Investigating the Effect of Fluid and Formation Parameters on Mud Cake Thickness, Filtration Velocity and Invasion Depth

by

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

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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 AYUB BIN KHALID

ABSTRACT

Mud cake formation is a layer of mud emulsion that is formed from the drilling fluids during the drilling operation. Filtration process of drilling mud takes place as the drilling operation in carried out under a certain condition called overbalanced conditions, which means that the pressure of drilling mud injected is higher than the pressure of the formations. Due to this differential in pressure, drilling fluids will tend to be invaded into the porous part of the formation; where by the smaller particles of the drilling fluid will invade further into the formation, while the larger particles will accumulate at front surface of the pore size, creating a layer of mud cake. Understanding the behavior of mud cake thickness is important because it can reduce the mud circulation loss into the formation. Specifically, they are few objectives to be achieved within this project. They are i) to investigate the necessary parameters of the drilling mud properties in order to study the mud cake formation around the wellbore, ii)to investigate the necessary parameters of the drilling mud properties in order to study the mud cake formation around the wellbore. The formation permeability, mud cake permeability, porosity, mud filtrate viscosity, mud cake density, pressure, solid particle concentration in drilling mud, length of core and also the time measured have been identified as the main factors that will manipulate the mud cake thickness, filtration velocity and invasion depth of mud filtrate; meanwhile water-based mud drilling fluid is chosen for a shallow depth well under a static condition with constant pressure and constant low temperature. At the end of this project, it is expected that core with high cake permeability will result in higher mud cake thickness and filtration velocity compared to core with low mud cake permeability.

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CHAPTER 1

INTRODUCTION

1.1. PROJECT BACKGROUND

Drilling mud is pumped down through the drill string from the top to the bottom of the wellbore during a rotary drilling operation. It passes through the nozzle of the bit and comes up back to the surface via the annulus created between the borehole and the drill string. In addition, the drilling mud has the tendency to invade into the porous part of the rock formation due to the differential pressure of the injected drilling mud fluid which is higher than the formation pressure, and this is only occur during the overbalanced drilling conditions. Hence, the invaded of the smaller solid particles of mud fluids will create a damage zone around the wellbore, and the bigger solid particles in the mud are filtered out creating a mud cake layer on the borehole wall.

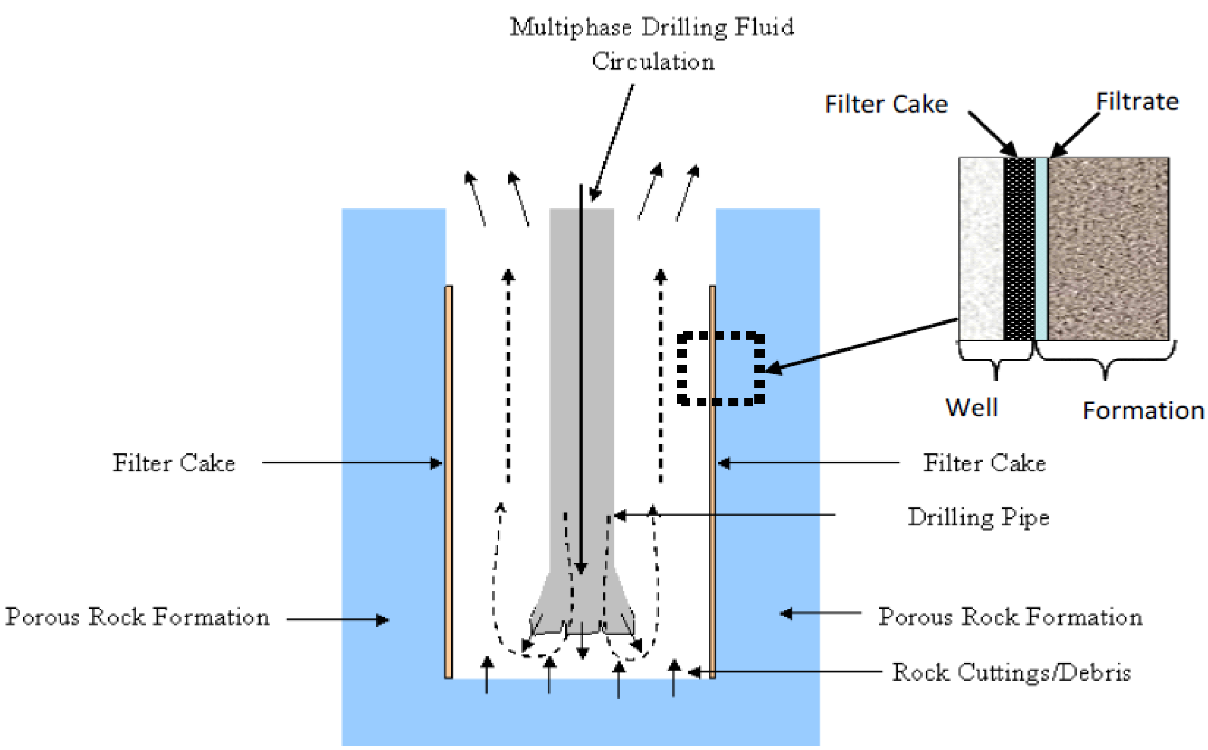


Figure 1.1 Drilling fluid circulation schematic diagram during the drilling process (Kabir & Gamwo, 2011).

Figure 1.1 shows a schematic diagram of drilling fluid circulation during the drilling process is carried out and how is the invasion of mud occurs around the formation and also the location of the mud cakes layer around the invaded zone. Damaged zone around the wellbore will be formed as mud filtrate invades the porous media.

Mud cake is really important because it will decrease the drilling fluids loss; hence reduce damage to the formation. It is vital to optimize the mud cake thickness because thicker mud cake will contribute and raise few problems during drilling operations as per discussed in literature review. An ideal drilling mud will form a thin, impermeable mud cake resulting in a limited fluid leak-off.

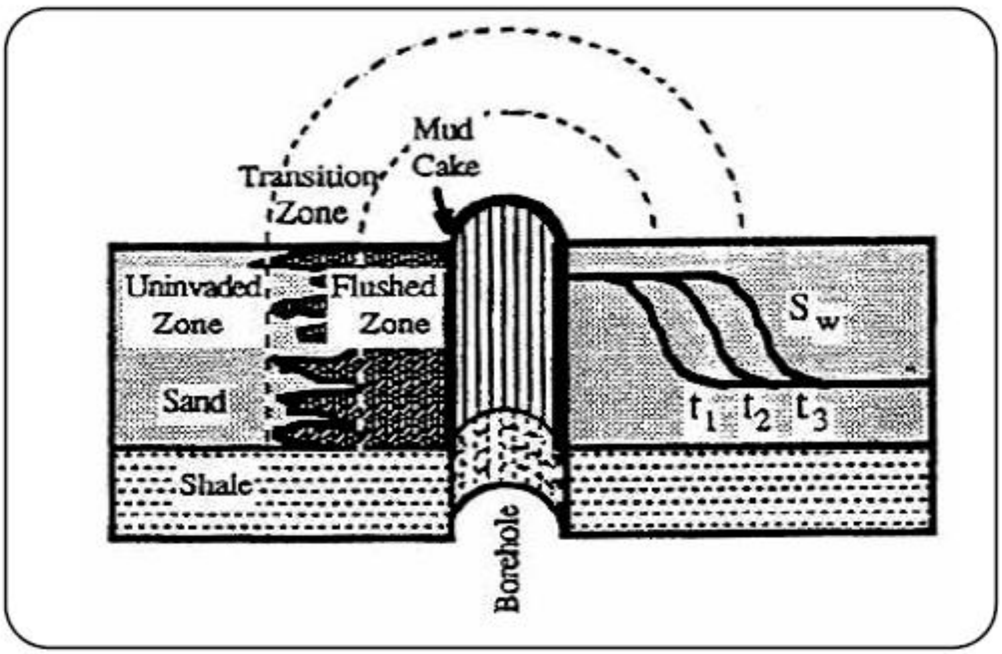


Figure 1.2 Detailed schematic of the various zone and the mud filtrate invasion profile at different times in near wellbore formation (Zahedzadeh*et al*., 2010).

1.2. PROBLEM STATEMENT

During the overbalanced pressure drilling process, drilling mud is injected into the well and the pressure is kept to be higher compared to the pressure of the formation. Because of the difference in pressure condition, mud filtrate will be invaded into the formation due to the absence of the mud cake layer at the outer part of the formation's wall. Invasion rate of the filtrate will be controlled by this layer of mud cake. The problem is that, the drilling mud invasion and the filtrate invaded into the formation and the smaller particles will move further into the formation and hence will clog the pores and disturb the matrix bonding, creating damages to the formations. This will disturb the natural properties of the formation's permeability, porosity and mobility properties, and hence will decrease the production of oil and gas.

Since mud cake is a recurring issue and it is very crucial that steps to be taken to keep it as ideal and optimum as possible, a more effective and easy approach need to be identified. This is important because even smaller particles will damage the formations the bigger particles will create a thicker mud cake which later will lead to a few problems during drilling process.

Author has identified that ideal mud cake thickness will increase the production of oil and gas especially in a shallow well by using a water-based drilling mud. In this study, the author will investigate the mud cake thickness towards the filtration velocity of the mud filtrate and also the invasion depth of the mud filtrate based on the water-based mud, formation data from the literature and the predicted parameters.

1.3. OBJECTIVE

The objectives of this project are:

1) To investigate the necessary parameters of the formation & drilling mud properties in order to study the mud cake formation around the wellbore.
2) To determine the mud invasion depth, mud cake thickness and filtration velocity based on the model validation and parameters from the literature.
3) To proceed with the parametric studies on the identified and selected parameters.

1.4. SCOPE OF STUDY

The project starts by studying and understanding the fundamental and concept of drilling mud fluids and also the formation of mud cakes. It is include the properties of the formation and the type of the drilling mud that is being used. Throughout this project, mud filtrate invasion model in linear flow is presented, and water-based mud is used as drilling fluid and is injected uniformly throughout the core sample and a single flow of mud filtrate is considered. The mathematical of mud filtrate invasion, which is consists of filtration velocity and mud cake thickness model is also presented for a linear flow system.

CHAPTER 2

LITERATURE REVIEW

2.1 What is a Mud cake?

Mud cake or filter cake is actually a layer of mud emulsion that is formed from the drilling fluids that is used during the drilling operation. To prevent the fluid from invading the formations, hydrostatic head pressure is maintained above the formation fluid pressure. Filtration process of drilling mud takes place as the drilling operation takes part under a certain condition called overbalanced conditions (Nandurdikar, 1999). Overbalanced condition means that the pressure of the drilling mud injected into the well is higher that the pressure of the formation. Overbalanced drilling is usually used in many formations because it will create a larger downhole pressure by using the fluid densities compared to the in situ formation pressure (Bennion and Thomas, 1994; Bennion et al., 1995). Gunawan, et al. (2011) agree that overbalanced drilling is safer than underbalance drilling, as underbalanced drilling has higher probability to produce blowout, expensive and does not effective in eliminating all type of reservoir damages .

According to Kabir and Gamwo (2011), mud cakes reduce fluid loss and damage to the formation. It is very important to optimize mud cake thickness as thicker mud cake will reduce the effective diameter of hole and raise problems such as stuck of drill pipes, excessive torque when rotating the drill bit and excessive drag when pulling it. On the other hands, thick cakes can lead to high swab, a decrease in wellbore pressure during the movement of drill strings up the wellbore. Such pressure reduction, if significant, may lead to premature reservoir fluids flowing into the wellbore and towards the surface. Thick mud cakes may also lead to sudden increase in surge pressure if the casing or drill string is quickly put into a wellbore, which may be great enough to create loss of drilling fluid circulation. A comprehensive analysis of mud-related drilling problems has determined the importance of maintaining good mud properties such as mud viscosity and weight which is to control the bottom hole stability as well as gas influx (Dzialowski et al., 1990).

2.2 Filtration Process and Formation of Mud cakes

There are two types of filtrations mechanism. The first one is static filtration and the second one is dynamic filtration. Static filtration means that the cake thickness will control the filtrate rate; meanwhile dynamic filtration means the cake thickness is a result from the dynamic equilibrium of solid particle deposition rate and the erosion rate (Elkatatny *et al.*, 2013). Nandurdikar (1999) states that in dynamic filtration due to the differential pressure effect, the base fluid will loss as it is invaded into the formation because of the flowing mud from the pipe's annulus down to the formation. The difference in sizes and densities of the particles and components of the mud hence lead them to be deposited on the surface of the formation, forming a "mud cake".

