Applied Reservoir Simulation*. 2001, Richardson, Texas: Henry L. Doherty Memorial Fund of AIME Society Of Petroleum Engineers.
28. Weixuan Li, D.O., Dave Stern, Xiao-Hui Wu, Dongxiao Zhang, *Probabilitic Collocation Based Kalman Filter for Assisted History Matching*. 2011.
29. Wang, C. and T. Tang, *Recursive least squares estimation algorithm applied to a class of linear-in-parameters output error moving average systems*. Applied Mathematics Letters, 2014. **29**(0): p. 36-41.
30. Vaerenbergh, S.V., *Kernel Recursive Least-Squares Tracker for Time-Varying Regression*. IEEE TRANSACTIONS ON NEURAL NETWORKS AND LEARNING SYSTEMS, AUGUST 2012. **23**(8).
31. Radojka Krneta, S.A.a.D.S., *Recursive Least Squares Method in Parameters Identification of DC Motors Models*. 2005.
32. Hu, Y., *Iterative and recursive least squares estimation algorithms for moving average systems*. Simulation Modelling Practice and Theory, 2013. **34**(0): p. 12-19.
33. Durdu, O.F., *A Comparison Of Recursive Least Squares and Kalman Filtering for Flow in Open Channels*. 2005.
34. Leou, M.-L., Y.-C. Liaw, and C.-M. Wu, *A simple recursive least square algorithm of space-temporal joint equalizer*. Digital Signal Processing, 2012. **22**(6): p. 1145-1153.
35. Paul Zarchan, H.M., *Fundamentals of Kalman Filtering: Apractical Approach* Third ed. Vol. 232. 2009, 1901 Alexander Bell Drive, Reston, Virginia: American Institute of aeronautics and Astronautics Inc. 883.
36. Bhark, E.W., B. Jafarpour, and A. Datta-Gupta, *A New Adaptively Scaled Production Data Integration Approach Using the Discrete Cosine Parameterization*, 2010, Society of Petroleum Engineers.
37. Jafarpour, B. and D. McLaughlin, *History Matching with an Ensemble Kalman Filter and Discrete Cosine Parameterization*, 2010, Society of Petroleum Engineers.

38. Jafarpour, B. and D. McLaughlin, *Efficient Permeability Parameterization With the Discrete Cosine Transform*, 2007, Society of Petroleum Engineers.
39. William E. Brigham, A.R.K., Louis M. Castanier, *Supri Heavy Oil Research Program*, in *U.S. Department of Energy* 1998, Stanford University: Oklahoma.
40. Ken Cabeln, P.G., *Image Compression and The Discrete Cosine Transform*. 1994.
41. Vasconcelos, N., *Discrete Cosine Transform*. UCSD, 2000.
42. Strang, G., *Discrete Cosine Transform*. 2002.

