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Modeling and analysis of mud filtrate invasion using Computational Fluid Dynamics

تحليل و نمذجة غزو طين الحفر باستخدام الحسابات الديناميكية للموائع (CFD)

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الإستهلال

قال تعالى:

(لَوْ كَانَ الْبَحْرُ مِدَادًا لِّكَلِمَاتِ رَبِّي لَنَفِدَ الْبَحْرُ قَبْلَ أَن تَنفَدَ كَلِمَاتُ رَبِّي وَلَوْ جِئْنَا بِمِثْلِهِ مَدَدًا)

الآية (109)سورة الكهف

Dedication

We dedicate this work to our Prophet Mohammed peace be upon him. Also to our families, a special feeling of gratitude to our loving parents whose words of encouragement and push of tendency ring in our ears, we will always appreciate all they have done. We also dedicate this work to our dear friends **Muaaz Tajaldeen** who left the university and went to France, **Mohammed Abu-elqasem** who motivates us along project duration, and to the spirit of **D. Mohammed Naiem**

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We thank Allah for giving us the courage and the determination, as we as guidance in conducting this project, despite all difficulties.

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Finally, we thank all those who assisted encouraged and supported us during the project, be assured that Allah will bless you all for the contributions you made.

Abstract

In spite of continued improvements in logging technology, mud-filtrate invasion and related formation damage due to drilling fluids can result in misinterpreted values of rock and fluid properties in the reservoir. Well planning with accurate information of target reservoir will optimize drilling operation, completion and maximize production of oil and gas. In this study, the dynamics filtration process into the gas and oil bearing reservoir are studied in vertical open hole system using computational fluid dynamics (CFD) module of the commercial software COMSOL. This study investigates the communication between the fluids and formations during drilling with special emphasis on effect of formation porosity, permeability, time, overbalanced pressure.

The results provided an insight in the formation damage around wellbore and related reduction in hydrocarbons flow due to altered fluid saturation. The CFD simulation results of fluid saturation profile have, been validated against published correlations which showed good agreement. This enabled the process of predicting the influence of various parameters on the invasion process.

This simulation study will enable accurate prediction of damaged zone around the wellbore which will benefit different operations such as drilling fluid design, log interpretation, hydraulic fracturing and well completion.

التجريد

علي الرغم من التطور في تقنيات تسجيلات الابار ، إلا ان غزو راشح سائل الحفر و الضرر الناتج من سائل الحفر يمكن ان ينتج عنه تشويش في قراءات قيم خواص الصخر و موائع الطبقه في المكمن. التخطيط الجيد والمعلومات الدقيقة للمكمن المستهدف لا تقود فقط الي افضل عمليات حفر واكمال و لكن ايضا انها تزيد من انتاج النفط والغاز.

لإنتاج النفط والغاز بصوره فعالة يجب ان تتصل حفره البئر مع الطبقات المجاوره لمنطقة الإنتاج وهذا ممكن ان يتم باستخدام عمليات تثقيب مناسبة او بعمل شق.

في هذه الدراسة، عملية الرشح الفعال و والتثقيب المترابط في منطقة النفط والغاز في المكمن تم دراستها في نظام بئر رأسية مفتوحة باستخدام (computational fluid dynamic (CFD) module).

هذه الدراسة تبحث عن مدي الاتصال بين السوائل والطبقات خلال عمليات الحفر و تبحث بصوره ادق عن مدي تأثير كل من المسامية و النفاذية و الضغط غير الاعتيادي والزمن.

تزود النتائج المتحصل عليها بمعرفة الضرر حول قاع البئر و مدى انخفاض سريان الهيدروكربونات نتيجة تغير تشبع الموائع

هذه النتائج تمثل تشبع الموائع وقد تمت مقارنتها بنتائج سابقة واظهرت المقارنة تطابق جيد للنتائج مما يسمح لمعلية التوقع الجيد لمعرفة تأثير العناصر المختلفة علي عملية الغزو.هذه الدراسة التمثيلية تتيح التوقع الدقيق للمنطقة المتضررة حول البئر مما يتيح فوائد كثيره خلال عمليات اخري مثل تصميم سائل اللحفر، تفسيرات الجس، التشقيق الهيدروليكي، استكمال الابار.

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Chapter 1 : Introduction

1.1 General Introduction:

Formation damage is an undesirable operational and economic problem that can occur during the various phases of oil and gas recovery from subsurface reservoirs including production, drilling, hydraulic fracturing, and work-over operations. Formation damage assessment, control, and remediation are among the most important issues to be resolved for efficient exploitation of hydrocarbon reservoirs. Formation damage indicators include permeability impairment, skin, damage and decrease of well performance. Flow of suspensions in rocks with particle capture and consequent permeability impairment is an essential phenomenon in many oil industry processes. Particle capture by rock and permeability decline takes place during drilling fluid invasion into reservoir resulting in formation damage. It also occurs during fines migration, mostly in reservoirs with low consolidated sands and heavy oil.

Deep bed filtration of fines with capture and permeability damage takes place near to production wells, in drilling operation. The particles in drilling fluid are captured by size exclusion (straining) or by different attachment mechanisms (electric forces, gravity segregation and diffusion).

The classical mathematical model for suspension flow in rocks consists of particle balance and capture kinetics equations .It is assumed that the mean particle speed is equal to carrier water velocity.

The characteristics of the porous medium play a role; for example the size distribution of the pore throats, the connectivity of the pore bodies and the surface chemistry of the grains comprising the porous medium.

The main concern in this project is studying drilling fluid invasion into formation by taking different values of formation’s properties to know the effect of these differences on the formation damage.

1.2 Problem Statement

During overbalanced drilling operations, hydraulic pressure of the borehole is greater than the pressure of the porous rock. Therefore, the circulating drilling fluid forces the mud into the permeable horizons. In hydrocarbon bearing formations, the drilling fluids push hydrocarbons out from the permeable formation near the borehole region thus impairing hydrocarbon productivity. In addition, the flushed zone with the filtrate from the drilling fluids causes misinterpretation of rock and fluid properties due to replacement of formation water and hydrocarbons, particularly formation porosity and permeability when measured by wire line logging methods. Especially, the mud-filtrate invasion affects the shallow investigation devices such as CNL (Compensated Neutron log), LDT (Litho Density log), and MLL (Micro Laterolog) when water-base mud penetrates into oil bearing reservoirs. It also affects the wireline formation testing. The flushed zone inside oil or gas bearing reservoirs serves as a blockage to produce oil or gas. Therefore there is a growing need for predicting the horizontal extent of the invasion and the factors affecting it using simulation methods.

1.3 Objectives

1.3.1 General Objectives:

The general objectives of this study are to:

- Build a computational model using CFD for formation damage analysis.
- Study the factors affecting the invasion mechanism.

1.3.2 Specific Objectives:

- Build the computational domain (mesh building).
- Study the effects of different parameters on invasion profile.
- Study and predict the invasion through the formation.

Chapter 2 : Literature Review & Background

2.1 Introduction:

Because of the fact that the hydraulic borehole pressure during overbalanced drilling is greater than the formation pressure, mud is forced into the permeable zones. The prediction of the invaded zone is critical since the wellbore must communicate with formations beyond the invaded zone through perforation or fracturing. So, numerical model can be used for planning purposes. Also accurate prediction of damaged zone around the wellbore will help in the drilling fluids design, interpretation of well logs, completion operations and hydraulic fracturing.

In order to study the mud filtrate invasion, it is required to review some of the petro-physical properties such as porosity, permeability, saturation, wettability, capillary pressure and rock compressibility (Ahmed tarek 2000).

In the next section, these properties will be reviewed:

The porosity is the ratio of the pore volume to the total volume (bulk volume) these properties determined by the following generalized relationship:

$$Ø = \frac{\text{pore volume}}{\text{bulk volume}} \dots\dots\dots\dots\dots\dots \text{(2-1)}$$

Where Ø = porosity

Permeability is a property of the porous medium that measures the capacity and ability of the formation to transmit fluids. There is two type of it absolute permeability and effective permeability. These properties determined by the following generalized relationship:

$$K= \frac{q\mu L}{A\Delta P} \dots\dots\dots\dots\dots\dots \text{(2-2)}$$

Where L= length of core, cmA=ccross-sectional area , cm^2

Flow rate q and pressure drop ΔP

Saturation is defined as that fraction, or percent, of the pore volume occupied by a particular fluid (oil, gas, or water).

$$\text{Fluid saturation} = \frac{\text{total volume of the fluid}}{\text{pore volume}} \quad \text{................ (2-3)}$$

Applying the above mathematical concept of saturation to each reservoir fluid gives:

$$S_o = \frac{\text{volume of oil}}{\text{pore volume}} \quad \text{................ (2-4)}$$

$$S_g = \frac{\text{volume of gas}}{\text{pore volume}} \quad \text{................ (2-5)}$$

$$S_w = \frac{\text{volume of water}}{\text{pore volume}} \quad \text{............. (2-6)}$$

Where:

S_o = oil saturation

S_g = gas saturation

S_W = water saturation

By definition, the sum of the saturations is 100%, therefore:

$$S_o + S_g + S_w = 1 \quad \text{.............. (2-7)}$$

Another important parameter is the wettability which is defined as the tendency of one fluid to spread on or adhere to a solid surface in the presence of other immiscible fluids.
Capillary pressure is pressure difference between pressure of the non-wetting phase and pressure of the wetting phase $p_c = p_{nw} - p_w$. According to the fluid system there are three types of

capillary pressure: Water-oil capillary pressure (denoted as p_{cwo}) Gas-oil capillary pressure (denoted as p_{cgo}) Gas-water capillary pressure (denoted as p_{cgo}).

Rock compressibility is defined as the fractional change in volume of the solid rock material (grains) and pore volume with a unit change in pressure. Type of compressibility is rock matrix compressibility, rock matrix compressibility and pore compressibility.