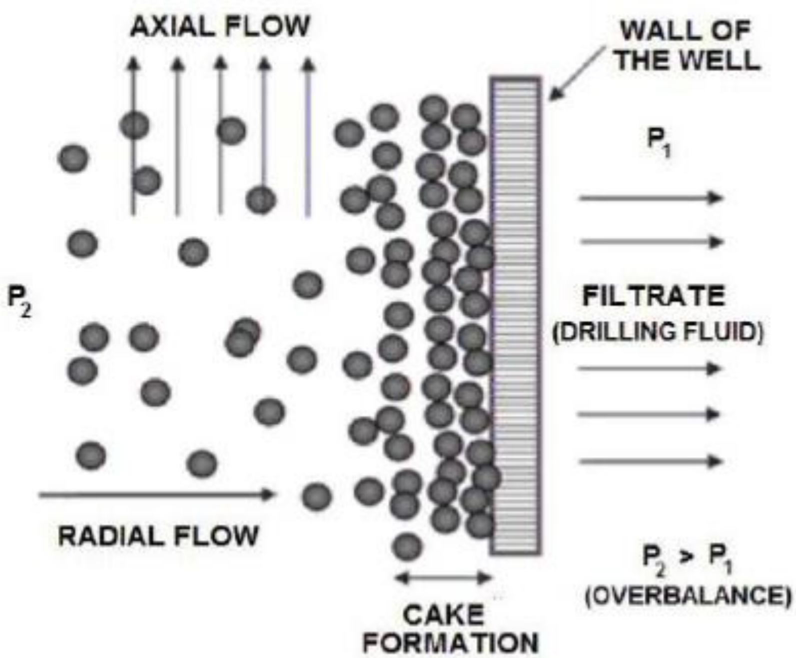


Figure 2.1 A schematic for the mud cake buildup in dynamic filtration (Calcada *et al*., 2011)

However Krueger (1986) states that damage from drilling mud are associated to the formation’s pore size distribution, the drilling fluid’s particle size distribution, chemical reactions, thermodynamics considerations and the overpressure of the wellbore (driving force). A laboratory simulated drilling test is carried out and it is shown that a well productivity can be decreased around 1% to 10% and this results will be changed depending on the particle invasion depth. Fluid base loss into the formation before the mud cake is formed is called as “spurt-loss”. During the mud flow, filtrate loss continues to take place as the cake’s permeability is not zero yet. The spurt loss is less damaging the formation compared to the filtrate invasion as filtrate invasion pushes the fluids away from the wellbore wall (Nandurdikar, 1999). Ding et al. (2002) however state that there is mud invasion (spurt loss) into the formation when the drilling bit first touches and penetrates the formation. Mud invasion occurs because of the absence of the mud cake that will prevent the smaller particles to invade into the oil formation. This situation is called spurt period, where it takes few minutes and short time. An internal mud cake will form at the end of spurt period. After that, an external layer of mud cake is formed at the outer wall of the formation after the solid particles retain process inside the wellbore has taken place and settled down. The created mud cake layer will control the invasion rate of mud filtrate. Physical properties of mud cake and absolute permeability are assumed to be unchanged while the mud filtrate is continuing invading the both of the cake layers (Ding and Renard, 2003, 2005; Ding et al, 2002). It is a common knowledge that the filtrate invasion is greater compared to penetration of drilling mud solids.

Engelhardt & Witherspoon (1954) agreed that clay penetration depth is very limited. Every clay particle will tend to get caught as the move further into the tiny rock pore. As these activities continuously occurring, an area named impregnated zone containing clay will be formed around the borehole at first, and after that mud cake will be deposited on the hole wall only after there is no clay can be absorbed throughout this impregnated zone. Deeper into the formations, there might be a zone called *infiltrated* zone where it contains microporous rocks. In microporous rock, the pore spaces are too small to be penetrated by drilling mud, and is called infiltrated zone because there are only rocks filled with filtrate. The zones stated just now are shown in the following

Figure 2.2 and Figure 2.3. P_w is the effective mud pressure at the surface of mud cake, P_o is the pressure at the mud cake-rock boundary, P_i is the pressure at the outer boundary of the infiltrated zone, P_e is original rock pressure, and r_e is the distance from center of wellbore where in all case of mud cake formation these conditions are given as follow: $P_w > P_o > P_i > P_e$. On the other hands, macroporous rocks have four concentric zones, which are mud cake, impregnated zone, infiltrated zone and original pore content of rocks. See Figure 2.3 for macroporous rocks.

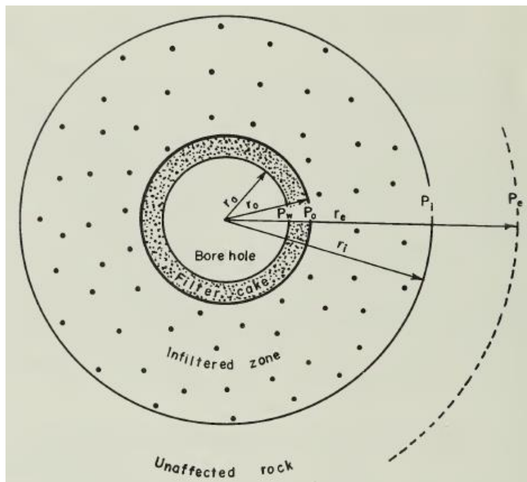


Figure 2.2 Formation of mud cake in microporousrock (Engelhardt & Witherspoon, 1954).

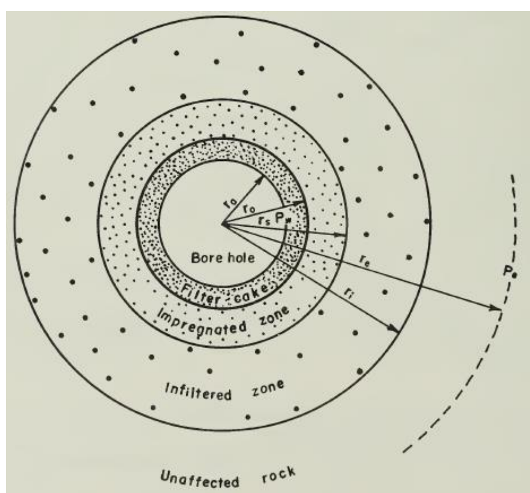


Figure 2.3 Formation of mud cake in macroporous rocks (Engelhardt & Witherspoon, 1954).

Narnudikar (1999) has come to conclusion that the cake permeability must be low and the study of the effects of filtration must be deeper in order to reduce the formation damage .The water saturation will increase and the oil saturation will decrease near the affected wellbore zone. The zone affected just now is known as damaged zone or the invaded zone (skin zone). As a result of decreasing in oil saturation, the effective permeability of oil of formation will also be decreased. Inversely, the flow resistivity of oil into the wellbore will increase, meaning that the ease of flow of the oil will be harder. Hence, as a result the productivity of a well will be declined (Bennion, 1999). Skin factor is used to determine the degree of the formation damaged. There are two factors the skin factor depends on, the first one is the reduction of permeability around the wellbore, and the second one is the mud filtrate's invasion radius (Gunawan et al., 2011).

2.3 Drilling Fluids

Basically fluids can be classified according to their effect to the external pressure applied, which means that is it their volume are dependent on its pressure or not, and can be firstly classified as "compressible" and "incompressible". Secondly, they can be classified depending on their response to the shear stress applied or shear rate, which then only can be called either "Newtonian" or "non-Newtonian" fluids (Chhabra and Richardson, 1999). Partal and Franco (2010) agreed that if the flow characteristics of gases are influenced by the compressibility factor, however liquids is said to be incompressible based on the shear stress rate they responded to. Normally the drilling fluids used are classified as a non-Newtonian fluid. They are called non-Newtonian fluids because their behavior based on the basis of the Navier-Stokes equations cannot be described. Flow curve of apparent viscosity versus flow conditions such as shear rate, geometry and sometimes its kinematic history of the fluid also can be used to define the meaning of a non-Newtonian fluid (Partal & Franco, 2010).

There are two types of drilling mud fluids that commonly been used in today's application namely; (1) water-based mud and (2) oil-based mud. Proper selection of the best type of drilling mud is very crucial to lower down the impact of formation damage in order to maintain and increase the productivity. Normally, the selection process of the best type of drilling mud to be used in drilling process are based on several aspects of the well, such as the depth of the well to be built, the type and composition of rocks nearby the targeted area, pressure (high or low), temperature (high or low), gases contained down in the wellbore such as carbon dioxide (CO2) and many more.

Table 2.1 Density of principal components of mud (Gray & Darly, 1980)

Densities of Common Mud Components

Material	Unit: gram/cm³	lb/gal	lb/ft³	lb/bbl	kg/m³
Water	1.0	8.33	62.4	350	1000
Oil	0.8	6.66	50	280	800
Barite	4.3	35.8	268	1500	4300
Clay	2.5	20.8	156	874	2500
Salt	2.2	18.3	137	770	2200

Adebayo and Thomas (2012) carried out an experiment to compare the effect of CO2 on Water-based and Oil-based drilling fluids to help them to select the best drilling fluid for nearby reservoir with the presence of carbon dioxide gas. The percentage change in the density of both oil-based and water-based mud were negligible. They observed that the oil-based mud density increase about 7%, on the contrary the density of water-based mud decrease about 17% at the end of 25 days, but it was negligible because same mud cannot be used to drill for a very long duration, without changing the mud for deeper depth. So the water based mud density is more stable in CO2 contamination compared to water-based mud. However, the yield point for oil-based mud is observed to keep increasing until 296% in 16 days, instead of the yield-point of water-based mud reduced by 75% only in 11 days. Moreover, they viscosity of oil-based mud shows an increasing index rapidly until 394% in day 16^{th}, while the viscosity of water-based mud shows in reduction about 75.4% for the same period. Hence, based on the results, the agreed that water-based mud is found to be more stable in CO2 contamination compared to oil-based mud, but with the help of other additives to enhance it (Adebayo and Thomas, 2012).

A literature review shows that little research has been carried out on mud cake formation during deep drilling (Klotz, 1954; Maurer, 1997; Cerasi, 2001; Ali, 2006; Fisher, 2008. However, limited reports and numerical research do exist on mud cake for shallow-wellbore drilling, although these sources lack detailed information on mud cake formations (Klotz, 1954; Delhommer, 1987; Maurer, 1997; Ali, 2006; Fisher, 2008). Literature review further reveals that no mud cake formation modeling has yet been performed for deep drilling conditions under high temperature and high pressure. Many of the researches that have been done using the Newtonian, single phase and isothermal conditions are only for shallow drilling process. Thus Kabir and Gamwo(2011) come out with a research to use a computational fluid dynamics (CFD) technique to numerically simulate the mud cake in vertical wellbore under a high pressure and high temperature which are about 25,000 psi or 175.8 MPa and 170ºC conditions respectively. Results shows that solid volume fractions and cake thickness are higher in deep drilling compare to shallow drilling process. They also state that based on study carried out, larger particles will create thicker mud cake and vice versa. Small particles tend to penetrate through the porous formation while the larger particles will clog the pores of the porous rock formation. Hence larger particles are much recommended to be used in drilling fluids for deep drilling process to enhance and promote the formation of mud cake.

2.4 Linear Flow Mud Filtrate Invasion Model

2.4.1 Limitation and assumption of the model

To produce mud filtrate invasion model, there are few assumptions need to be considered so that a mathematical model can be derived based on these assumptions. There are:

1) All core samples are injected with water-based mud uniformly and single phase flow of mud filtration is considered.
2) To keep the circulation rate of drilling fluid constantly as well as the erosion rate as the surface of mud cake.
3) Assuming the isothermal flow.
4) Overbalance pressure is assumed to be constant during the drilling mud injection into cores.
5) The variations of mud cake physical properties, mud cake porosity and permeability is neglected.
6) During mud filtrate invasion, effective permeability and porosity of the core are assumed to be unchanged.
7) To allow invasion of solid particles into the formation to take place, the size of solid particles in the drilling mud is smaller than the pore size.
8) Under immiscible displacement (formation fluid (oil) by mud filtrate).

2.4.2 Mathematical model of mud filtrate invasion

A mathematical of mud filtrate invasion will be presented throughout this section which consists of mud cake thickness and filtration velocity and is developed for a linear flow system. Parn-anurak and Engler (2005) model is extended where only a part of solid particle will be penetrate in the present. A mud cake layer may be formed on the surface of the core during the process of injecting the drilling fluid into a core sample as this might be due to the deposition of the drilling fluid solid particle (Figure 2.5).