APPENDIX

Coding for Eclipse

```
-- =====
-- THIS IS A MODEL PRODUCE FROM MODIFICCATON OF ODEH FIELD.
-- IT IS A NON SWELLING AND SWELLING STUDY. A REGULAR
-- GRID WITH FIVE WELLS (INJECTOR AND PRODUCER)AND A IMPES SOLUTION METHOD
-- IS USED FOR THIS SIMULATION.THE PRODUCTION IS CONTROLLED BY BHP
-- AND MIN. BHP. OIL RATE, GOR, PRESSURE AND GAS SATURATION ARE TO BE REPORTED.
-- =====
RUNSPEC
TITLE
  MODIFIED ODEH PROBLEM - IMPLICIT OPTION - 1511 DAYS
DIMENS
  10 10 3 /
NONNC
OIL
WATER
GAS
DISGAS
FIELD
EQLDIMS
  1 100 50 1 50 /
TABDIMS
  1 1 16 12 1 12 /
WELLDIMS
  5 16 5 2 /
NUPCOL
  4 /
START
  19 'OCT' 2013 /
NSTACK
  24 /
--FMTOUT
--FMTIN
UNIFOUT
UNIFIN
--NOSIM
GRID =====
----- IN THIS SECTION , THE GEOMETRY OF THE SIMULATION GRID AND THE
----- ROCK PERMEABILITIES AND POROSITIES ARE DEFINED.
-----
-- THE X AND Y DIRECTION CELL SIZES ( DX, DY ) AND THE POROSITIES ARE
-- CONSTANT THROUGHOUT THE GRID. THESE ARE SET IN THE FIRST 3 LINES
-- AFTER THE EQUALS KEYWORD. THE CELL THICKNESSES ( DZ ) AND
-- PERMEABILITIES ARE THEN SET FOR EACH LAYER. THE CELL TOP DEPTHS
-- ( TOPS ) ARE NEEDED ONLY IN THE TOP LAYER ( THOUGH THEY COULD BE.
-- SET THROUGHOUT THE GRID ). THE SPECIFIED MULTZ VALUES ACT AS
-- MULTIPLIERS ON THE TRANSMISSIBILITIES BETWEEN THE CURRENT LAYER
-- AND THE LAYER BELOW
INIT
-- ARRAY VALUE ----- BOX -----
EQUALS
  'DX' 1000 /
  'DY' 1000 /
  'PORO' 0.3 /
  --First Layer
  'DZ' 20 1 5 1 5 1 1 /
  'PERMX' 135.7 /
  'MULTZ' 0.64 /
  'TOPS' 8325 /
  'DZ' 20 6 10 1 5 1 1 /
  'PERMX' 126.6 /
  'MULTZ' 0.64 /
  'TOPS' 8325 /
  'DZ' 20 1 5 6 10 1 1 /
  'PERMX' 115 /
  'MULTZ' 0.64 /
```

```

TOPS' 8325 /
'DZ' 20 6 10 6 10 1 1 /
'PERMX' 138 /
'MULTZ' 0.64 /
TOPS' 8325 /
--second Layer
'DZ' 20 1 5 1 5 2 2 /
'PERMX' 138 /
'MULTZ' 0.265625 /
'DZ' 20 6 10 1 5 2 2 /
'PERMX' 207 /
'MULTZ' 0.265625 /
'DZ' 20 1 5 6 10 2 2 /
'PERMX' 195.5 /
'MULTZ' 0.265625 /
'DZ' 20 6 10 6 10 2 2 /
'PERMX' 172.5 /
'MULTZ' 0.265625 /
--Third Layer
'DZ' 80 1 5 1 5 3 3 /
'PERMX' 460 /
'DZ' 80 6 10 1 5 3 3 /
'PERMX' 345 /
'DZ' 80 1 5 6 10 3 3 /
'PERMX' 384.1 /
'DZ' 80 6 10 6 10 3 3 /
'PERMX' 414 /
/ EQUALS IS TERMINATED BY A NULL RECORD
-- THE Y AND Z DIRECTION PERMEABILITIES ARE COPIED FROM PERMX
-- SOURCE DESTINATION ----- BOX -----
COPY
'PERMX' 'PERMY' 1 10 1 10 1 3 /
'PERMX' 'PERMZ' /
/
-- OUTPUT OF DX, DY, DZ, PERMX, PERMY, PERMZ, MULTZ, PORO AND TOPS DATA
-- IS REQUESTED, AND OF THE CALCULATED PORE VOLUMES AND X, Y AND Z
-- TRANSMISSIBILITIES
RPTGRID
1 1 1 1 1 1 0 0 1 1 0 1 1 0 1 1 1 /
PROPS =====
----- THE PROPS SECTION DEFINES THE REL. PERMEABILITIES, CAPILLARY
----- PRESSURES, AND THE PVT PROPERTIES OF THE RESERVOIR FLUIDS
-----
-- WATER RELATIVE PERMEABILITY AND CAPILLARY PRESSURE ARE TABULATED AS
-- A FUNCTION OF WATER SATURATION.
-- SWAT KRW PCOW
SWFN
0.12 0 0
1.0 0.00001 0 /
-- SIMILARLY FOR GAS
--
-- SGAS KRG PCOG
SGFN
0 0 0
0.02 0 0
0.05 0.005 0
0.12 0.025 0
0.2 0.075 0
0.25 0.125 0
0.3 0.19 0
0.4 0.41 0
0.45 0.6 0
0.5 0.72 0
0.6 0.87 0
0.7 0.94 0
0.85 0.98 0
1.0 1.0 0
/
-- OIL RELATIVE PERMEABILITY IS TABULATED AGAINST OIL SATURATION
-- FOR OIL-WATER AND OIL-GAS-CONNATE WATER CASES