2.2 Filtration Process:

During drilling a well, drilling fluids are specially formulated to be used while perforating operations to control fluid loss and minimize formation damage. They can be formulated to help minimizing fluid invasion when perforating oil or gas bearing zones with an over-balanced fluid. In this condition, dynamic and static filtration and fluid invasion can occur

Static filtration occurs when fluid pumping is interrupted. The interruption creates a difference between the hydrostatic pressure in the wellbore and that in the reservoir, and from that point on, static filtration occurs and it's controlled by continuous thickening of the mud cake.

On the other hand, dynamic filtration occurs when drilling fluids are pumped through the well. In this process, the mud cake thickness is determined by dynamic equilibrium of two factors: the amount of solid particles deposited and the erosion rate caused by shear stresses generated by the fluid flow in the wellbore. (Calcada et. al. 2011)

2.3 Mud invasion effects:

Although logging technology has improved, mud-filtrate invasion and related formation damage caused by drilling fluid can result in misinterpretation of reservoir rock and fluid properties.

During logging process , mud-filtrate invasion and related formation damage caused by drilling fluid can result in misinterpretation of reservoir rock and fluid properties and the mud-filtrate invasion affects the shallow investigation devices such as CNL (Compensated Neutron log), LDT (Litho Density log), MLL (Micro Later log) when water-base mud penetrates into oil and gas bearing reservoirs (S. Won 2008).

2.4 Modeling and analyzing Filtrate invasion:

The prediction of the invaded zone is critical since the wellbore must communicate with formations beyond the invaded zone through perforation or fracturing. So, both experimental and numerical model can be used for planning purposes.

(Jiao1992) conducted experiments to measure permeability during mud circulation across the face of the sandstone cores employing a specially designed core holder. Several characteristics which affect the formation damage were considered such as mud type, salinity, filtration rates, cuttings concentration and size, and concentration of polymer additive. Throughout the experiments they found that water-based mud induces more migration and releases more clay particles than oil-based mud. In addition, low salinity, small particle size and low particle concentration induces deep mud-filtrate invasion. Lastly, during the backflow experiments using the same apparatus, it was concluded that once the particles are inserted into the pore space, it is very hard to extract them and this results in permanent formation damage.

The results of accurate and detailed laboratory simulation of mud filtrate invasion have been translated using innovative software applications (modeling) to give a prediction of well performance. (S. Won 2008) studied the dynamic filtration process and the related penetration into the gas and oil bearing reservoirs in a vertical open hole system using a Computational Fluid Dynamics software package. Their study investigated the communication between fluids and formations during drilling with special emphasis on the effects of formation porosity, permeability, time, and overbalanced pressure. They found that the amount and depth of invasion was greatly affected by duration of contact and amount of overbalanced pressure as well as formation porosity and permeability. Also increasing in formation porosity resulted in decreasing in the depth of mud filtrate penetration. On the other hand, deep mud filtrate invasion can take place even in low permeability formations. Also, the depth of invasion increased with increase in formation permeability, duration of contact, and pressure gradient between wellbore and formation.

(Wu et. al. 2001) replicated the phenomena of mud-filtrate invasion in overbalanced vertical, inclined, and horizontal wells using a commercially available numerical model and an in-house developed software package. Their algorithms remark the form of water saturation extent in the formation, by describing the effects of mud-cake buildup with time-lapse on the dynamic process of mud filtration were more emphasized in the study. In addition, a function of wellbore angle, formation layers, and horizontal and vertical permeability values in the reservoir had been considered in their algorithm. Their model consisted of formation porosity equal to 20 volume percent, formation permeability in the range of 100 to 800 md and irreducible water saturation equal to 37 volume percent. Only water-based mud as the injection fluid and oil-based reservoir as the formation type had been considered. The results of their study indicated that the depth and extent of mud-filtrate invasion are extremely affected by capillary pressure, and deviation of borehole.

(Chowdhury and Torres-VERDIN 2004) used numerical study to determine the influence of mud filtrate invasion on simulated formation tester, nuclear, and resistivity measurements acquired in laminated sand-shale and sand-sand sequences. They used synthetic 2D model to simulate mud filtrate invasion process for drilling with water base mud in an oil bearing reservoir and these parameter (water saturation, capillary pressure and relative permeability) were acquired by the 2D model. They found that not only mud-filtrate invasion but also rock type are directly affected by those logging measurement. Especially, the mud-filtrate invasion causes significant errors on relative permeability values obtained by the measurement of dual-packer formation tester.

2.5 Previous studies using Computational Fluid Dynamics

New computing power and commercially available software have made CFD (Computation Fluid Dynamics) of reservoir fluid flow possible and routine. The models presented here illustrate how knowledge of and measurement of formation damage mechanisms can now be translated and lead to direct predictions of mud invasion. This enables multiple scenarios of drilling, completion and damage sensitivity to be run.

CFD has recently been exploited in many applications in the oil and gas industry. For example, (Blanco et. al 2007) compared Coiled Tubing (CT) friction pressures which were generated from the CFD simulation to measured friction pressures of the tubing. Different software was used to create the model and process simulation, and the non-Newtonian turbulence model was utilized with the Euler equations in the solution process. The tubing consisted of a 50 ft straight section, two layer transition section, and three layers on the reel. Results indicated that the recorded pressures and simulated pressures have less than 10% differences. They concluded that pressure drop is in direct proportion to the sand concentration, and it is in inverse proportion to the reel diameter.

In 2002, Bilgesu et. al. implemented a study of cutting transport parameters in both vertical and horizontal wellbores using CFD. They used the CFD model for an incompressible solid-liquid flow as cuttings and drilling fluids which were presented by a Power Law Model. The cutting transport was strongly affected by the cutting size and density, mud circulation rate and density. In the study, the CFD model runs were carried out using various drilling fluid densities, casing-drill pipe annuli, annular velocities, and particle sizes. They reported effects of mud weight, viscosity, and flow rate on cutting transport. (Bilgesu et. al. 2002)

In drilling engineering, (Mishra 2007) used CFD simulations to research hole cleaning parameters such as flow rate, cutting size, rate of penetration(ROP), drill pipe rotation and inclination angle in directional and horizontal drilling using water as the transportation fluid. The parameters were graphically analyzed using the Eulerian model for the calculations of intricate multiphase models. Iterations of runs were conducted at steady state using the Newtonian fluid. It was observed that the more the fluid velocity increased, the more cutting concentration decreased. Drill pipe rotation affects cutting transport of all sizes but small size particles can notably be easily conveyed by the rotation. It was also reported that more cuttings were cleaned as a result of increase in the angle of direction. The first time CFD has been employed to predict well performance in next section.

The first time CFD has been employed to predict well performance in next section.

According to (Michael Byrne 2009), inflow performance relationship models are inadequate tools to capture the detail and complexity of damage distribution. They used a process involves the use of CFD. The fluid dynamics are modeled on a cell by cell basis and the passage of fluid and its transmission of physical forces can be simulated in almost any resolution or scale and in three dimensions. The models created are indeed created to match any well geometry. There are two examples included in their study. The first example presented models a long horizontal wellbore with sand control in two dimensions and illustrated the contraction of a model.

The second example presented was a vertical gas well with multiple layers of significantly different reservoir quality and damage sensitivity. Multilayer flow, damage sensitivity and the potential for underbalanced drilling are examined. The process of near wellbore modelling using CFD is being used by colleagues to model fracture growth and performance during hydraulic fracturing but in their paper they restrict the examples to more conventional well geometry. The mesh represented by reservoir of width 3000ft and height 74 ft was created in Meshing software with well and associated restrictions (6 5/8'') sand screens, annular gap, mud cake, Invaded Zone 1 and Invaded Zone 2 in the form of concentric circles. The aim of this study was to assess the potential impact of formation damage based on permeability variations for different reservoir drill in fluids (RDIF). CFD approach was taken to incorporate other restrictions namely sand screens, mud cake, invaded zone etc.

(M.T. Byrne 2010) used CFD to study formation damage through symmetric modeling of near wellbore in horizontal well. The reservoir is represented by porous media, as the mud cake is placed inside the well. The well itself is assigned different flowing pressures in order to simulate the pressure drop down the well as fluids travel from toe to heel. Five different pressure differences or draw downs along the well are defined. The useful parameters that can be captured by the CFD model is the velocity profile of the near wellbore area, mass flow and Pressure profile along well. They made the first use of Computational Fluid Dynamics to model asymmetric formation damage in a horizontal well is presented. Two zones of formation damage were simulated. The mud cake and the filtrate invaded zone and there is damage asymmetry from heel to toe and high to low side together with drawdown differences along the well. Their study shows that the damage asymmetry can yield variations in inflow performance along the well and around the well circumference. So, anomalous high velocity areas can be generated by fixing different drawdown along the well. An overestimation of drawdown can lead to results where clean-up dominates any damage effects.

The second model presented includes the fluid flow in the open horizontal wellbore with full connection to the reservoir. This consistent, harmonic and integrated system enables fluid flow in to the well to be properly analyzed. The low pressure drop along the well leads to a damage distribution dominated system where mass flow is greatest at the toe. Capturing fluid flow in wells and the near wellbore enables quantification of the impact of formation damage and drawdown on well performance.

Additional sensitivities tested in the model they examined the impact of a reduced vertical direction permeability. We used Kv= 0.7Kh (Kv Vertical permeability, Kh Horizontal permeability). The results indicated that in the undamaged well the permeability anisotropy reduced the well mass flow by 17%.

(JR et. al. 2012) also used CFD to study Drilling Fluid Losses in Fractured Reservoirs. They use of Discrete Element Method (DEM) coupled with CFD simulation by using of ANSYS FLUENT® software. In those simulations, it was possible define interesting quantitative information, such as: the pressure difference where particles start to enter into the fracture, the total drilling fluid lost over the operation and the time necessary to fill out the fracture. They suggested that experimental data will be needed to calibrate and validate their models. For this purpose, the development and construction of the fracture flow test rig is very important. It will provide the engineers with detailed experimental results under controlled conditions, adequate to reproduction using the simulation methods.