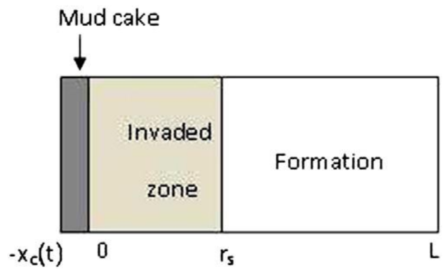


Figure 2.4 Mud cake formation and invaded zone for linear flow system is illustrated in figure above (Parn-anurak and Engler, 2005)

Parn-anurak and Engler (2005) state that mass of mud solid particles (m_c) is given by:

$$m_c(t) = Ax_c(t)(1\text{-}Øc)\rho_c \tag{1}$$

A is the cross-sectional area of the core, $Øc$ is the porosity, ρ_c is density and x_c is thickness of the mud cake. Physical properties such as permeability, density and porosity vary with time during the initial mud cake formation. Mud cake build-up rate depends on the difference between rate of mud cake erosion (e_c) and rate of mud cake deposition (d_c), and is expressed by Parn-anurak and Engler (2005) as

$$\frac{\mathrm{dmc}}{\mathrm{dt}} = \mathrm{dc} - \mathrm{ec} \tag{2}$$

In drilling fluid, the depositional rate is proportional to the mass flux of solid particle. Invasion of solid particle is taken into account in Eq. (3)

$$d_c = Au(t)(1\text{-}Ø)C_{solid} \tag{3}$$

Erosion rate is related to shear stress, τ on mud cake and is given by Parn-anurak and Engler (2005) as

$$e_c = k_\tau A\tau \tag{4}$$

Mass conservation equation for mud cake formation in (2) can be identified as

$$\frac{\mathrm{dmc}}{\mathrm{dt}} = \mathrm{Au(t)(1 - Ø)C_{solid} - k_\tau A\tau} \tag{5}$$

Mud cake formation by taking derivative from equation (1) with respect of time

$$\frac{dm_c}{dt} = A\frac{dx_c}{dt}(1 - Ø_c)\rho_c \tag{6}$$

From eq. (5) and (6), mud cake thickness reads

$$\frac{dx_c}{dt} = \frac{u(t)(1-\emptyset)C_{solid} - k_\tau \tau}{(1-\emptyset_c)\rho_c} \tag{7}$$

Given filtration velocity u (t) as

$$u(t) = \frac{q(t)}{A} \tag{8}$$

Volumetric invasion rate q (t)

$$q(t) = \frac{q(0)}{1+\frac{k}{k_c}\frac{x_{c(t)}}{L}} = \frac{kA\Delta p}{\mu_f L}\frac{k_c/k}{\left(\frac{k_c}{k}+\frac{x_{c(t)}}{L}\right)} \tag{9}$$

2.5.3 Distribution model of mud filtrate

Famous skin factor parameter, s, from Hawkins is used to measure the extent formation damage. The two parameters affect skin factors are permeability reduction in the invaded zone and also the invasion depth of mud filtrate. Water saturation is represented by the water-based mud drilling mud filtrate concentration. Distance from the core face will determine the filtrate concentration, depending on formation velocity, time, porosity and also the dispersivity of the formation. Assuming constant incompressible fluids and formation velocity, for a linear flow system, the mud concentration can be expressed as

$$\frac{dC}{dt} = D\frac{d^2C}{dx^2} - \frac{u(t)}{\emptyset(1-S_{wi}-S_{or})}\frac{dC}{dx}, t > 0, 0 < x < L \tag{10}$$

With the initial condition given as

$$C(x,0) = 0, 0<x<L \tag{11}$$

And the boundary conditions as follow

$$C(0,t) = C_f \tag{12}$$

$$\frac{dC}{dx}(L,t) = 0 \tag{13}$$

Filtration velocity u(t) in Eq. (8) is obtained by the derivation in the previous section, and by solving below equations (14) and (15). ΔP is overbalance pressure. From Eq. (8) and (9), filtration velocity is expressed as

$$u(t) = \frac{k\Delta p}{\mu_f L}\frac{k_c/k}{\left(\frac{k_c}{k}+\frac{x_{c(t)}}{L}\right)} \tag{14}$$

$$\frac{dx_c}{dt} = \frac{kA\Delta p(1-\emptyset)C_{solid}}{\mu_f L(1-\emptyset_c)\rho_c}\frac{k_c/k}{\left(\frac{k_c}{k}+\frac{x_{c(t)}}{L}\right)} - \frac{k_\tau \tau}{(1-\emptyset_c)\rho_c}, x_c(0) = 0 \tag{15}$$

Invasion of mud filtrate radius is determined from mud filtrate concentration profile. To estimate invasion radius r_s of mud filtrate from the initial condition in (11), a propose criterion has been made as follows

$$r_s = \max \{ x : c (x, t_{inj}) > C^*_d \} \tag{16}$$

Eqs. (10), (14) and (15) can be changed into dimensionless form

$$u(t) = \frac{k_c/k}{\left(\frac{k_c}{k}+x_c(t)\right)} \tag{17}$$

$$\frac{\partial C}{\partial t} = \frac{1}{Pe}u(t)^g \frac{\partial^2 C}{\partial x} - u(t)\frac{dC^2}{dx}, t > 0, 0 < x < 1 \tag{18}$$

Where Pe represents Peclet number

$$Pe = \frac{Lu_0}{fu_0^g \emptyset(1-S_{wi}-S_{or})} \tag{19}$$

The empirical parameter *f* is set to 51.7, while g is set to

$$g = \begin{cases} 1.47, k_c \le 2 * 10^{-9}\mu m^2 \\ 1.47 + 0.0225 * \left(\frac{k_c}{10^{-9}\mu m^2} - 2\right), 2 * 10^{-9}\mu m^2 < k_c \le 10^{-8}\mu m^2 \\ 1.65 + 0.03 * \left(\frac{k_c}{10^{-9}\mu m^2} - 10\right), 2 * 10\ \mu m^{-8} < k_c \le 2 * 10^{-8}\mu m^2 \\ 1.95, k_c > 2 * 10^{-8}\mu m^2 \end{cases} \tag{20}$$

CHAPTER 3

METHODOLOGY

3.1 RESEARCH METHODOLOGY

Figure 3.1 shows the project phases of the whole study. The project is divided into four phases which are the background study and literature review, calculation for the inputs, model validation and lastly the numerical simulation and parametric studies.

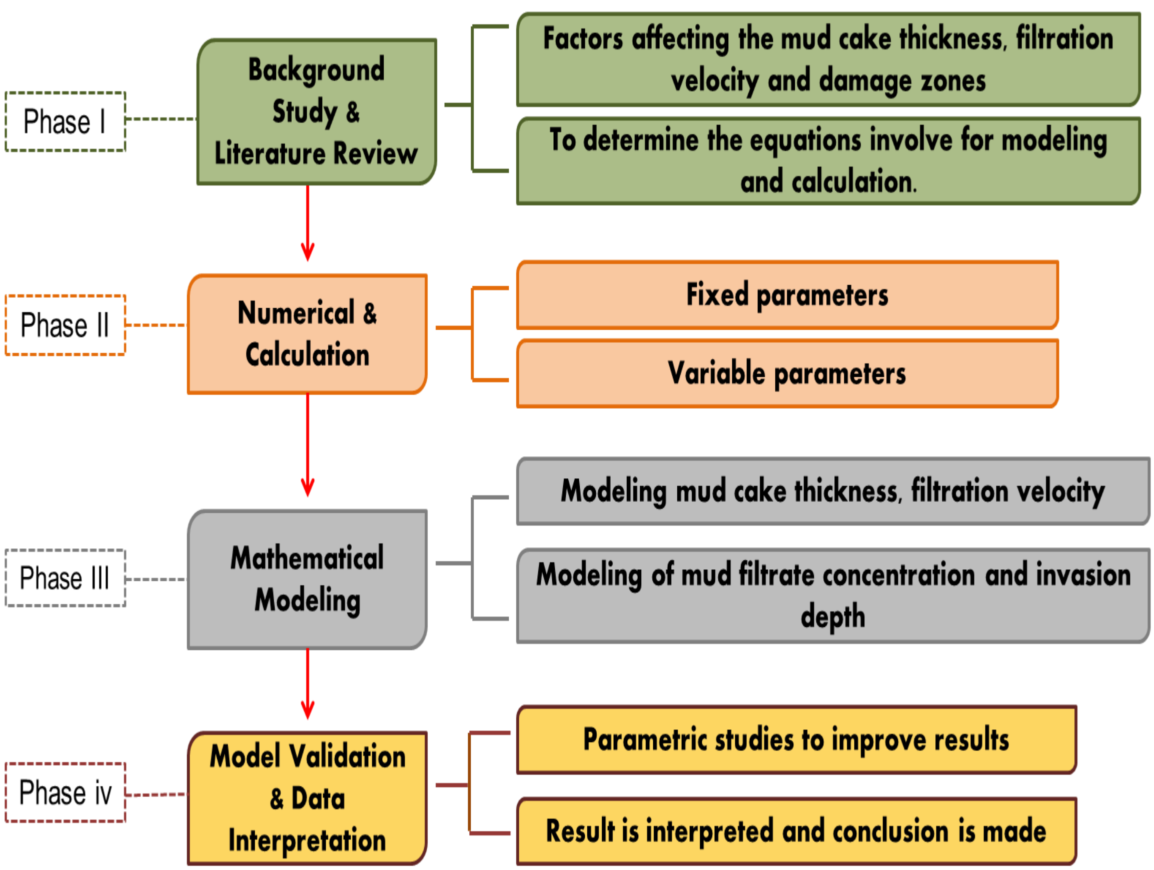


Figure 3.1 Research Methodology Flow.

3.2 PROJECT ACTIVITIES

Figure 3.2 below shows the description of the project activities based on research methodology in the previous page.

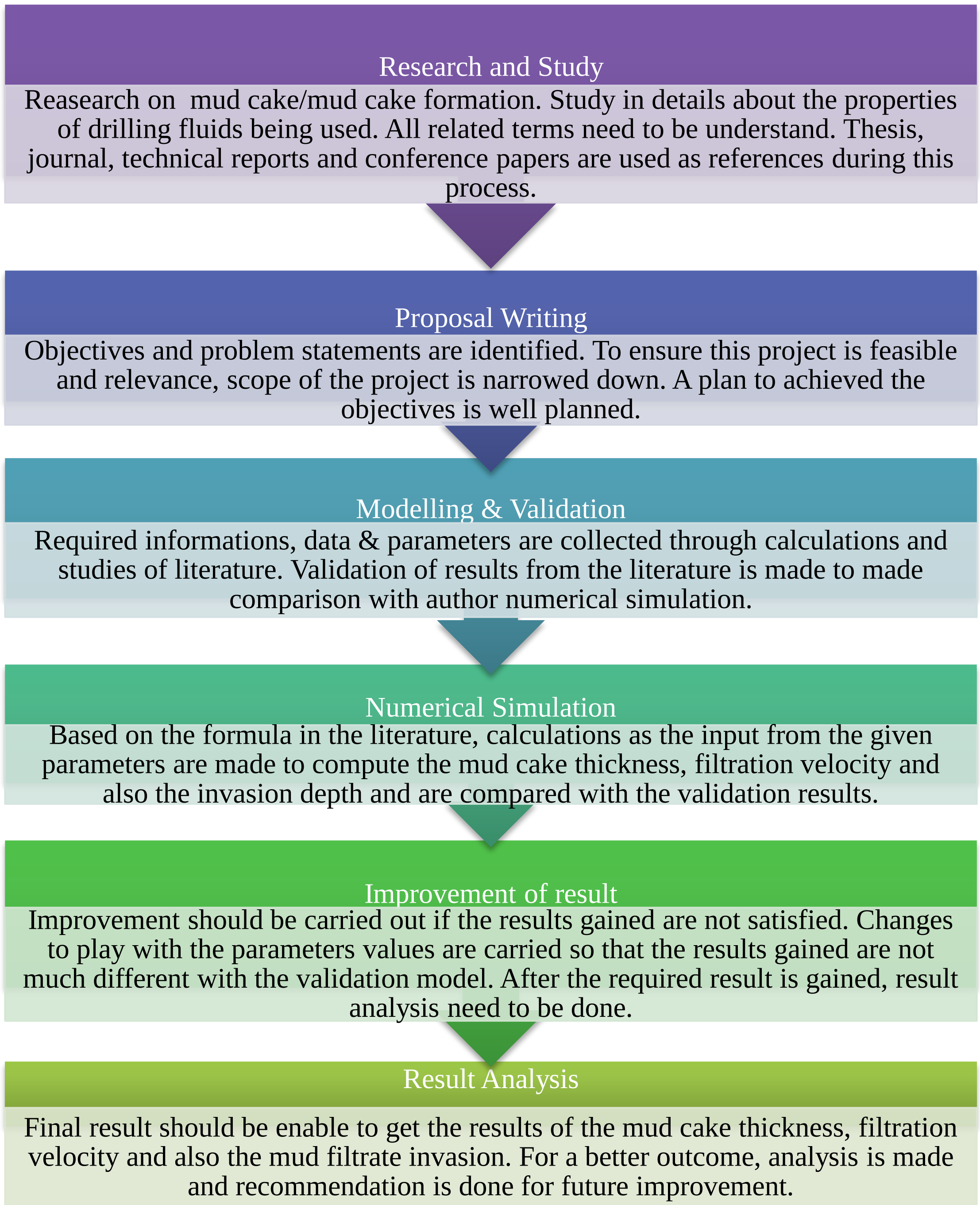


Figure 3.2 Project Activities based on Research Methodology.