```



```

-- SOIL  KROW  KROG
SOF3
0 0 0
0.18 0 0
0.28 0.0001 0.0001
0.38 0.001 0.001
0.43 0.01 0.01
0.48 0.021 0.021
0.58 0.09 0.09
0.63 0.2 0.2
0.68 0.35 0.35
0.76 0.7 0.7
0.83 0.98 0.98
0.86 0.997 0.997
0.879 1 1
0.88 1 1 /
-- PVT PROPERTIES OF WATER
-- REF. PRES. REF. FVF COMPRESSIBILITY REF VISCOSITY VISCOSIBILITY
PVTW
4014.7 1.029 3.13D-6 0.31 0 /
-- ROCK COMPRESSIBILITY
-- REF. PRES COMPRESSIBILITY
ROCK
14.7 3.0D-6 /
-- SURFACE DENSITIES OF RESERVOIR FLUIDS
-- OIL WATER GAS
DENSITY
49.1 64.79 0.06054 /
-- PVT PROPERTIES OF DRY GAS (NO VAPOURISED OIL)
-- WE WOULD USE PVTG TO SPECIFY THE PROPERTIES OF WET GAS
-- PGAS BGAS VISGAS
PVDG
14.7 166.666 0.008
264.7 12.093 0.0096
514.7 6.274 0.0112
1014.7 3.197 0.014
2014.7 1.614 0.0189
2514.7 1.294 0.0208
3014.7 1.080 0.0228
4014.7 0.811 0.0268
5014.7 0.649 0.0309
9014.7 0.386 0.047 /
-- PVT PROPERTIES OF LIVE OIL (WITH DISSOLVED GAS)
-- WE WOULD USE PVDO TO SPECIFY THE PROPERTIES OF DEAD OIL
-- FOR EACH VALUE OF RS THE SATURATION PRESSURE, FVF AND VISCOSITY
-- ARE SPECIFIED. FOR RS=1.27 AND 1.618, THE FVF AND VISCOSITY OF
-- UNDERSATURATED OIL ARE DEFINED AS A FUNCTION OF PRESSURE. DATA
-- FOR UNDERSATURATED OIL MAY BE SUPPLIED FOR ANY RS, BUT MUST BE
-- SUPPLIED FOR THE HIGHEST RS (1.618).
--
-- RS POIL FVFO VISO
PVTO
0.001 14.7 1.062 1.04 /
0.0905 264. 7 1.15 0.975 /
0.18 514.7 1.207 0.91 /
0.371 1014.7 1.295 0.83 /
0.636 2014.7 1.435 0.695 /
0.775 2514.7 1.5 0.641 /
0.93 3014.7 1.565 0.594 /
1.270 4014.7 1.695 0.51
5014.7 1.671 0.549
9014.7 1.579 0.74 /
1.618 5014.7 1.827 0.449
9014.7 1.726 0.605 /
/
-- OUTPUT CONTROLS FOR PROPS DATA
-- ACTIVATED FOR SOF3, SWFN, SGFN, PVTW, PVDG, DENSITY AND ROCK KEYWORDS
RPTPROPS
1 1 1 0 1 1 1 1 /
SOLUTION =====