2.5 Computational Fluid Dynamics (CFD)

2.5.1 What is the CFD

(H K VERSTEEG & W MALALASEKERA1995) Computational fluid dynamics (CFD) is the science of predicting fluid flow, heat transfer, mass transfer, chemical reactions, and related phenomena by solving the mathematical equations which govern these processes using a numerical process.

CFD can be used to simulate fluid, gas, and granular flow phenomena in complex geometries such as pipe, reactor, porous medium, rotating frame, and etc. It has the capability to deal with flows of compressible or incompressible, laminar or turbulent, in-viscid or viscous, etc. Boundary geometry and a two-dimensional or three-dimensional mesh are created by the pre-processor. Then the program imports the generated grid and solves the governing equations using the finite-volume method. Utilization of the CFD has been extended broadly across all industries, and it has been used increasingly in the oil and gas field. The use of CFD gives reliable results without full-scale testing and provides great economic advantages in terms of cost and time.

2.5.2 How does CFD code work

• Analysis begins with a mathematical model of a physical problem.

• Conservation of matter, momentum, and energy must be satisfied throughout the region of interest.

• Fluid properties are modeled empirically.

• Simplifying assumptions are made in order to make the problem tractable.

• Provide appropriate initial and boundary conditions for the problem.

• CFD applies numerical methods (called discretization) to develop approximations of the governing equations of fluid mechanics in the fluid region of interest.

– Governing differential equations: algebraic.

– The collection of cells is called the grid.

– The set of algebraic equations are solved numerically (on a computer) for the flow field variables at each node or cell.

– System of equations is solved simultaneously to provide solution.

• The solution is post-processed to extract quantities of interest.

2.5.3 Element of CFD code:

CFD codes are structured around the numerical algorithms that can tackle fluid flow problems. Hence all codes contain three main elements: a pre-process, a solver and a post-process.

2.5.3.1 Preprocess:

The user activities at the Preprocessing stage involve:

Definition of the geometry of the region of interest grid generation selection of the physical and chemical phenomena, that needs to be modeled definition of fluid properties.

Specification of appropriate boundary condition at cells which coincide with or touch the domain boundary.

The solution of flow problem is defined at node inside each cell. The accuracy of a CFD solution is governed by the number of cell grid. In general the larger number of cells gives more solution accuracy.

2.5.3.2 Solver:

There are three distinct streams of numerical solution techniques: Finite difference, Finite element, Spectral method

In outline the numerical methods that form the basis of the solver perform the following steps:

1. Approximation of the unknown flow variables by means of simple function.
2. Discretization by substitution of the approximation into the governing flow equation and subsequent mathematical manipulation.
3. Solution of algebraic equation.

The main difference between the three separate are associated with the way which the flow variables are approximated and with the discretization process.

- **Finite difference method :**

It describes the unknown's **Φ** of the flow problem by means of point samples at the node point of a grid of co-ordinate lines. Truncated Taylor series expansion is often used to generate finite difference approximations of derivatives of **Φ** in term of point samples of **Φ** at each grid point and its immediate neighbors.

- **Finite element method :**

It uses simple piecewise functions valid on element to describe the local variations of unknown flow variables **Φ**. The governing equation is precisely satisfied by the exact solution **Φ**.

- **Spectral method:**

Approximate the unknowns by means of truncated Fourier series o series of chebyshev polynomials.

Unlike the finite difference or finite element approach the approximations are not local but valid throughout the entire computational domain.

[Rate of change of Φ in the control volume with respect to time] = [net flux of Φ due to convection into the control volume] + [net flux of Φ due to diffusion into the control volume] + [net rate of creation of Φ inside the control volume]

2.5.3.3 Post process:

As in pre-processing a huge amount of development work has recently taken place in the post-processing field. The leading CFD packages are now equipped with versatile data visualization tools. These include:

- Domain geometry and grid display
- Vector plots
- Line and shaded counter plots

- 1D, 2D and 3D surface plots
- 3D volume plots
- Particle tracking
- View manipulation (translation, rotation, scaling etc.) color postscript output

2.5.4 Problem solving with CFD:

In solving fluid flow problems we need to be aware that the underlying physics complex and the results generated by a CFD code are at best as good as physics (and chemistry) embedded in it and at worst as good as its operator.

The use of computational fluid dynamics was another integral component for the completion of this project since it was the main tool of simulation. In general, CFD is a means to accurately predict phenomena in applications such as fluid flow, heat transfer, mass transfer, and chemical reactions. CFD is computer-based and requires users to follow a general protocol in order to obtain simulation results. The first step is to define geometry, followed by creating a series of finite volumes that, altogether, make up the whole of the desired geometry. This pattern of finite volumes (or “elements”) is referred to as a “mesh” and is typically formed using triangular/quadrilateral elements for 2-d applications and hexahedral/tetrahedral/pyramidal/prismatic elements for 3-d applications. The purpose of the mesh is to allow for the discretization of the navier-stokes partial differential equations so that the computer is capable of the computations required. After creating a mesh, boundary conditions and transport properties must be specified as well as any appropriate turbulence models before the user can initialize a solution. Some issues to bear in mind with CFD problems are the need for a fine mesh (small element sizes), the need to attain result convergence prior to analysis, and the need to use appropriate transport and physical properties in the simulation. CFD is a popular tool for solving transport problems because of its ability to give results for problems where no correlations or experimental data exist and also to produce results not possible in a laboratory situation. CFD is also useful for design since it can be directly translated to a physical setup and is cost-effective.

Chapter 3 : Methodology

3.1 Methodology Employed in this Project:

The purpose of this project is to study the effects of reservoir and operational parameters such as formation porosity, permeability and saturation, time and overbalanced pressure, and drilling fluid type on the mud invasion in low-permeability oil formations. To achieve this objective we need to develop unsteady-state three-dimensional multi-phase fluid flow model for mud invasion using CFD. Then validate the simulation model against published data.

3.2 Description of the Problem:

Consider the radius of mud invasion in the low permeability oil bearing formations were predicted in a vertical open hole system. The grid system developed for this study is shown in **Figure 3-1**, **Figure 3-3**, and **Figure 3-5**.

Consider an isotropic homogeneous formation saturated by hydrocarbon. Assumptions for this reservoir model are:

1. Geometry used is define a region around wellbore.
2. To reduce the computation time a drill pipe was not used since the velocity adjacent to the surface of the wall is not different than the case with drill pipe present in the wellbore.
3. Pressure based solver which solves the Navier-Strokes algorithm and physical velocity for the porous formulation are specified.
4. The COMSOL software using CFD models applies the Darcy's law to solve the fluid flow problem in the porous media.
5. Since the radial distance of mud filtrate invasion from the borehole is time-dependent, unsteady state solver was selected for all cases.
6. Negligible capillary forces and gravity.
7. Constant viscosity of fluids.
8. Chemical reactions are not considered.

9. Immiscible fluids.
10. Laminar flow.
11. Negligible cutting effect.
12. Fresh water was used as drilling fluid.

3.3 Simulation cases and geometry:

In this project three cases were studied in three geometries to know the effect of drilling fluid invasion, shown in details below:

3.3.1 2D rectangular geometry

A Rectangle permeable formation was considered with 5ft height and 5ft width. A borehole was located in the corner of the formation at 0ft, show in below figure:

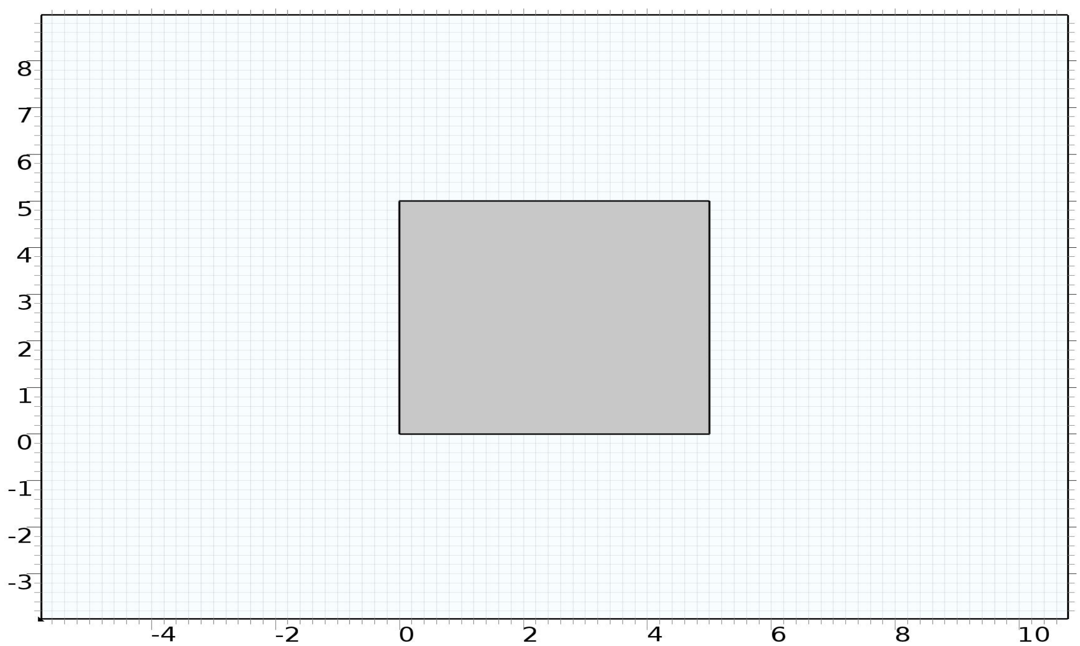

Figure 3-1: 2D rectangular geometry

Grid system used to represent model (mesh):