3.3 KEY MILESTONE

The following figures explained the key milestone (Fig 3.3) for FYP 1 and FYP 2 based on the submission dates which are set by FYP 1 coordinator.

Milestone 1	Determining Necessary Parameters for Simulation
Expected Date of Completion	20th of May 2014
Description	The author will established and finalize the key parameter which are the fix and the variable parameters for his study before running simulations.

Milestone 2	Validation, Modeling & Numerical Simulation
Expected Date of Completion	20th of June 2014
Description	The author has to calculate the inputs which are the mud cake thickness, filtration velocity and peclet number as the input for the numerical simulation based on the coding given and to compare the results with the validation model from the previous project as in the literature. All the data & parameters are taken from the literature studies.

Milestone 3	Data Interpretation
Expected Date of Completion	30th of June 2014
Description	The author will interpret and examine the data obtained from the numerical simulation and compare with the validate model so that the results are in the range of the accepted value.

Milestone 4	Develop Conclusion and Recommendations
Expected Date of Completion	10th of July 2014
Description	The author will finalize the outcome of the simulation and decide whether the objectives set are met or not. He will also make recommendations in order to refine the experiment.

Figure 3.3 Key Milestone of Final Project

3.4 GANTT CHARTFOR FYP 1

Table 3.4 Gantt chart of Final Year Project I

NO	TASK	JANUARY				FEBRUARY				MARCH				APRIL				MAY			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	**Mud Invasion & Formation of Mud cakes Study**																				
	1.1 Confirmation of Project Title																				
	1.2 Literature Review & Compose Project Proposal																				
	1.3 Submit Project Proposal to Supervisors																				
2	**Project Preliminary**																				
	2.1 Gathering information to calculate mud cake thickness, filtration velocity & Invasion Depth																				
	2.2 Methodology Studies																				
	2.2.1 Identifying Necessary Parameters to achieve objectives																				
	2.3 Submission of Interim Report																				
3	**Project Execution**																				
	3.1 Model Validation																				
	3.2 Numerical Modelling/Calculation with neccessaries parameters																				
4	**Result Analysis**																				
	4.1 Data Collection from the developed results																				
	4.2 Analyse the numerical simulation results																				
5	**Project Finalization**																				
	5.1 Develop Conclusion and Recommendations																				
	5.2 Final Report Preparation																				

3.5 GANTT CHART FOR FYP II

Table 3.5 Gantt chart of Final Year Project I

NO	TASK	MAY				JUNE				JULY				AUGUST				SEPTEMBER			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	**Mud Invasion & Formation of Mud cakes Study**																				
	1.1 Confirmation of Project Title																				
	1.2 Literature Review & Compose Project Proposal																				
	1.3 Submit Project Proposal to Supervisors																				
2	**Project Preliminary**																				
	2.1 Gathering information to calculate mud cake thickness, filtration velocity & Invasion Depth																				
	2.2 Methodology Studies																				
	2.2.1 Identifying Necessary Parameters to achieve objectives																				
	2.3Submission of Interim Report																				
3	**Project Execution**																				
	3.1 Model Validation																				
	3.2 Numerical Modelling/Calculation with neccessaries parameters																				
4	**Result Analysis**																				
	4.1 Changing values of parameters to get well result																				
	4.2 Analyse the numerical simulation results																				
5	**Project Finalization**																				
	5.1 Develop Conclusion and Recommendations																				
	5.2 Final Report Preparation																				

3.6 Verification of the Numerical Model with Experiment Data

Yan *et al*. (1997) did an experiment to evaluate the formation damage caused by drilling and completion fluids in a horizontal well. In this section, the simulation and numerical model is verified using the experimental data from literature. Invasion depths of drilling fluid were measured from 30 minutes to 10.0 hours during this test and 14 core samples data from the literature are taken to be tested.

No mud circulation is run on the core sample surface as this is a static filtration condition. The drilling mud data used before is not available; however we still have the formation characteristics, measured invasion depth, parameter values and also the empirical correlation depth to be used which are shown in table 3.6.1.

In the case of static filtration, mud cake thickness can be measured and analytically calculated by using this equation:

$$x_c(t) = -\frac{k_c}{k} + \sqrt{\left(\frac{k_c}{k}\right)^2 + 2\,\frac{k_c \Delta p (1-\emptyset) C_{solid} t_0}{\mu_f L^2 (1-\emptyset_c)\rho_c}\,t} \tag{21}$$

Meanwhile, dimensionless filtration can be calculated by using this equation:

$$u(t) = \frac{k_c/k}{\sqrt{\left(\frac{k_c}{k}\right)^2 + 2\frac{k_c \Delta p (1-\emptyset) C_{solid} t_0}{\mu_f L^2 (1-\emptyset_c)\rho_c}t}} \tag{22}$$

Mud cake permeability will affect both mud cake thickness and filtration velocity. We can estimate this parameter by controlling and changing the predicted fluid loss equals the measured fluid loss. Fluid loss from filtration velocity model can be predicted and expressed as:

$$FL_{predicted} = \mu_o t_o \int_0^{\frac{t_{inj}}{t_o}} Au(t)dt \tag{23}$$

By rearranging the Coates and Denoo's permeability model (Wu and Berg, 2003), we can estimate the irreducible water saturation parameter, S_{wi}. In below equation, the formation permeability is in milidarcy unit.

$$k = \left[\frac{100\emptyset^2(1-Swi)}{Swi}\right]^2 \qquad (24)$$

Rearrange,

$$Swi = \frac{100\emptyset^2}{100\emptyset^2 + \sqrt{k}} \qquad (25)$$

Formation permeability is in millidarcy unit. The mud cake permeability and predicted irreducible water saturation is presented in the last two columns of Table 3.6.1. Below are the formation data from Yan et al. (1997) and the predicted parameters that will be used in order to be verified in this numerical simulation of mud cake thickness and dimensionless filtration velocity.

. **Table 3.6.1** Predicted parameters & formation data from Yan et al. (1997)

Core No	ΔP (Pa)	FL (m^3)	k (m^2)	φ	$r_{s,m}$ (m)	$r_{s,c}$ (m)	Swi, p	$k_{c,p}$ (m^2)
1	2.76E+06	2.33E-06	3.31E-14	0.075	0.0662	0.0695	0.0885	2.22E-21
2	1.50E+06	7.37E-06	6.48E-14	0.0953	0.065	0.0649	0.1008	3.96E-20
3	2.76E+06	1.77E-06	1.90E-14	0.1451	0.0572	0.0539	0.3245	1.18E-21
4	2.76E+06	2.53E-06	1.71E-13	0.2482	0.0566	0.0517	0.3190	2.12E-21
5	2.41E+06	5.17E-06	1.28E-13	0.2376	0.0553	0.0591	0.3312	1.03E-20
6	3.90E+06	2.44E-06	1.53E-13	0.2434	0.0631	0.0616	0.3222	1.40E-21
7	2.10E+06	7.98E-06	7.20E-14	0.224	0.0587	0.0626	0.37	2.85E-20
8	1.50E+06	5.34E-06	4.53E-14	0.244	0.0485	0.0461	0.4677	1.74E-20
9	2.76E+06	2.78E-06	3.30E-13	0.2953	0.0562	0.0509	0.323	2.39E-21
10	1.50E+06	7.51E-06	1.13E-13	0.0932	0.0661	0.0657	0.075	4.14E-20
11	3.10E+06	2.52E-06	7.10E-13	0.3025	0.0545	0.0532	0.2544	1.74E-21
12	3.10E+06	2.29E-06	3.79E-13	0.2804	0.0554	0.0522	0.2862	1.48E-21
13	3.10E+06	2.61E-06	3.07E-13	0.2895	0.0591	0.05345	0.322	1.90E-21
14	2.76E+06	2.78E-06	5.96E-13	0.2965	0.0557	0.05148	0.2635	2.39E-21

Where;

FL = fluid loss,

$r_{s,m}$ = measured invasion depth,

$r_{s,c}$ = calculated invasion depth from Yan et al. correlation,

$S_{wi,p}$ = predicted irreducible water saturation,

$k_{c,p}$ = predicted mud cake permeability.

However, there are also additional parameters values used in the simulation which are shown in Table 3.6.2 below.

Table 3.6.2 Additional data to estimate the mud filtrate

Parameter	**Value**
L	0.1016m
A	2.04E-03
S_{or}	0.3
ϕ_c	0.1
ρ_c	2440 kg/m³
C_{solid}	40 kg/m³
μ_f	1 cp
C_f	1000 kg/m³
C^*_d	0.001

3.6.1 Mud Cake Thickness and Filtration Velocity

The core samples in Table 3.6.1 are divided into two group which is low and high mud cake permeability. High mud cake permeability is ranging from $1.026\text{x}10^{-8}$ m^2 to $4.135\text{x}10^{-8}$ m^2 meanwhile low cake permeability is ranging from $1.026\text{x}10^{-9}$ m^2 to $2.390\text{x}10^{-9}$ m^2. Core 2, core 5, core 7, core 8, core 10 are high in mud cake permeability, meanwhile core 1, core 3, core 4, core 6, core 9, core 11, core 12, core 13 and core 14 are classified as mud low mud cake permeability.

The results for mud cake thickness and dimensionless filtration velocity is shown in the graph in chapter 4 and equation (21) and (22) is used to calculate and model the mud cake thickness and filtration velocity mathematically. Time is set to be changed, with the initial time measured is at 30 minutes of filtration until 600 minutes which is 10 hours to complete the test in 14 core samples. Overbalance pressure of all samples are greater than 1.50MPa (217.56 psi). In core 7 and core 8, the formation porosity and formation permeability are almost the same, while in core 7 the overbalance pressure is higher compared to core 8.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Formation data and predicted parameters

To numerically model the present model of mud cake thickness, dimensionless filtration velocity, and the mud invasion depth, formation data and predicted parameters from Yan et al. (1997) is used for the calculation and mathematical simulation. The data is presented in the Table 4.1.1 and Table 4.1.2.

Table 4.1.1 Parameters and formation data from Yan et al. (1997) used to determine the mud cake thickness, dimensionless filtration velocity and invasion depth.

Core No	ΔP (Pa)	FL (m^3)	k (m^2)	φ	$r_{s,m}$ (m)	$r_{s,c}$ (m)	Swi, p	$k_{c,p}$ (m^2)
1	2.76E+06	2.33E-06	3.31E-14	0.075	0.0662	0.0695	0.0885	2.22E-21
2	1.50E+06	7.37E-06	6.48E-14	0.0953	0.065	0.0649	0.1008	3.96E-20
3	2.76E+06	1.77E-06	1.90E-14	0.1451	0.0572	0.0539	0.3245	1.18E-21
4	2.76E+06	2.53E-06	1.71E-13	0.2482	0.0566	0.0517	0.3190	2.12E-21
5	2.41E+06	5.17E-06	1.28E-13	0.2376	0.0553	0.0591	0.3312	1.03E-20
6	3.90E+06	2.44E-06	1.53E-13	0.2434	0.0631	0.0616	0.3222	1.40E-21
7	2.10E+06	7.98E-06	7.20E-14	0.224	0.0587	0.0626	0.37	2.85E-20
8	1.50E+06	5.34E-06	4.53E-14	0.244	0.0485	0.0461	0.4677	1.74E-20
9	2.76E+06	2.78E-06	3.30E-13	0.2953	0.0562	0.0509	0.323	2.39E-21
10	1.50E+06	7.51E-06	1.13E-13	0.0932	0.0661	0.0657	0.075	4.14E-20
11	3.10E+06	2.52E-06	7.10E-13	0.3025	0.0545	0.0532	0.2544	1.74E-21
12	3.10E+06	2.29E-06	3.79E-13	0.2804	0.0554	0.0522	0.2862	1.48E-21
13	3.10E+06	2.61E-06	3.07E-13	0.2895	0.0591	0.05345	0.322	1.90E-21
14	2.76E+06	2.78E-06	5.96E-13	0.2965	0.0557	0.05148	0.2635	2.39E-21

In table above, the 14 core samples are divided into two group which are low and high mud cake permeability. High mud cake permeability is ranging from 1.026×10^{-8} μm^2 to 4.135×10^{-8} μm^2 meanwhile low cake permeability is ranging from 1.026×10^{-9} μm^2 to 2.390×10^{-9} μm^2. Core 2, core 5, core 7, core 8, core 10 are high in mud cake permeability, meanwhile core 1, core 3, core 4, core 6, core 9, core 11, core 12, core 13 and core 14 are classified as mud low mud cake permeability. Core 1 has the lowest formation porosity and formation permeability, meanwhile core 11 has the highest formation porosity and formation permeability. The lowest overbalanced pressure is 1.50 MPa and the highest overbalanced pressure is 3.90 MPa. Both mud cake thickness and filtration velocity depends on mud cake permeability.