```

```

----- THE SOLUTION SECTION DEFINES THE INITIAL STATE OF THE SOLUTION
----- VARIABLES (PHASE PRESSURES, SATURATIONS AND GAS-OIL RATIOS)
-----
-- DATA FOR INITIALISING FLUIDS TO POTENTIAL EQUILIBRIUM
--
-- DATUM DATUM OWC OWC GOC GOC RSVD RVVD SOLN
-- DEPTH PRESS DEPTH PCOW DEPTH PCOG TABLE TABLE METH
EQUIL
  8400 4800 8500 0 8200 0 1 0 0 /
-- VARIATION OF INITIAL RS WITH DEPTH
--
-- DEPTH RS
RSVD
  8200 1.270
  8500 1.270 /
-- OUTPUT CONTROLS (SWITCH ON OUTPUT OF INITIAL GRID BLOCK PRESSURES)
RPTSOL
  1 11*0 /
SUMMARY =====
----- THIS SECTION SPECIFIES DATA TO BE WRITTEN TO THE SUMMARY FILES
----- AND WHICH MAY LATER BE USED WITH THE ECLIPSE GRAPHICS PACKAGE
-----
EXCEL
SEPARATE
--REQUEST PRINTED OUTPUT OF SUMMARY FILE DATA
RUNSUM
--TOTAL OIL PRODUCTION
FOPT
/
-- FIELD OIL PRODUCTION
FOPR
-- WELL GAS-OIL RATIO FOR PRODUCER
WGOR
'PRODUCER'
/
-- WELL BOTTOM-HOLE PRESSURE
WBHP
'PRODUCER'
/
-- GAS AND OIL SATURATIONS IN INJECTION AND PRODUCTION CELL
BGSAT
10 10 3
1 1 1
/
BOSAT
10 10 3
1 1 1
/
-- PRESSURE IN INJECTION AND PRODUCTION CELL
BPR
4 4 2
5 4 2
6 4 2
4 5 2
5 5 2
6 5 2
4 6 2
5 6 2
6 6 2
/
SCHEDULE =====
----- THE SCHEDULE SECTION DEFINES THE OPERATIONS TO BE SIMULATED
-----
-- CONTROLS ON OUTPUT AT EACH REPORT TIME
RPTSCHED
  1 0 1 1 0 0 2 2 2 0 0 2 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 /
--IMPES
-- 1.0 1.0 10000.0 /

```

```

-- SET 'NO RESOLUTION' OPTION
-- DRSDT
-- 0 /
-- SET INITIAL TIME STEP TO 1 DAY AND MAXIMUM TO 6 MONTHS
TUNING
1 182.5 /
1.0 0.5 1.0E-6 /
/
-- WELL SPECIFICATION DATA
--
-- WELL GROUP LOCATION BHP PI
-- NAME NAME I J DEPTH DEFN
WELSPCS
'PRODUCER' 'G' 5 5 8400 'OIL' /
'INJ1' 'G' 1 1 8335 'GAS' /
'INJ2' 'G' 10 1 8335 'GAS' /
'INJ3' 'G' 1 10 8335 'GAS' /
'INJ4' 'G' 10 10 8335 'GAS' /
/
-- COMPLETION SPECIFICATION DATA
--
-- WELL -LOCATION- OPEN/ SAT CONN WELL
-- NAME I J K1 K2 SHUT TAB FACT DIAM
COMPDAT
'PRODUCER' 5 5 3 3 'OPEN' 0 -1 0.5 /
'INJ1' 1 1 3 3 'OPEN' 1 -1 0.5 /
'INJ2' 10 1 3 3 'OPEN' 1 -1 0.5 /
'INJ3' 1 10 3 3 'OPEN' 1 -1 0.5 /
'INJ4' 10 10 3 3 'OPEN' 1 -1 0.5 /
/
-- PRODUCTION WELL CONTROLS
--
-- WELL OPEN/ CNTL OIL WATER GAS LIQU RES BHP
-- NAME SHUT MODE RATE RATE RATE RATE RATE
WCONPROD
'PRODUCER' 'OPEN' 'BHP' 75000 4* 1000 /
/
-- INJECTION WELL CONTROLS
--
-- WELL INJ OPEN/ CNTL FLOW
-- NAME TYPE SHUT MODE RATE
WCONINJ
'INJ1' 'GAS' 'OPEN' 'RATE' 25000 /
'INJ2' 'GAS' 'OPEN' 'RATE' 25000 /
'INJ3' 'GAS' 'OPEN' 'RATE' 25000 /
'INJ4' 'GAS' 'OPEN' 'RATE' 25000 /
/
-- YEAR 1
TSTEP
1.0 14.0 13*25.0
/
TSTEP
25.0
/
-- YEAR 2
TSTEP
13*20.0 7*13.0
/
TSTEP
14.0
/
-- YEAR 3
TSTEP
29.5*10.0
/
-- 912.50 --> 1000.0

```

```
TSTEP
  8.5 21*5.0
  /
-- 1000.0 --> 1100.0
TSTEP
  24*5.0
  /
-- 1100.0 --> 1200.0
TSTEP
  159*5.0
  /
IMPLICIT
TUNING
10 /
/
/
TSTEP
10.0 /

END =====
```