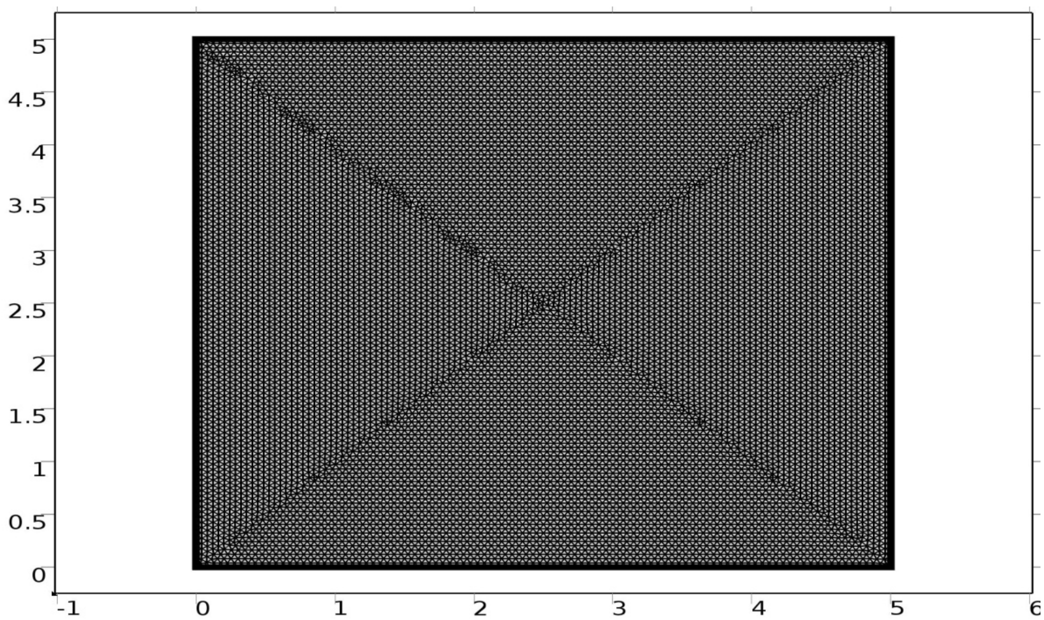

Figure 3-2: 2D rectangular geometry mesh

3.3.2 2D Radial geometry

A circular permeable formation was considered with 5ft diameter. A borehole was located in the center of the formation at 0.3ft radius, show in this figure:

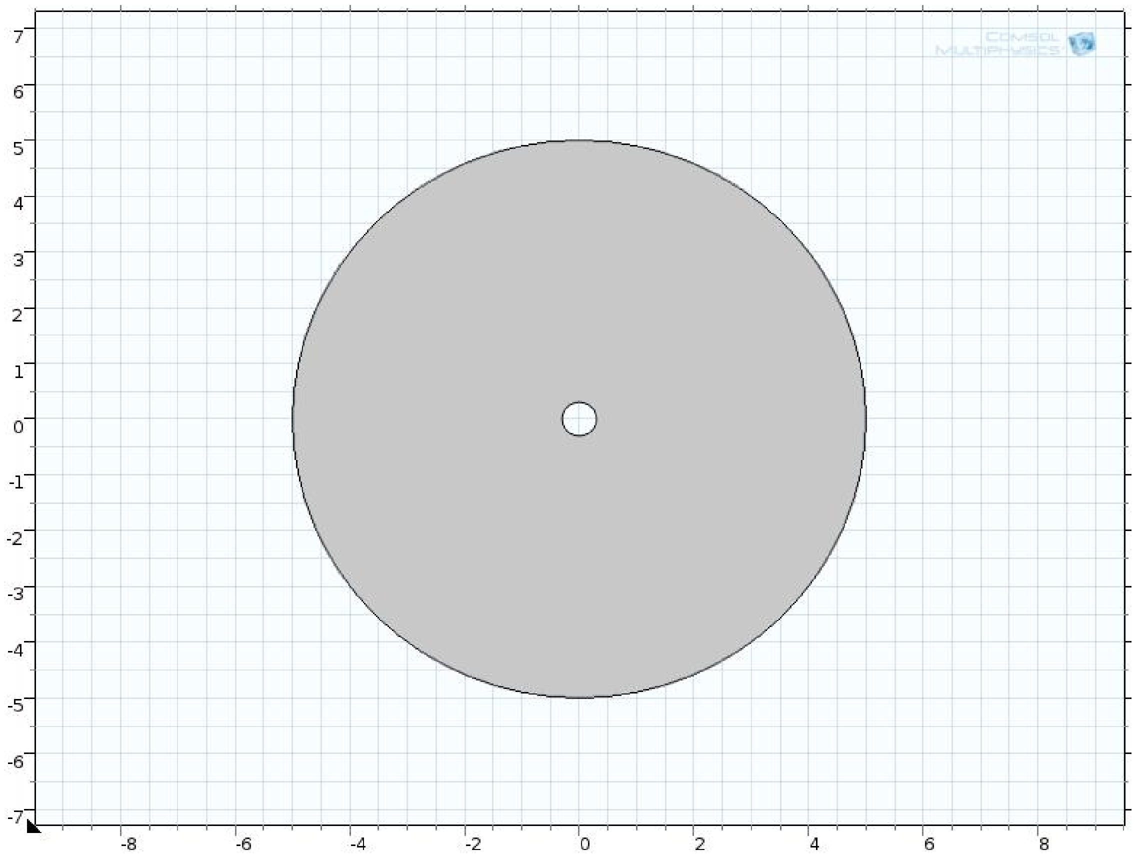

Figure 3-3: 2D Radial geometry mesh

Grid system used to represent model (mesh):

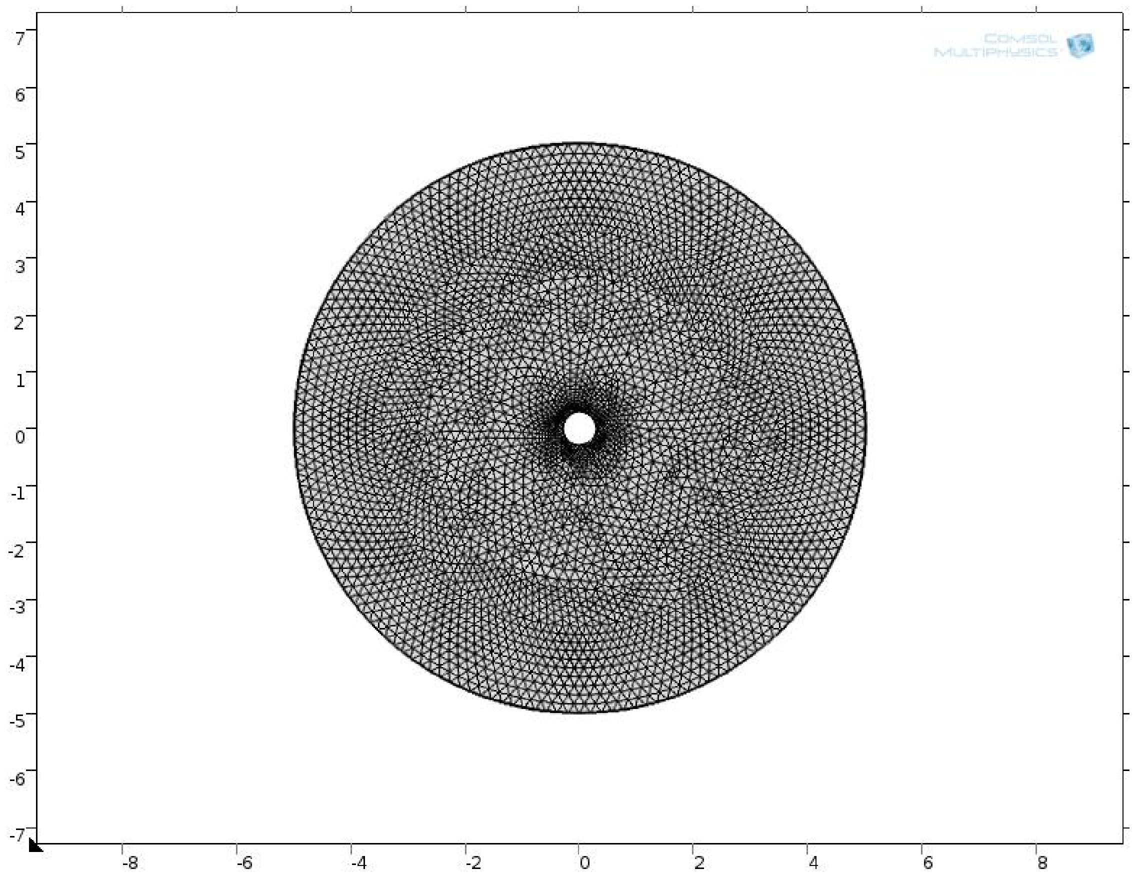

Figure 3-4: 2D Radial geometry

3.3.3 3D cylindrical geometry

A Cylindrical permeable formation of 5 ft height and 10 ft diameter borehole centered with r 0.3 ft. shown in figure below:

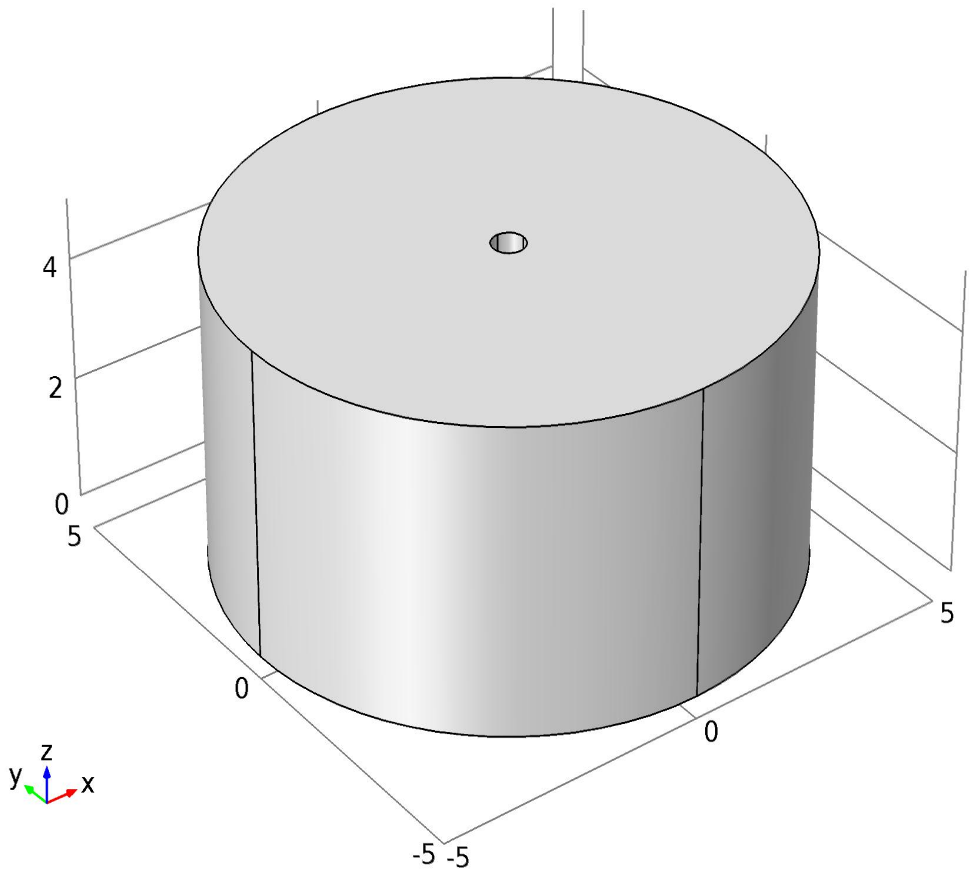

Figure 3-5: 3D cylindrical geometry

Grid system used to represent model (mesh):