4.2 Mud Cake Thickness Model for Low and High Cake Permeability

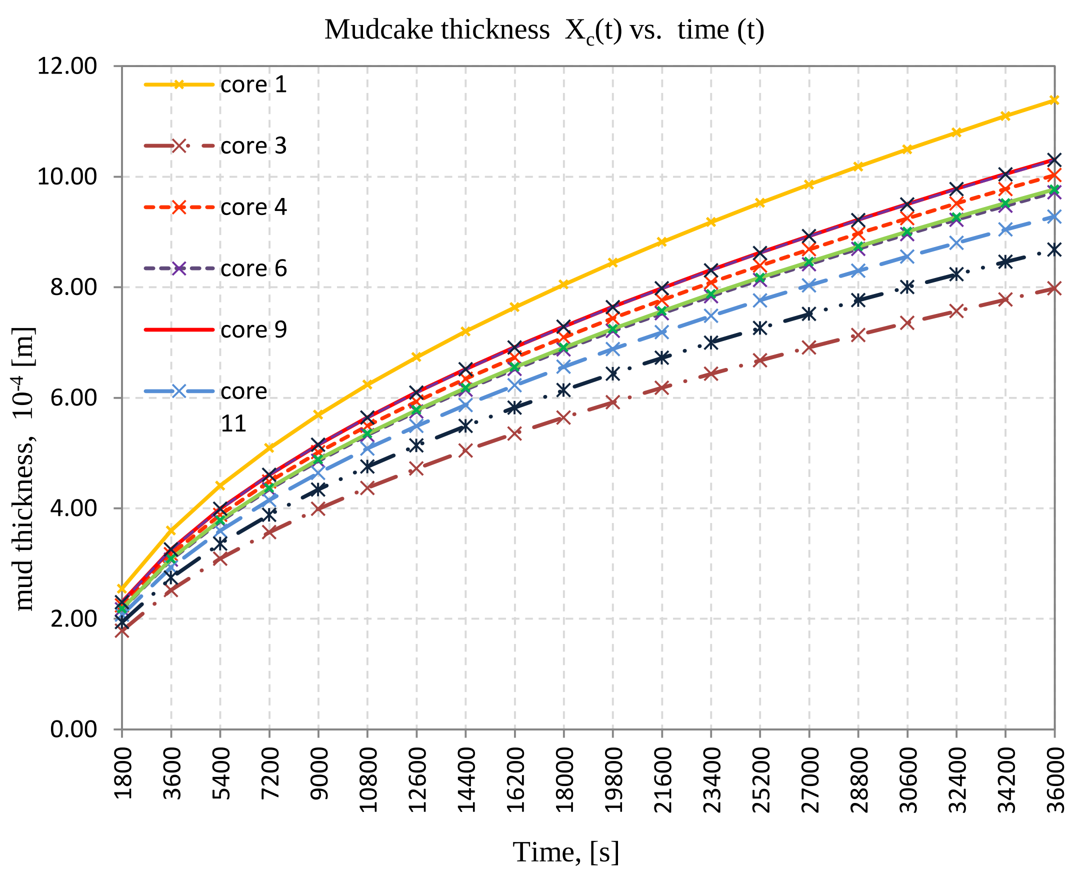


Figure 4.2.1 The mud cake thickness model for low cake permeability.

Above graph is the mud cake thickness model for low cake permeability as per defined in chapter 4.1. The model is calculated using equation (21). We can see that the mud cake thickness increase as the time taken to test the core samples increase and is directly proportional to time. From the graph, the mud cake thickness looks very uniform for all 9 core samples of low permeability. However, we can see that core 1 produce the higher reading of mud cake thickness compared to other cores. This might be because of core 1 has higher predicted mud cake permeability as presented in the last column of table 4.1 and larger overbalance pressure. Core 1 has the lowest formation porosity follow by core 3 which is 0.075 and 0.1451 respectively and core 11 has the highest formation porosity which is 0.3025. Core 3 shows the lowest mud cake thickness because core 3 has the lowest predicted cake permeability which is 1.180×10^{-15} μm^2 and also has the lowest formation permeability at 18.96×10^{-9} μm^2 (group of low cake permeability).

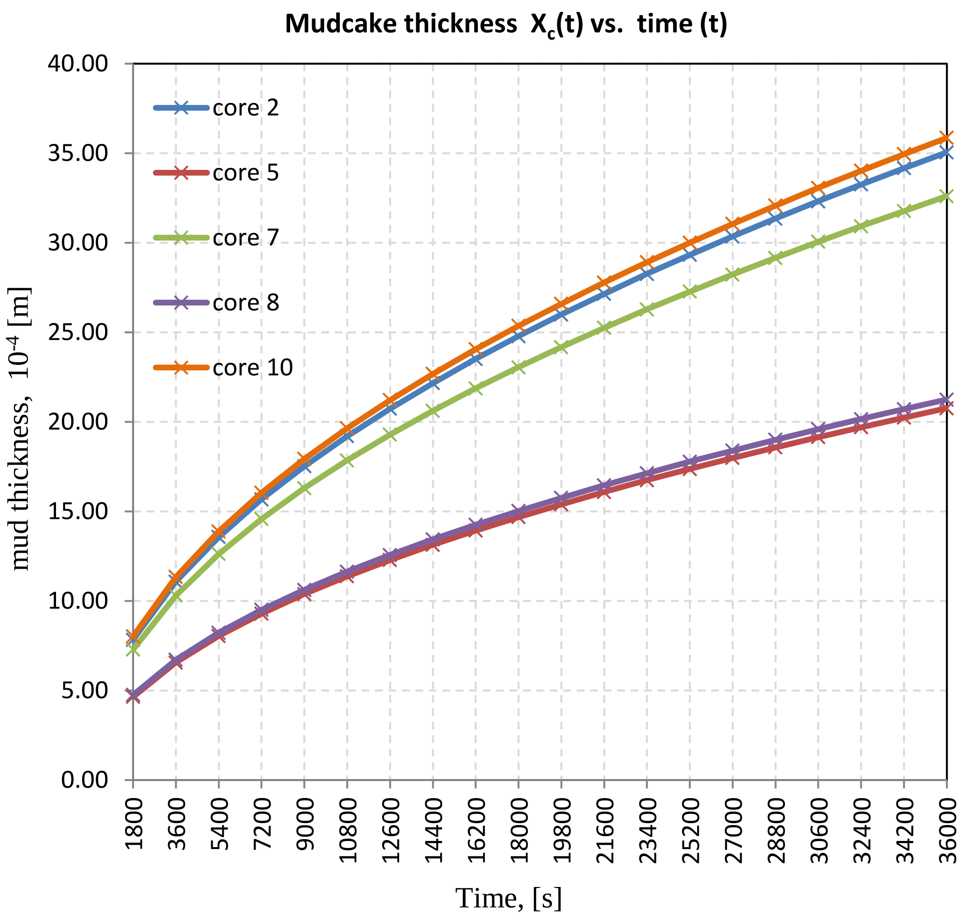


Figure 4.2.2 The mud cake thickness model for high cake permeability.

Graph in Figure 4.2.2 above shows the mud cake thickness model for the high cake permeability which is indicated by core 2, core 5, core 7, core 8 and core 10. The mud cake thickness details results for each sample can be seen in Appendix A (ii). The mud cake thickness for core samples of high cake permeability is higher; range from 0 to 36×10^{-4} m which is much higher compared to core samples with low permeability; ranging from 0 to 11.5×10^{-4} m. Graph in Figure 4.2.2, we can observe that the mud cake thickness is increasing uniformly, but is divided into two groups. Cake permeability in core 5 and core 8 is lower compared to core 2, core 7 and core 10 and this might be the factor which differentiates the mud cake thickness between these five cores. The highest mud cake thickness with increasing time is core 10 and the lowest is the core 5. We can see that in Table 4.1.1, core 10 has the highest cake permeability which is 4.135x10^{-14} μm^2 compared to core 5 with only 1.026x10^{-14} μm^2 of cake permeability.

4.3 Filtration Velocity Model for Low and High Cake Permeability

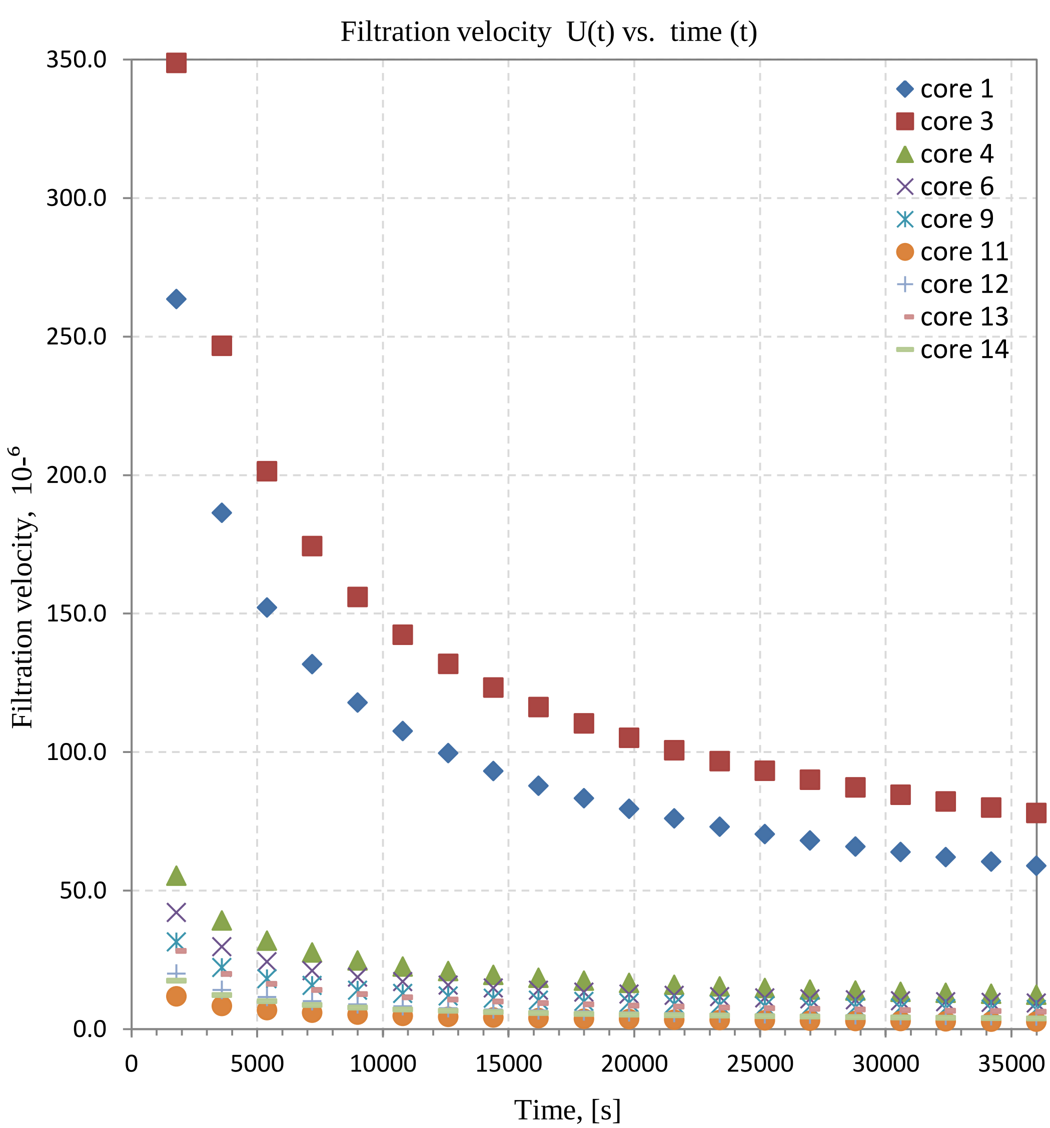


Figure 4.3.1 The filtration velocity model low cake permeability.

Figure 4.3.1 illustrates the dimensionless filtration velocity model with increasing injection time, ranging from 1800 seconds (30 minutes) to 36000 seconds (10 hours). The filtration velocity is low if the mud cake permeability is low. The filtration velocity is decreasing as the time increasing, and this can be explained as the time of injection is increasing, the mud cake thickness will be increased, hence the velocity will be decrease because the invasion of filtrate is now harder to invade trough the formation as the mud cake keeps forming thicker. Mud filtrate invasion is called a diffusion-dominated process for this case. The value of dimensionless filtration can be seen in Appendix A (i) and Appendix A (ii). In above graph, the dimensionless filtration velocity is lower and range from 0 to $350x10^{-6}$, where the highest reading is about $348.81x10^{-6}$ which is tested in core 3, compared to the core samples with the high mud cake permeability, their dimensionless filtration velocity are much higher. In low mud cake permeability the mud cake thickness is quite uniform, but the filtration velocities are segregated as in the figure 4.3.1. This is might be affected by the big differences of the parameters value. As the filtration velocity is depending on the formation permeability, k, we can assume that the smaller values of formation permeability in core 1 and core 3 lead to higher dimensionless filtration velocity.

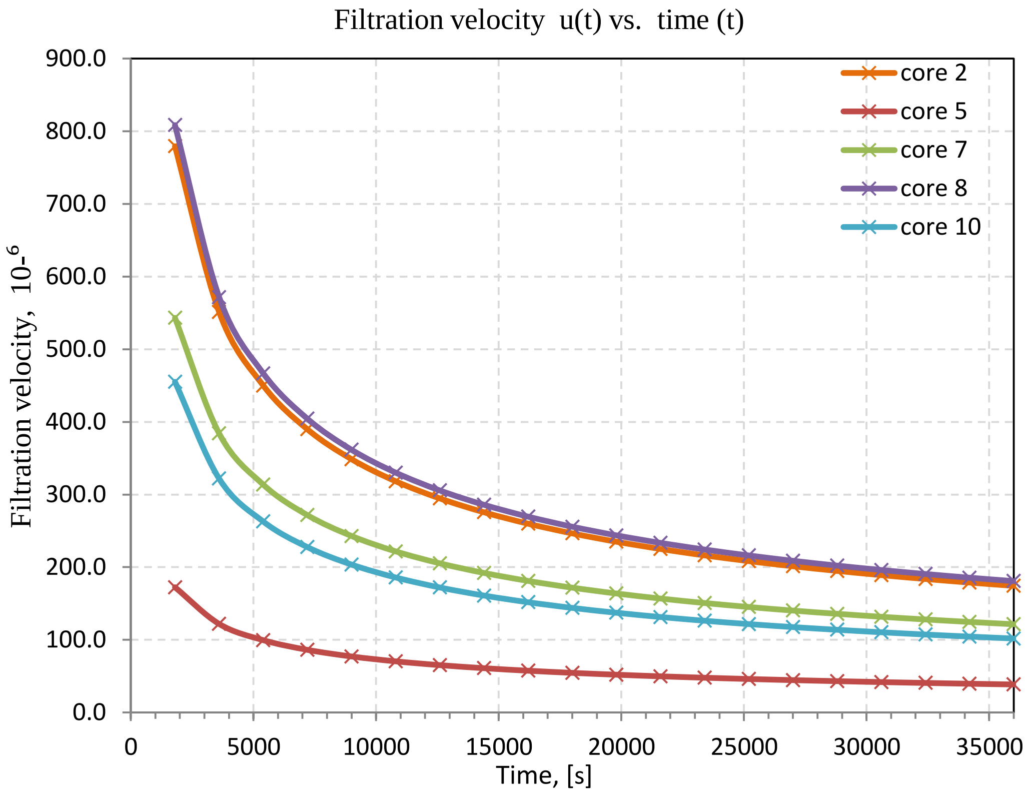


Figure 4.3.2 The filtration velocity model for high cake permeability.

Figure 4.3.2 indicates the filtration velocity model for high cake permeability in 5 core samples. If the mud cake permeability is high, then the filtration velocity is high also. This is called a convection-dominated process. This situation can be seen in Figure 4.3.2 above, whereas core 2, core5, core 7, core 8 and core 10 have higher dimensionless filtration velocity ranging from 0 to 800x10^{-6} compared to other core samples (in figure 4.3.1) with only values ranging from 0 to 350x10^{-6} dimensionless in unit. The highest filtration velocity is recorded by core 8, which is about 808.528x10^{-6} and the lowest filtration velocity is recorded by core 5 which is about 172.336x10^{-6} unit less, with both at the initial time which is 1800 seconds (30 minutes) of injections up until 36000 seconds (10 hours). Core 8 has higher cake permeability, k_c which is 1.741x10^{-6} compared to core 5 only with 1.026x10^{-6}. As the mud cake thickness increase, the filtration velocity will be decreased due to the hardness for the mud filtrate to invade into the thicker mud cake thickness.

4.4 Depth Invasion for Low and High Cake Permeability

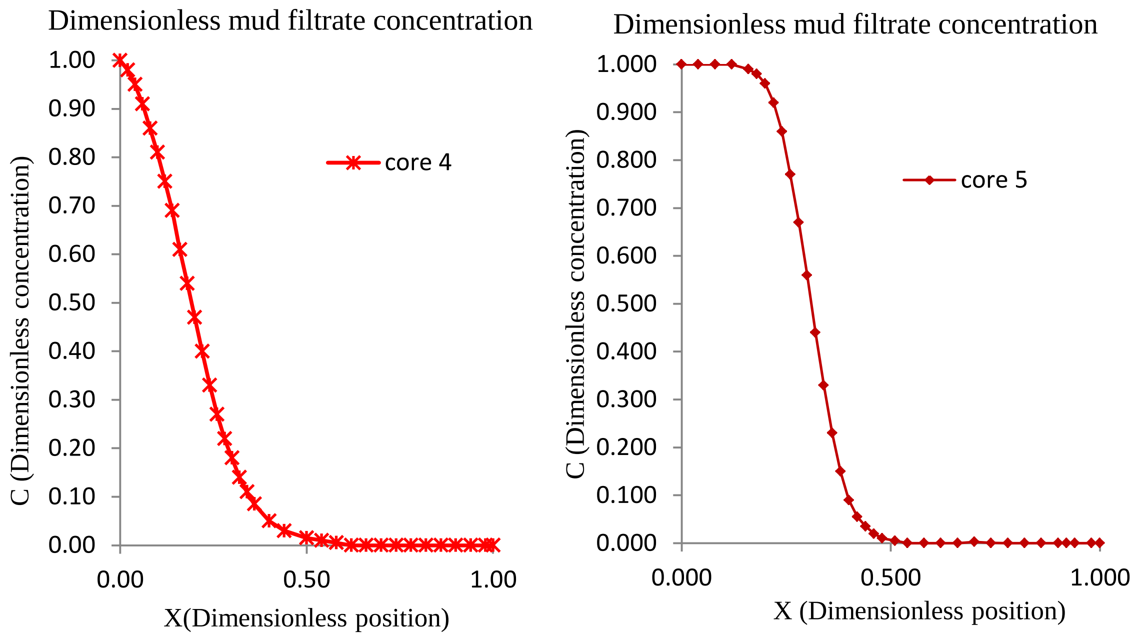


Figure 4.4.1 Dimensionless concentration profile after the time of injection is ended for 2 selected core samples. Left: low mud cake permeability, right: high mud cake permeability.

One selected core from low and high cake permeability respectively which is core 4 (low k_c) and core 5 (high k_c) is chosen to determine the invasion depth of mud filtrate from the dimensionless concentration profile and the predicted invasion radius of mud filtrate is as follow using the formula of $r_{s,}$

$$r_{s}=\max\langle x : c\left(x,\frac{t_{inj}}{t_0}\right) > C_d^*\rangle$$

Table 4.4.1 Predicted vs experimental radius of invasion of mud filtrate.

Core no.	$r_{s,model}$ (cm)	$r_{s,m}$ (cm)	Relative error (%)
4	5.94	5.66	4.95
5	5.4	5.53	-2.35

In table 4.4.1, we can see that the predicted radius of invasion as not much differences from the measured data from Yan et al. (1997) with relative error about 4.95% for core 4 and -2.35% for core 35. Relative error is calculated using:

$$Relative\ errors(\%) = \frac{\mathrm{rs,model} - \mathrm{rs,m}}{\mathrm{rs,m}} \times 100\%$$

Here we can say that the predicted cake permeability in the early of the project are not really different from the cake permeability of Yan et al. (1997) data as the invasion depth of mud filtrate are not much different from the measured invasion as what we can see above.

4.5 Parametric Studies on Core 4 towards the effect of Mud Cake Thickness, Filtration Velocity and Invasion Depth.

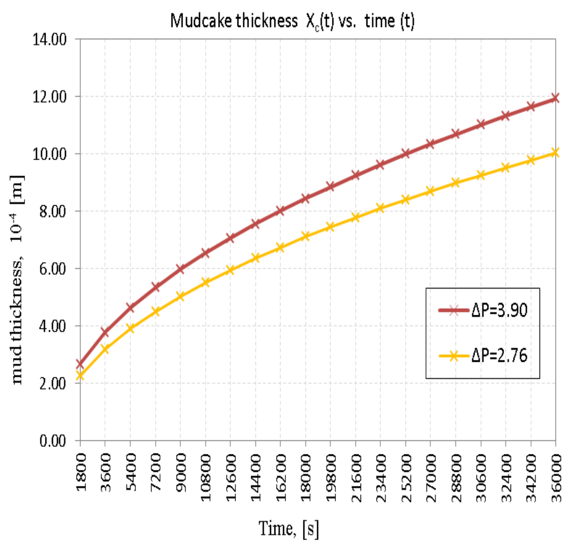
One core which is core 4 is selected from all the 14 core samples to proceed with the parametric studies on each core. In this section, some parameters are identified to affect the mud cake thickness, filtration velocity and also the invasion depth. Those selected parameters are overbalance pressure (Δp), formation permeability, porosity, cake permeability and many more. However only these four parameters are selected to be tested in this section to see what will be occurred to the mud cake thickness, filtration velocity as well as the invasion depth model to core sample no. 4.

4.5.1 Effect of Overbalance Pressure (ΔP) on Mud Cake Thickness, Filtration Velocity and Invasion Depth.

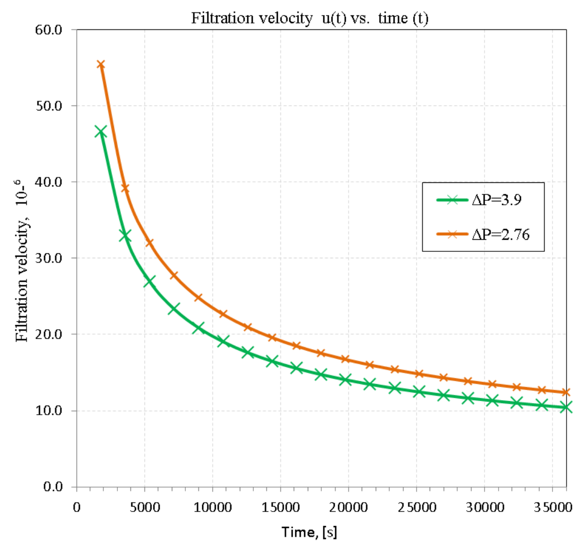
To see whether overbalance pressure brings great impact on the mud cake thickness, filtration velocity and also the invasion depth, another value of overbalance pressure (Δp) for core sample no. 4 is selected to test for the results, while another parameters are kept to be constant. The value of new (present study) overbalance pressure is taken to be as 3.9 MPa as it was the highest value of among the 14 core samples. The data is shown in table 4.5.1

Table 4.5.1 Validation and new value of overbalance pressure for core 4.

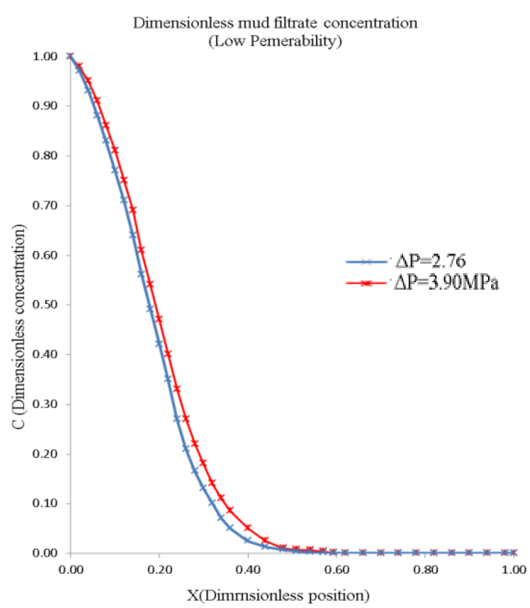
Overbalance Pressure (Δp)	Validation	Present Study
Core 4	2.76 MPa	3.9 MPa



(a)



(b)



(c)

Figure 4.5.1. The effect of different value of over balance pressure, ΔP on; a) mud cake thickness, b) dimensionless filtration, velocity and c) mud filtrate invasion depth.