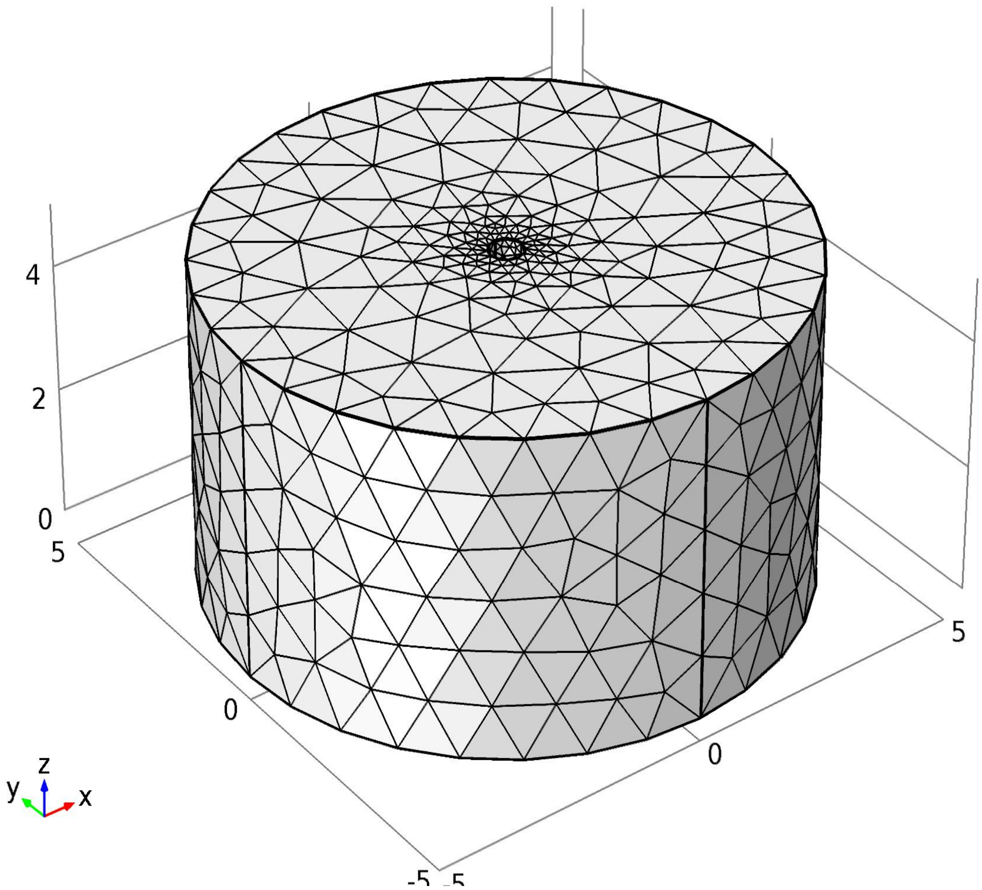

Figure 3-63D Cylindrical geometry mesh

3.4 Two-phase flow model

(COMSOL Multiphysics ®) Darcy's law states that the velocity field is determined by the pressure gradient, the fluid viscosity, and the structure of the porous medium. According to Darcy's law, the velocity field is given by:

$$u = \frac{K}{\mu}\nabla P \ldots\ldots\ldots\ldots\ldots\ldots.. (3\text{-}1)$$

In this equation:

•u (SI unit: m/s) is the Darcy velocity vector

•k (SI unit: m2) is the permeability of the porous medium

•μ (SI unit: Pa.s) is the fluid's dynamic viscosity

•p (SI unit: Pa) is the fluid's pressure, and

•ρ (SI unit: kg/m3) is its density.

Here the permeability, κ, represents the resistance to flow over a representative volume consisting of many solid grains and pores.

The average density and average viscosity are calculated from the fluids properties and the saturation of each fluid

$$1 = S_1 + S_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3\text{-}2)$$

$$\rho = s_1\rho_1 + s_2\rho_2 \ldots\ldots\ldots\ldots\ldots\ldots (3\text{-}3)$$

$$\frac{1}{\mu} = s_1\frac{k_{r1}}{\mu_1} + s_2\frac{k_{r2}}{\mu_2} \ldots\ldots\ldots\ldots\ldots (3\text{-}4)$$

The Two-Phase Darcy's Law interface combines Darcy's law with the continuity equation:

$$\frac{\partial}{\partial t}(\rho\varepsilon_p) + \nabla.(\rho u) = 0 \ldots\ldots\ldots\ldots\ldots\ldots (3\text{-}5)$$

And the transport equation for the fluid content $c_1 = s_1\rho_1$

$$\frac{\partial}{\partial t}(c_1\varepsilon_p) + \nabla.(c_1 u) = \nabla.D_c\nabla c_1 \ldots\ldots\ldots\ldots\ldots (3\text{-}6)$$

Here, ε_p is the porosity, defined as the fraction of the control volume that is occupied by pores, and Dc (SI unit: m2/s) is the capillary diffusion coefficient.

Inserting Darcy's law Eq.(3-1) into the continuity equation Eq.(3-5)produces the generalized governing equation

$$\frac{\partial}{\partial t}(\rho\varepsilon_p) + \nabla.\left[-\frac{k}{\mu}\nabla p\right] = 0 \ldots\ldots\ldots\ldots\ldots\ldots (3\text{-}7)$$

If either of the fluids is compressible, its density must be related to the pressure (for instance using the ideal gas law).

3.5 Model Setup

(S. Won 2008) Predict radius of mud filtrate invasion in permeable oil bearing formation .was predicted in a vertical open hole system. A Cylindrical permeable formation of 5 ft. height and 10 ft. diameter borehole centered with r=0.3 ft.

Applied to general 2D and 3D, tow phase flow equations.

Fresh Water used as drilling fluid.

Applied Darcy's law to solve the fluid flow problem in the porous media.

Formation porosity and permeability: $\emptyset = 7\%$, $k = 0.1$ md

Formation was saturated $S_{oi} = 47.5\%$

Inlet: $p = 2950$ psia for the fluid entering the model at the upstream (bottom). Boundary/formation pressure, $p_i = 2275$ psia.

Chapter 4 : Results and Discussion:

In this chapter we are going to show the results obtained from the software program (COMSOL multiphysics), the results are compared with published data in order to validate the simulation model.

4.1 Model Verification and Validation

Model verification was performed using CFD and the simulated results were compared with published data (Demmelbeck.et.al. 1988)

4.2 Effect of formation porosity:

Figure **4-1**shows the comparison of published and predicted water saturation profiles using the CFD model for formation porosity (7%) at the end of 24 hours. In Figure **4-1**, all data other than formation porosity such as formation permeability and time are kept constant. Figure **4-1**shows that an increase in the value of formation porosity resulted in a decrease in the extent of mud filtrate invasion for both published data and predicted results. When all other parameters were kept constant the volume of formation fluid displaced by the drilling fluids were the same. Thus, increase in void spaces in the porous medium leads to decrease in the diameter of invasion. Further, Figure **4-1**shows the good agreement between reported data and results from the CFD model.

Water saturation in y-axis and distance from wellbore in x axis (feet)