Figure 4.5.1 illustrates the effect of changing the overbalance pressure (ΔP) on the cake thickness, filtration velocity and also invasion depth. In figure 4.5.1 (a), we can see the comparison of overbalance pressure towards the mud cake thickness whereby the increment of ΔP is made from 2.76 MPa to 3.90 MPa. The higher the overbalance pressure, the thicker the mud cake as time increasing.

However the dimensionless filtration velocity is smaller for the present study value (green line) compared to the validate result (orange). This shows that the thicker the mud cake, the lower the filtration velocity with respect to time and increasing overbalance pressure will not increase the filtration velocity. In figure 4.5.1(c), we can see that higher overbalance pressure (red line) will result in larger invasion depth and this is bad for the formation of mud cake around the wellbore. The new value of invasion depth is approximately about 6.1 cm, which is larger than the validate results (5.94 cm) as what we can see int the figure 4.5.1(c).

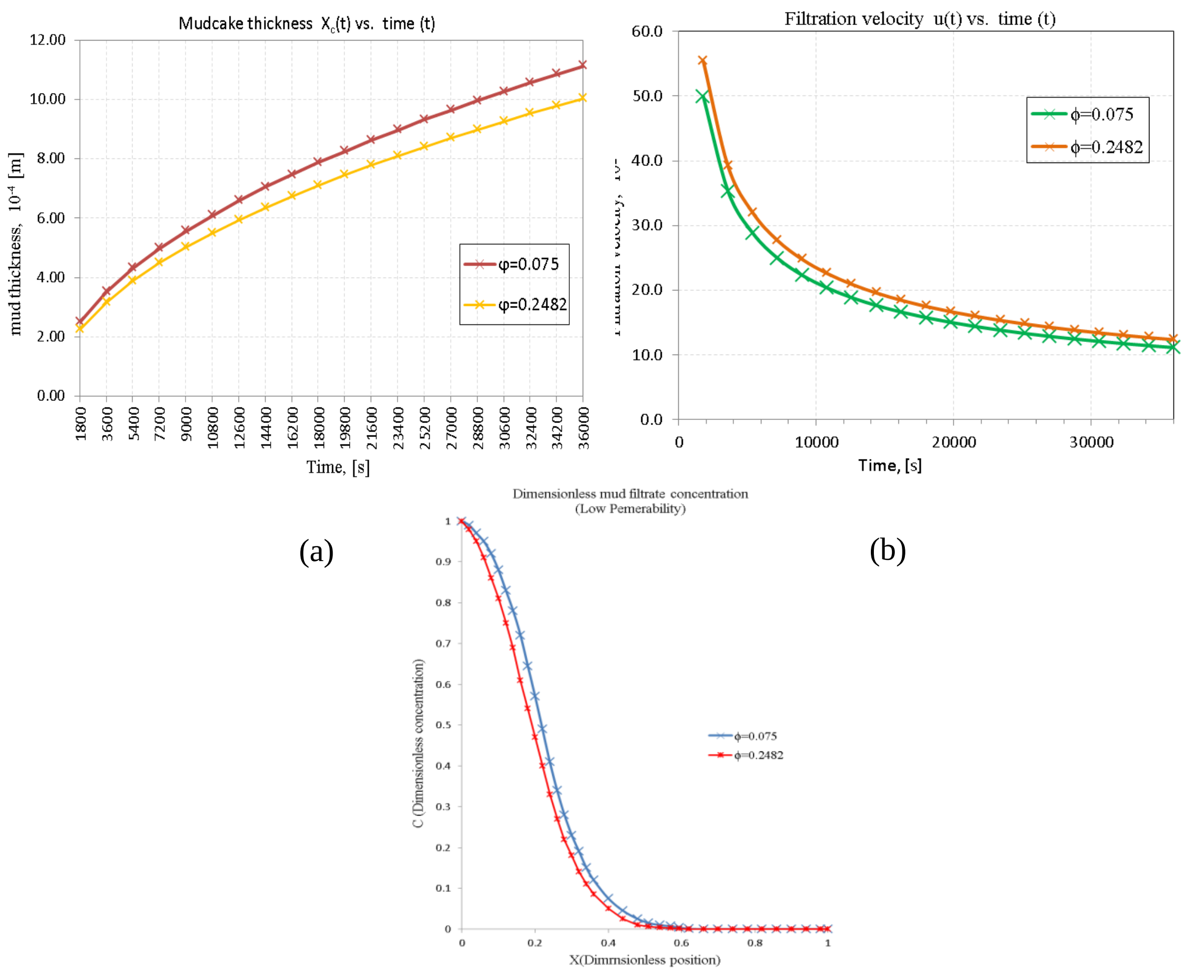
We can conclude that higher overbalance pressure, ΔP will result in thicker mud cake formation, lower dimensionless filtration velocity and higher invasion depth.

4.5.2 Effect of Formation Porosity (Ø) on Mud Cake Thickness, Dimensionless Filtration Velocity and Invasion Depth.

The formation porosity, Ø is tested in core 4 towards the effect of mud cake thickness, filtration velocity and invasion depth. The lowest porosity in the data from literature which is 0.075 is taken to test for the result. The data is shown in table 4.5.2 below.

Table 4.5.2 Validation and new value of formation porosity for core 4.

Porosity (Ø)	Validation	Present Study
Core 4	0.2482	0.075



(a)

(b)

(c)

Figure 4.5.2 The effect of formation porosity on on; a) mud cake thickness, b) dimensionless filtration, velocity and c) mud filtrate invasion depth.

Based on figure 4.5.2, we can we can know and discuss the effect of formation porosity towards mud cake thickness, dimensionless filtration velocity and invasion depth. During this validation, smaller value of formation porosity (present study) is chose which is 0.075 and the validation value is 0.2482. In figure 4.5.2(a), the mud cake thickness is larger for porosity 0.075 compared to porosity 0.2482. And the filtration velocity is smaller with formation porosity of 0.075 compared to 0.2482.

The mud cake thickness keep increasing as the time increase, meanwhile filtration velocity is decreasing as time increase. This is due to the hardness of the mud filtrate to invade into the formation as the mud cake gets thicker.

Figure 4.5.2(c) illustrates the concentration profile across the formation. The blue line represents the invasion depth using the present porosity value which is 0.075, and the red line represents the concentration profile for validation porosity value which is 0.2482. Here we can see the effect of porosity towards the invasion depth of mud filtrate. Lower formation velocity will result in higher invasion depth while other parameters are kept constant. The invasion depth for $\emptyset$=0.075 is estimated to be 6.20 cm, which is larger than the original depth which is 5.94 cm.

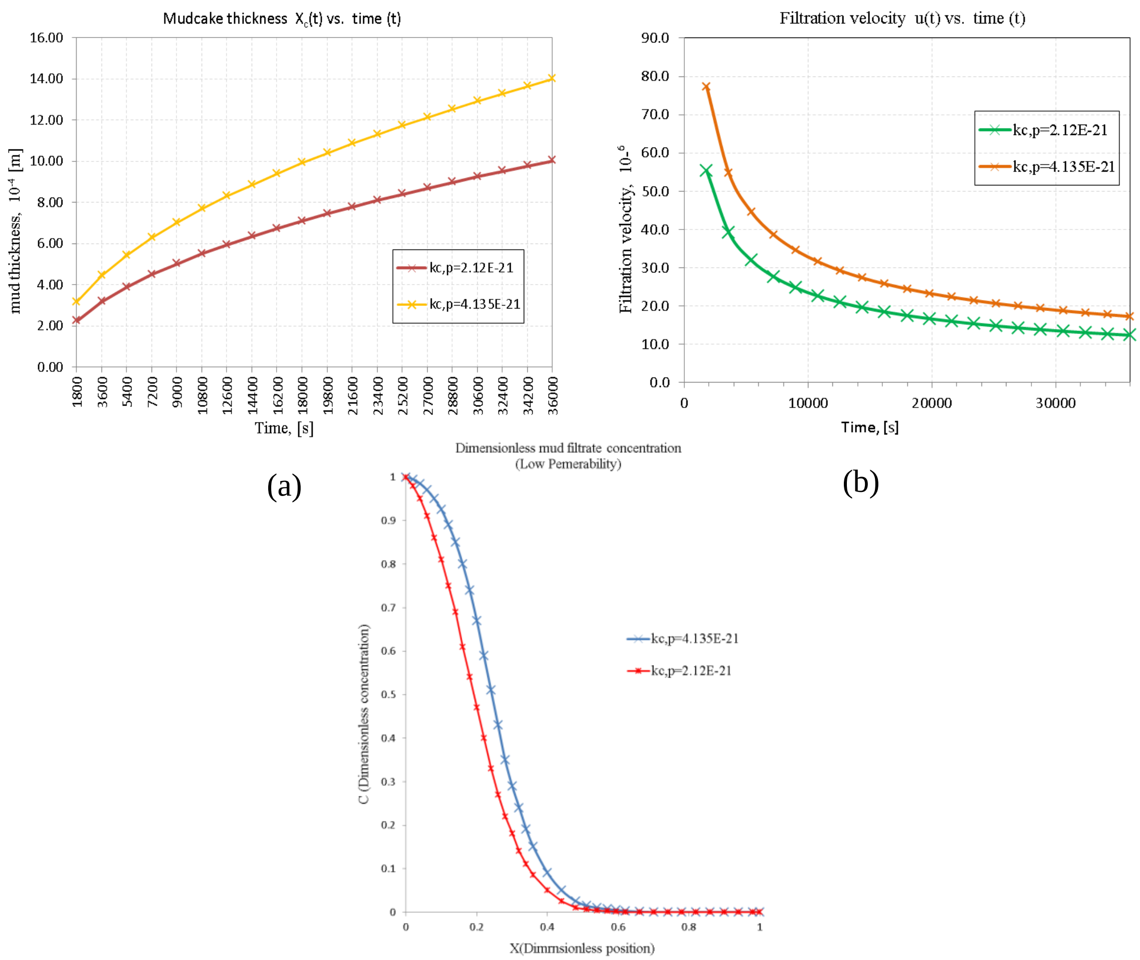
It can be concluded that smaller formation porosity will result in thicker mud cake, lower filtration velocity and higher invasion depth.

4.5.3 Effect of Cake Permeability (k_c) on Mud Cake Thickness, Dimensionless Filtration Velocity and Invasion Depth.

Cake permeability is one of the parameters that will affect mud cake thickness, filtration velocity and the invasion depth according to the formula in the literature. The new value of cake permeability for core sample number 4 is stated in the table 4.5.3 below.

Table 4.5.3 Validation and new value of cake permeability for core 4.

Cake Permeability (k_c)	Validation	Present Study
Core 4	2.120E-21 m^2	4.135E-21 m^2



(c)

Figure 4.5.3 The effect of cake permeability, k_c on; a) mud cake thickness, b) dimensionless filtration, velocity and c) mud filtrate invasion depth.

Figure 4.5.3 above shows the effect of cake permeability on mud cake thickness, filtration velocity and invasion depth for higher value of cake permeability,k_c which is k_c=4.135E-21 instead of k_c=2.12E-21. In is clearly shown that higher cake permeability with result in higher value of mud cake thickness and higher value of filtration velocity, with respect to time. Here we can conclude that the thicker the mud cake thickness, the lower the filtration velocity as the time is increasing.

Moreover, in figure 4.5.3(c), it is clearly illustrated that the concentration profile is increasing (indicates by the blue line), which also means that the invasion depth is also increasing compared to lower cake permeability. With the value of k_c=4.135E-21, the new invasion depth is approximately about 6.60 cm, larger than the validate k_c value which is 5.94 cm.

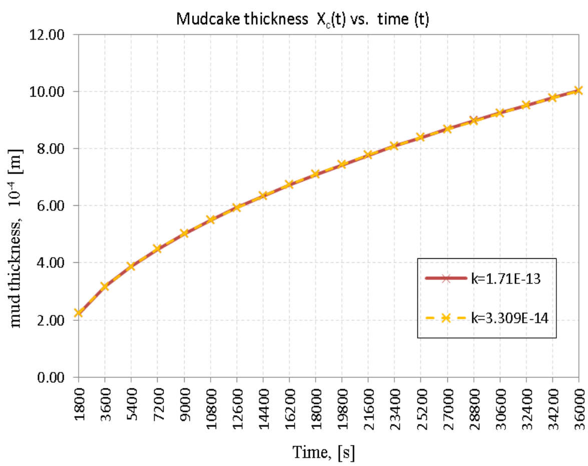
Hence we can conclude that cake permeability plays a vital role in determining the mud cake thickness, filtration velocity and also the invasion depth. The higher the cake permeability, the thicker the mud cake, the faster the velocity of filtration and the deeper the mud filtrate invasion.

4.5.4 Effect of Formation Permeability (k) on Mud Cake Thickness, Dimensionless Filtration Velocity and Invasion Depth.

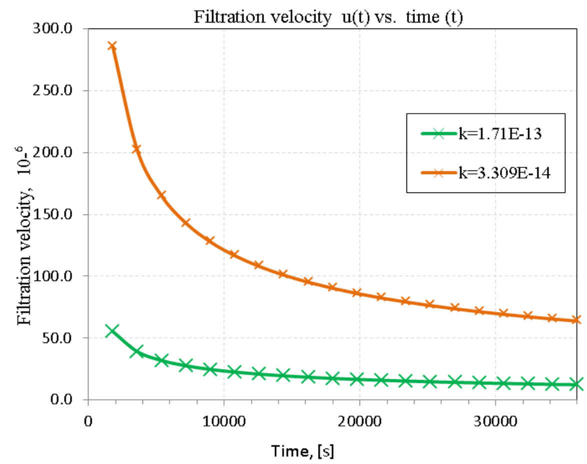
Formation permeability will affect mud cake thickness, filtration velocity and the invasion depth according to the formula in the literature. The new value of formation permeability for core 4 can be seen in the table 4.5.4 below.

Table 4.5.4 Validation and new value of formation permeability for core 4.

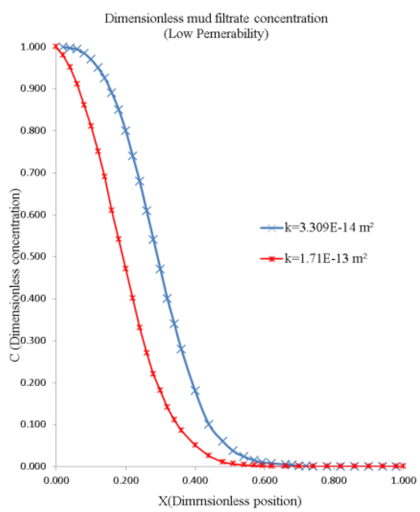
Formation Permeability (k)	Validation	Present Study
Core 4	1.71E-13 m^2	3.309E-14 m^2



(a)



(b)



(c)

Figure 4.5.4 The effect of cake formation permeability,k on; a) mud cake thickness, b) dimensionless filtration, velocity and c) mud filtrate invasion depth.

The effect of formation permeability,k towards the mud cake thickness, filtration velocity and mud invasion is shown in figure 4.5.4 above. The present study's value of formation permeability is chose to be 3.309E-14 μm^2 instead of 1.707E-13 μm^2. The effect of formation permeability brings great impacts toward the filtration velocity and invasion depth. However, different value of formation permeability does not change any of the mud cake thickness, as per illustrated in figure 4.5.4(a).

In figure 4.5.4(b), we can see that the difference of the filtration velocity,u(t) value is very big if we change the value of the formation permeability. The new reading of u(t) with k=3.309E-14 μm^2 is approximately about 285.67E-6 m/s compared to the k=1.71E-13 μ m^2 which is only about 55.380E-6 m/s.

The invasion depth of mud filtrate also is increasing as the value of formation velocity is decreasing and is illustrated in figure 4.5.4(c). The new invasion depth is about 6.80 cm which is the highest among those four other parameters. Here we can say that formation permeability bring the greatest impact towards the mud cake thickness, filtration velocity and invasion depth compared to overbalance pressure, formation porosity as well as the cake permeability.

We can conclude that lower value of formation velocity will give bigger impact in filtration velocity reading and also higher invasion depth reading as per discussed as and illustrated in this section.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

A mathematical model for mud filtrate invasion which consists of mud cake thickness model, filtration velocity model, and dimensionless mud filtrate concentration model has been presented. The mud filtrate invasion into oil formations occurred in a linear flow system. The model has been verified using the experimental data by Yan et al. (199) cited in the literature.

It is clearly can be seen that filtration velocity, mud cake thickness and invasion depth depends on the formation permeability, overbalance pressure, invasion time and also the mud cake properties such as its permeability, density and porosity. The invasion process can be either convection-dominated process or diffusion-dominated process. Mud cake thickness will be increased as time increase, and filtration velocity will decrease as time increased.

Based on the parametric studies, formation permeability plays the most important role in determining the filtration velocity and invasion depth as per discussed in section 4.5.4. Parameters such as overbalanced pressure, formation porosity, cake permeability and also formation permeability have been identified to affect the thickness of mud cake, the velocity of the filtration and also the invasion depth as per illustrated in figures in section 4.5.4.

It is recommended in the future that the core samples used should have lower overbalance pressure, larger porosity, smaller cake permeability and bigger formation permeability so that the invasion depth of mud filtrates is lesser, hence the formation damage around the wellbore can be reduced.

Nomenclature

FL	fluid loss of the drilling fluid (m^3)
f, g	empirical parameter (dimensionless)
k	formation permeability (m^2)
k_c	cake permeability (m^2)
$k_{c, p}$	predicted cake permeability (m^2)
L	core length (m)
p	pressure (Pa)
q	volumetric flow rate (m3/s)
rs	invasion depth of mud filtrate (m)
$r_{s, m}$	measured invasion depth of mud filtrate (m)
$r_{s, c}$	calculated (predicted) invasion depth of mud filtrate (m)
S_{or}	residual oil saturation (fraction)
S_{wi}	irreducible water saturation (fraction)
$S_{wi, p}$	predicted irreducible water saturation (fraction)
t	time (min)
t_{inj}	injection time (s)
u	filtration velocity (m/s)
x	position (m)
x_c	mud cake thickness (m)
Δp	overbalance pressure (Pa)
μ_f	mud filtrate viscosity (cp)
ϕ	formation porosity (fraction)
ϕ_c	mud cake porosity (fraction)
ρ_c	mud cake density (kg/m^3)
τ	shear stress of drilling fluid circulation (kg/m^2)

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APPENDIX A (i) – Mud Cake Thickness (Low Cake Permeability)

T (s)	Mud cake thickness Xc(t), 10^{-4} [m]								
	Core 1	Core 3	Core 4	Core 6	Core 9	Core 11	Core 12	Core 13	Core 14
1800	2.55	1.78	2.24	2.17	2.31	2.07	1.94	2.18	2.30
3600	3.60	2.52	3.17	3.07	3.26	2.93	2.74	3.09	3.26
5400	4.41	3.09	3.88	3.76	3.99	3.59	3.36	3.78	3.99
7200	5.09	3.57	4.49	4.35	4.61	4.15	3.88	4.37	4.61
9000	5.69	3.99	5.01	4.86	5.16	4.64	4.34	4.88	5.15
10800	6.24	4.37	5.49	5.32	5.65	5.08	4.75	5.35	5.64
12600	6.73	4.72	5.93	5.75	6.10	5.49	5.14	5.78	6.09
14400	7.20	5.05	6.34	6.15	6.52	5.87	5.49	6.18	6.52
16200	7.64	5.35	6.73	6.52	6.92	6.22	5.82	6.55	6.91
18000	8.05	5.64	7.09	6.87	7.29	6.56	6.14	6.91	7.28
19800	8.44	5.92	7.44	7.21	7.65	6.88	6.44	7.25	7.64
21600	8.82	6.18	7.77	7.53	7.99	7.19	6.72	7.57	7.98
23400	9.18	6.43	8.09	7.84	8.31	7.48	7.00	7.88	8.31
25200	9.52	6.68	8.39	8.13	8.63	7.76	7.26	8.17	8.62
27000	9.86	6.91	8.69	8.42	8.93	8.04	7.52	8.46	8.92
28800	10.18	7.14	8.97	8.69	9.22	8.30	7.76	8.74	9.21
30600	10.50	7.36	9.25	8.96	9.51	8.55	8.00	9.01	9.50
32400	10.80	7.57	9.52	9.22	9.78	8.80	8.23	9.27	9.77
34200	11.10	7.78	9.78	9.47	10.05	9.04	8.46	9.52	10.04
36000	11.38	7.98	10.03	9.72	10.31	9.28	8.68	9.77	10.30

APPENDIX A (ii) – Mud Cake Thickness (High Cake Permeability)

T (s)	Mud cake thickness Xc(t), 10^{-4} [m]				
	Core 2	**Core 5**	**Core 7**	**Core 8**	**Core 10**
1800	7.83	4.64	7.29	4.75	8.02
3600	11.08	6.57	10.31	6.72	11.34
5400	13.57	8.04	12.62	8.23	13.89
7200	15.67	9.28	14.58	9.50	16.04
9000	17.52	10.38	16.30	10.62	17.93
10800	19.20	11.37	17.85	11.63	19.64
12600	20.73	12.28	19.28	12.57	21.21
14400	22.17	13.13	20.62	13.43	22.68
16200	23.51	13.93	21.87	14.25	24.05
18000	24.78	14.68	23.05	15.02	25.36
19800	25.99	15.40	24.17	15.75	26.59
21600	27.15	16.08	25.25	16.46	27.78
23400	28.26	16.74	26.28	17.13	28.91
25200	29.32	17.37	27.27	17.77	30.00
27000	30.35	17.98	28.23	18.40	31.06
28800	31.35	18.57	29.16	19.00	32.07
30600	32.31	19.14	30.05	19.59	33.06
32400	33.25	19.70	30.92	20.15	34.02
34200	34.16	20.24	31.77	20.71	34.95
36000	35.05	20.76	32.60	21.24	35.86

APPENDIX B (i) - Filtration Velocity (Low Cake Permeability)

T (s)	Filtration velocity U(t), 10^{-6}								
	Core 1	Core 3	Core 4	Core 6	Core 9	Core 11	Core 12	Core 13	Core 14
1800	263.54	348.81	55.38	42.03	31.44	11.82	20.06	28.21	17.42
3600	186.35	246.64	39.16	29.72	22.23	8.35	14.18	19.95	12.32
5400	152.15	201.38	31.97	24.26	18.15	6.82	11.58	16.29	10.06
7200	131.77	174.40	27.69	21.01	15.72	5.91	10.03	14.11	8.71
9000	117.86	155.99	24.77	18.80	14.06	5.28	8.97	12.62	7.79
10800	107.59	142.40	22.61	17.16	12.83	4.82	8.19	11.52	7.11
12600	99.61	131.84	20.93	15.88	11.88	4.47	7.58	10.66	6.58
14400	93.18	123.32	19.58	14.86	11.11	4.18	7.09	9.98	6.16
16200	87.85	116.27	18.46	14.01	10.48	3.94	6.69	9.40	5.81
18000	83.34	110.30	17.51	13.29	9.94	3.74	6.34	8.92	5.51
19800	79.46	105.17	16.70	12.67	9.48	3.56	6.05	8.51	5.25
21600	76.08	100.69	15.99	12.13	9.07	3.41	5.79	8.14	5.03
23400	73.09	96.74	15.36	11.66	8.72	3.28	5.56	7.83	4.83
25200	70.43	93.22	14.80	11.23	8.40	3.16	5.36	7.54	4.66
27000	68.05	90.06	14.30	10.85	8.12	3.05	5.18	7.28	4.50
28800	65.89	87.20	13.84	10.51	7.86	2.95	5.01	7.05	4.35
30600	63.92	84.60	13.43	10.19	7.62	2.87	4.86	6.84	4.22
32400	62.12	82.21	13.05	9.91	7.41	2.78	4.73	6.65	4.11
34200	60.46	80.02	12.70	9.64	7.21	2.71	4.60	6.47	4.00
36000	58.93	78.00	12.38	9.40	7.03	2.64	4.48	6.31	3.90

APPENDIX B (ii) - Dimensionless Filtration Velocity (High Cake Permeability)

T(s)	Filtration velocity U(t), 10^{-6}				
	Core 2	**core 5**	**Core 7**	**Core 8**	**Core 10**
1800	779.471	172.336	543.142	808.528	455.132
3600	551.169	121.860	384.059	571.716	321.827
5400	450.028	99.498	313.583	466.804	262.770
7200	389.736	86.168	271.571	404.264	227.566
9000	348.590	77.071	242.900	361.585	203.541
10800	318.218	70.356	221.737	330.080	185.807
12600	294.612	65.137	205.288	305.595	172.024
14400	275.585	60.930	192.030	285.858	160.913
16200	259.824	57.445	181.047	269.509	151.711
18000	246.490	54.497	171.757	255.679	143.925
19800	235.019	51.961	163.763	243.781	137.227
21600	225.014	49.749	156.792	233.402	131.385
23400	216.186	47.797	150.640	224.245	126.231
25200	208.322	46.059	145.161	216.088	121.639
27000	201.259	44.497	140.239	208.761	117.515
28800	194.868	43.084	135.785	202.132	113.783
30600	189.050	41.798	131.731	196.097	110.386
32400	183.723	40.620	128.020	190.572	107.276
34200	178.823	39.537	124.605	185.489	104.414
36000	174.295	38.536	121.450	180.792	101.771