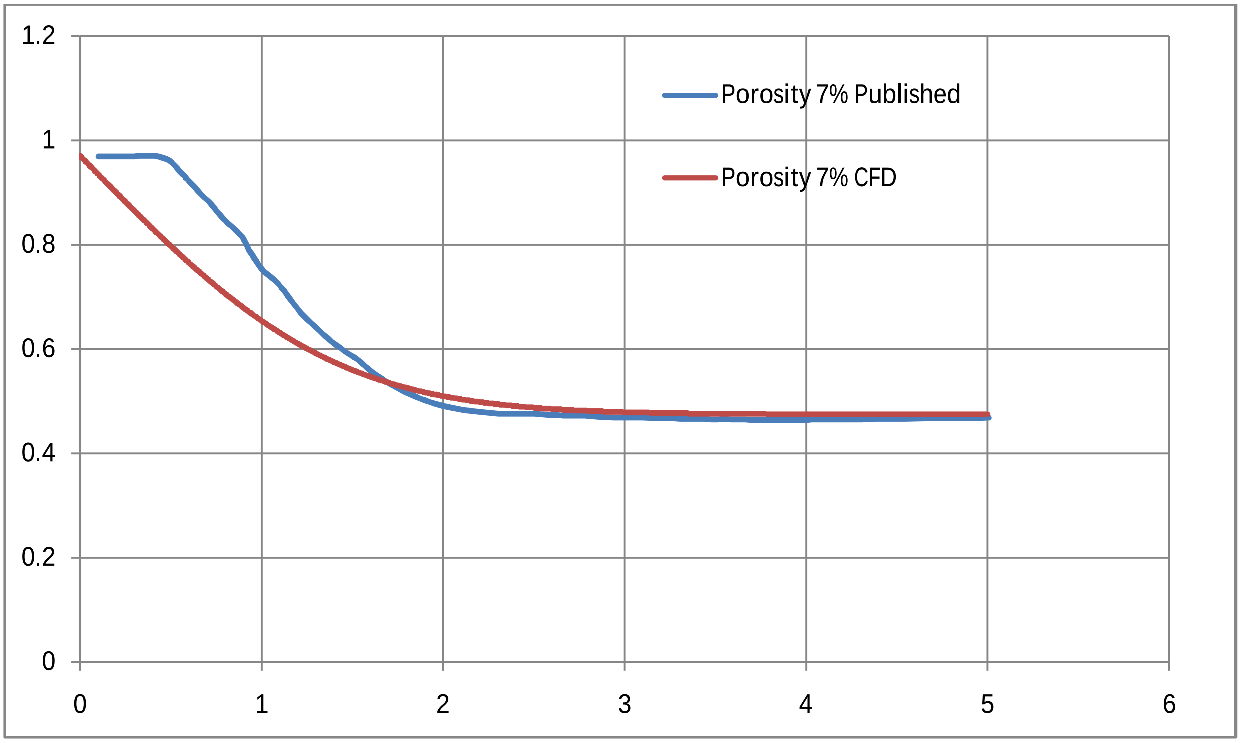

Figure 4-1: Comparison of reported and model predicted water saturation profiles for 7% formation porosity values with 0.1 md permeability after 24 hours.

4.2.1 Model predicted water saturation surface after 24 hours

Several simulations were conducted on formation by using different values of porosity (3.5%, 7%, 14%) with constant permeability (0.1 md) and contact time (24 hours). It has been found that the increase in formation porosity results in a reduction in the invasion profile as shown in figures below.

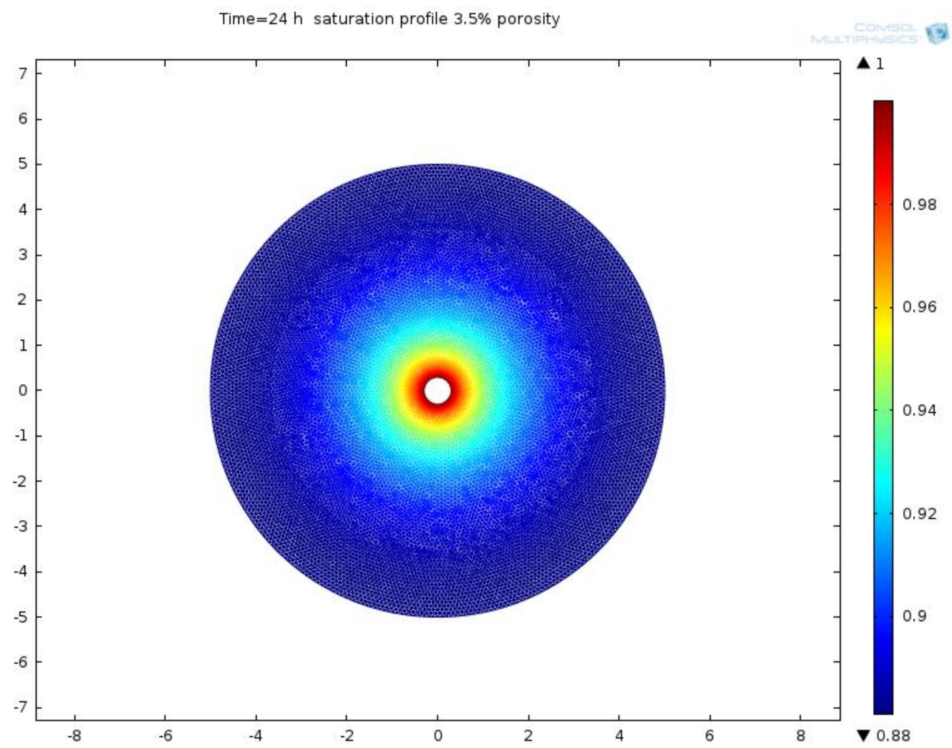

Figure 4-2:Model predicted water saturation surface after 24 hours at 3.5% porosity.

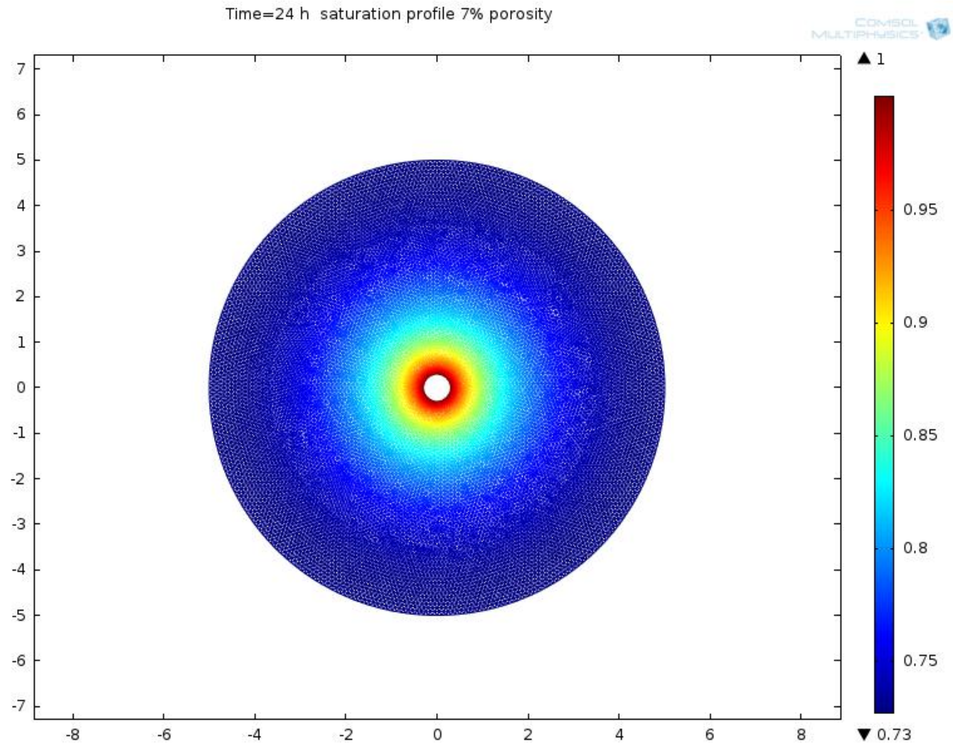

Figure 4-3: Model predicted water saturation surface after 24 hours at 7% porosity.

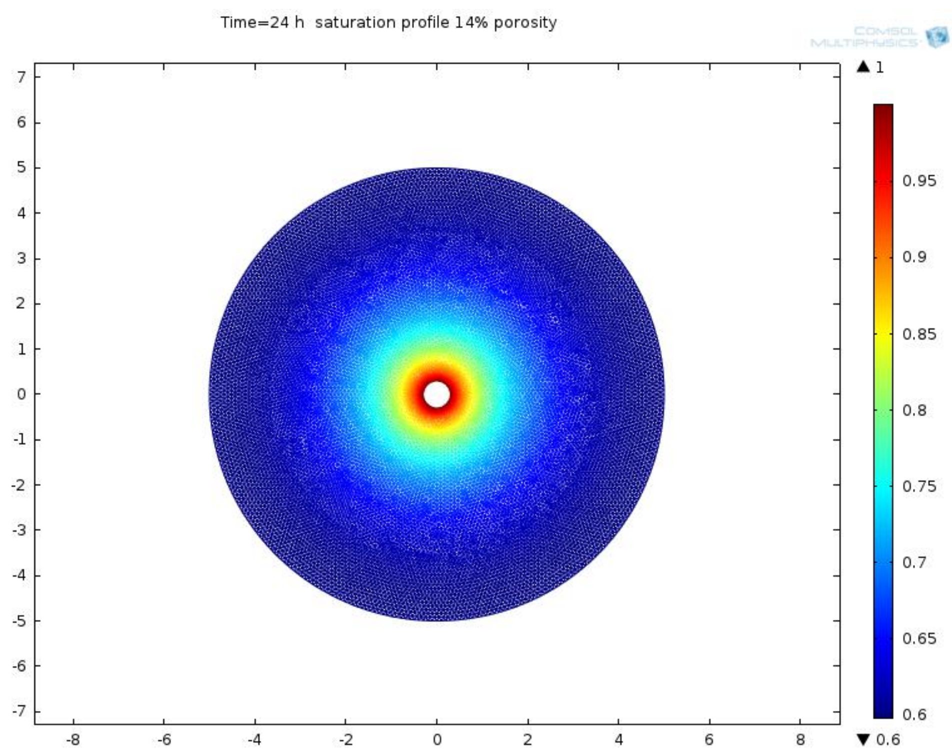

Figure 4-4:Model predicted water saturation surface after 24 hours at 14% porosity.

4.3 Effect of permeability:

The comparison of reported and predicted water saturation profiles for two different values of formation permeability values (0.1 md and 0.01 md) after one day of intrusion are shown in **Figure 4-5** below. It indicates a gentle slope of invasion front for water saturation with increase in slope with decrease in permeability as a result of rapid infiltration of drilling fluids in high permeability formations and also shows the closely agreement of all predicted values with the published data.

Water saturation in y-axis and distance from wellbore in x axis (ft.)

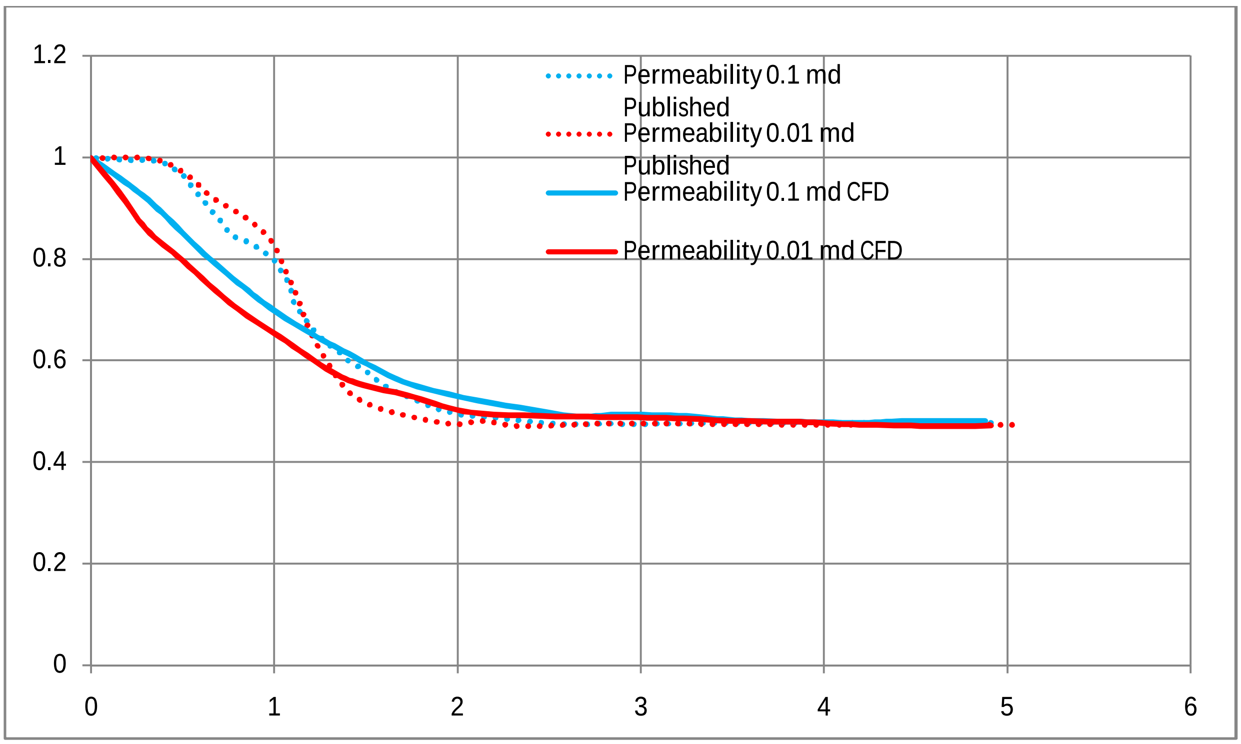

Figure 4-5: Comparison of reported and model predicted water saturation profiles for 7% porosity after 24 hours.

From the comparison between the simulated result using CFD model versus published data in **Figure 4-1**and **Figure 4-5** we noticed that there is small variation refer to the difference in drilling fluid used. Water base mud was used as drilling fluid for experimental study, in this study fresh water was used as drilling fluid to avoid complexity in simulation and reduce computational time. Also the difference between results refers to neglecting the effect of cuttings.

According to the assumption mentioned in chapter three the different in result shown in

Figure **4-6** between our study and (S. Won 2008) study relates to negligibility of many effects and factor that included in (S. Won 2008) simulation.

Water saturation in y-axis and distance from wellbore in x axis (ft.)

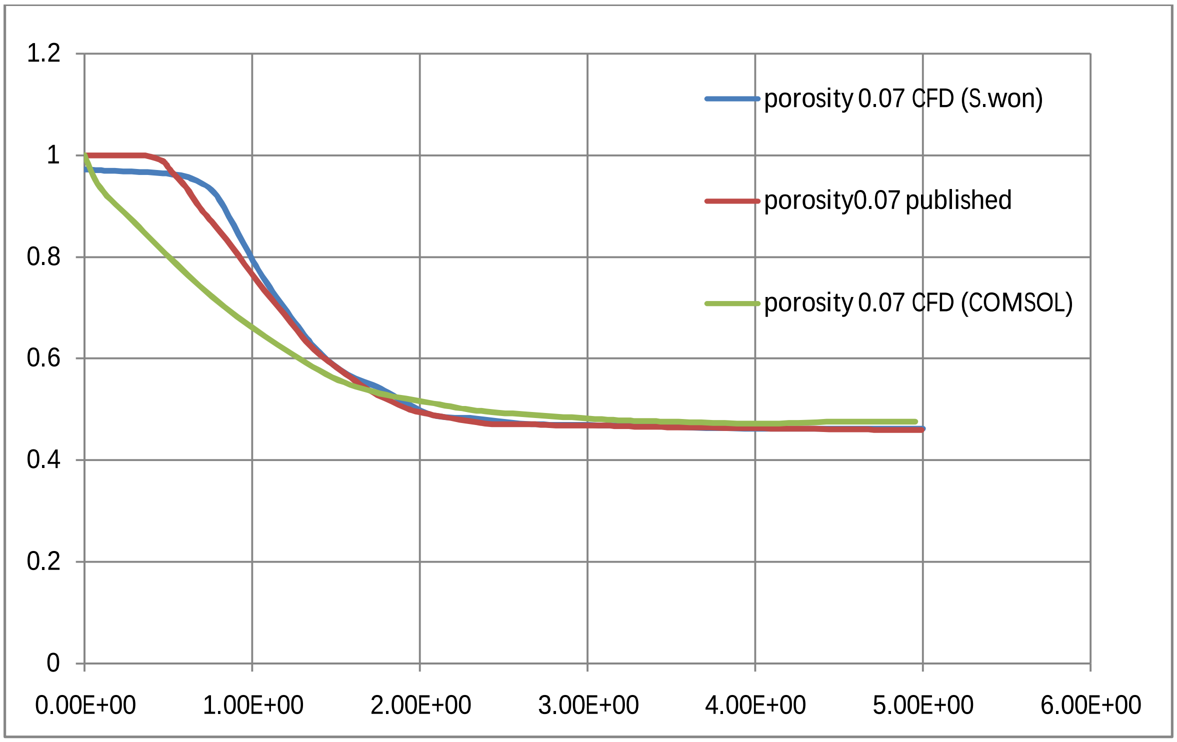

Figure 4-6: comparison between COMSOL CFD result and (S. Won 2008) CFD result with published data

After the CFD simulation results of fluid saturation profile have been validated against published correlations which showed good agreement. This enabled the process of predicting the influence of various parameters on the invasion process, now the model can predict the effects of contact time, pressure and saturation profile.

4.4 Effect of time contact:

The effect of contact time in porosity 7% and low permeability (0.1 md) oil-bearing formation is shown in Figure **4-7** below for three different times. At the end of 24 hours, the filtration of water mud reached approximately 2 feet, and the invasion radius in the reservoir increased at a slower rate as time progressed.

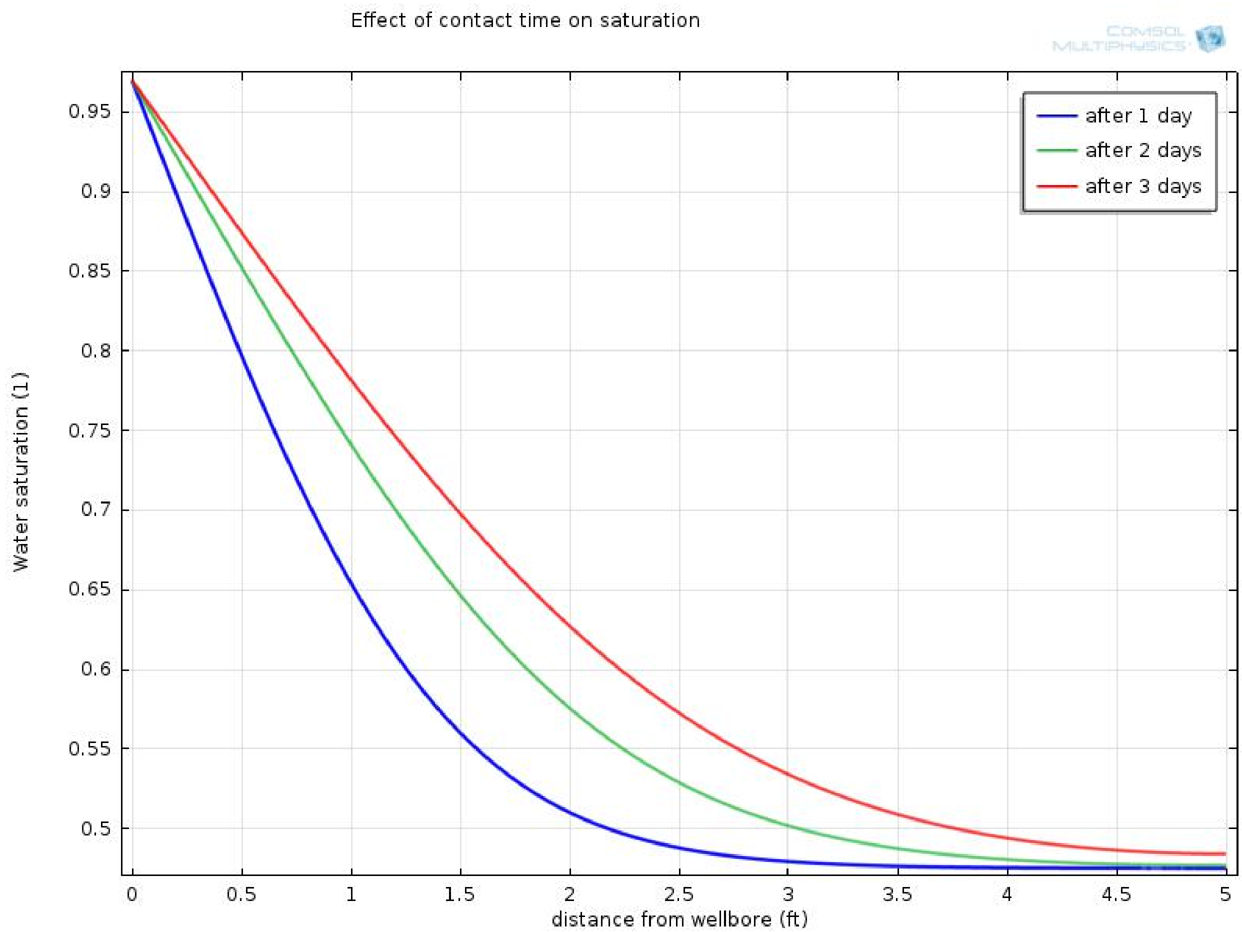

Figure 4-7: Variation of saturation profile with time for 7% porosity and 0.1 md permeability.

The cross-sectional profile of predicted static pressures for 7% porosity and 0.1 md permeability on 3D model is shown in below figure at the end of 24 hours of intrusion.

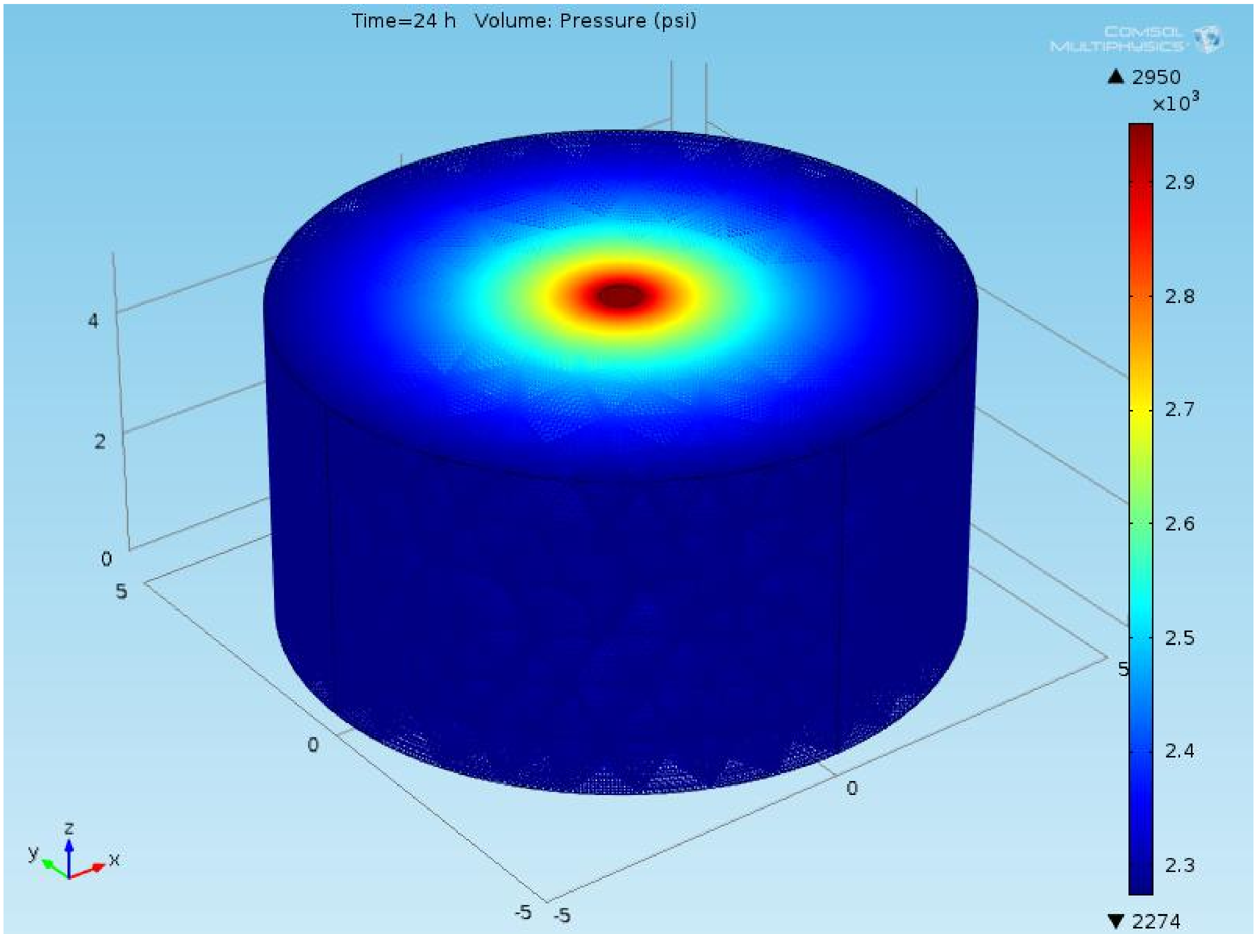

Figure 4-8: Cross-sectional view of model predicted pressure profile for 7% porosity and 0.1 md permeability after 24 hours.

The cross-sectional of predicted saturation profile for 7% porosity and 0.1 md permeability on 3D model is shown in below figure at the end of 24 hours.

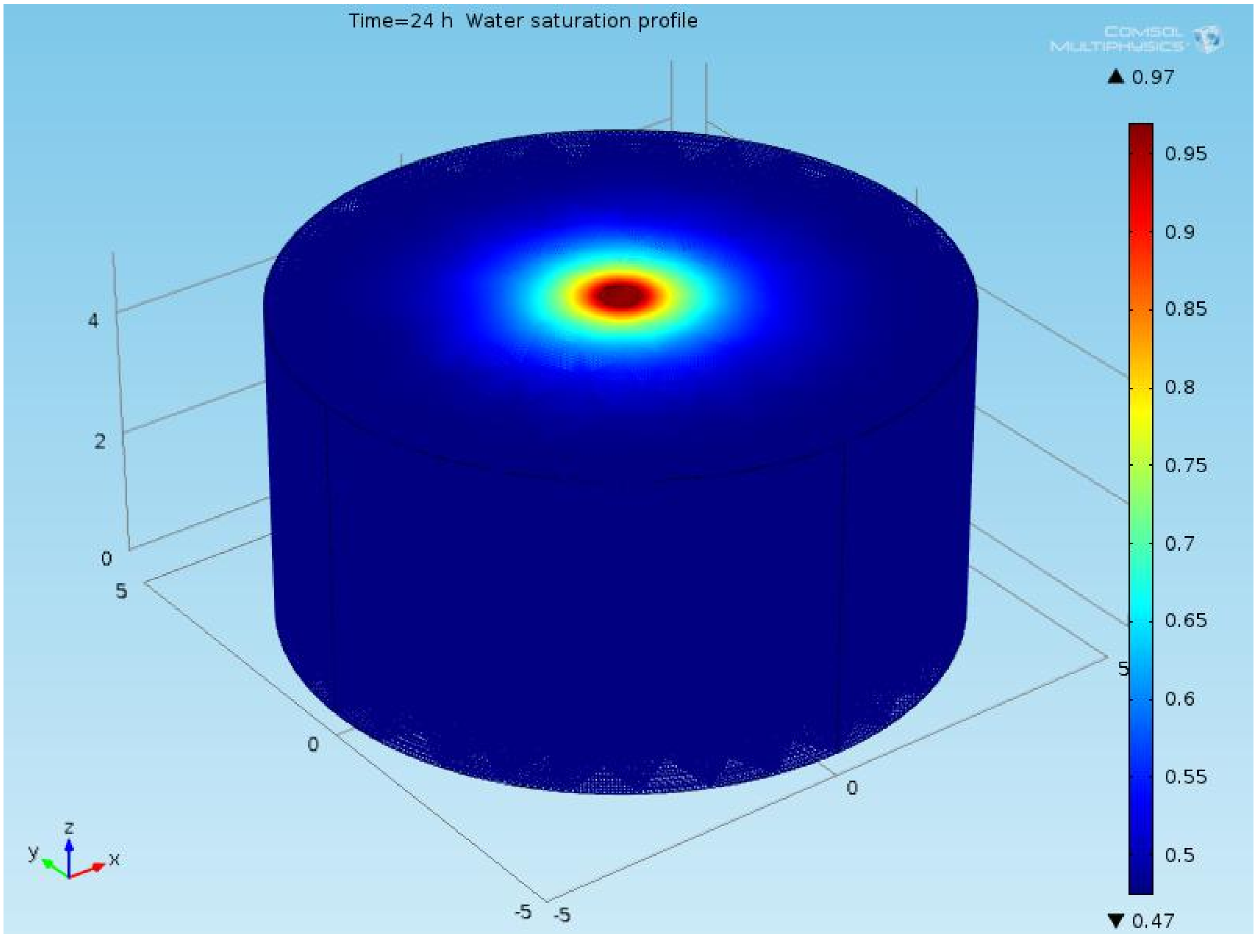

Figure 4-9: Model predicted water saturation after 24 hours.

Chapter 5 Conclusions and recommendations

5.1 Conclusion

In this project, the influences of different formation and operational parameters on mud-filtrate invasion were studied for oil bearing formations using Computational Fluid Dynamics. Based on the results, the following conclusions are presented:

- Deep mud-filtrate invasion can take place even in low-permeability formations.
- The amount and depth of invasion was greatly affected by duration of contact as well as formation porosity and permeability.
- The depth of invasion increased with increase in formation permeability, duration of contact, and pressure gradient between wellbore and formation.
- Increase in formation porosity resulted in decrease in the depth of mud-filtrate penetration.
- A numerical algorithm can be used to predict the depth and extend of invasion of drilling fluids. Hence this approach can provide a useful planning tool for designing drilling fluids.

5.1 Recommendation

First it recommended using CFD models in future studies in petroleum industry operations because of its speed, accuracy, costs are likely to decrease as computers become more powerful, and ability to simulate real conditions.

CFD allows great control over the physical process, and provides the ability to isolate specific phenomena for study.

As concluded, mud invasion simulations involve a large number of parameters and models and due to the limited timeframe and ability of engine many of these parameters have not been investigated in this study. To propose models/settings resulting in better agreement with the experimental data, especially regarding local profiles, a further study could be made on coupling more than one model to obtain more accurate results as well as on the effect of adding other forces of interest. Also could be on a purpose of designing ideal completion or fracturing fluids.

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