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A study of the interplay between capillary and gravitational forces with application to oil recovery in naturally fractured reservoirs

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Preface

Drawn by the low oil recover factor on some naturally fractured reservoir(NFRs), this thesis focus on the role played by driving mechanism in NFRs. Spontaneous imbibition and gravity drainage is the main involving and interplaying mechanism to be considered. Correspondingly, the effects from capillary and gravity force on final recovered oil and producing rate would be discussed under various reservoir conditions. Wettabilities and boundary conditions as well as properties of rock and fluids have been examined and explored numerically. Summaries and conclusions on how the gravity drainage and spontaneous imbibition working independently and interactively with each other has been outlined.

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Chunlei Zhang

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Chunlei.Z.

Summary and Conclusions

Built on literature views and formulation of oil recovery characteristics, three cases of numerical simulation have been performed on core scale which are gravity drainage(GD) individually, capillary pressure driven spontaneous imbibition(SI) only and the interaction of them. Simulations are performed on 1 dimension with different boundary conditions, namely top-opened(TO), bottom-opened(BO) and both-surface-opened(BSO). Following conclusions are drawn from this study:

- Significant oil recovery is obtained from the gravity drainage in absence of capillary pressure,while rate of oil recovering is distinctive for various parameters. Permeability has positive effect to oil recovery rate, while higher oil viscosity and core height lower it.In regarding to wettabilities, strongly water-wet and oil-wet lead to higher recovery rate comparing with neutral wet.

- Spontaneous imbibition is sensitive to wettability and interfacial tension(IFT). Water wettability improve the oil recovery as well as recovery rate,oil wettability harm those. Reduction of interfacial tension would lower the recovery rate, though the final oil recovery is identical for same wettability.

- With the assumption of non-existing capillary pressure,gravity works as enhancer of oil recovery and recovering rate on cases of TO and TSO ,while BO is responsible for the negative aspects of that. For capillary pressure work individually, BSO posses the highest production rate among those, while BO and TO own same imbibition rate. while final oil recovery is not influenced by the boundary conditions.

- The interplay of capillary pressure and gravity force under varying wettabilities and boundary conditions are differential. For boundary condition of top-opened, gravity prompts oil recovery rate at different wettabilities. In contrast, the bottom-opened cases decrease the recovery rate due to downwards gravity. In terms of final oil recovery, wettabilites and boundary condition also the determination factors for that. The final oil recovery is not sensitive to the gravity for the strongly water-wet in case of top-opened. In contrary, bottom-opened condition give rise to negative effect from gravity force, the oil re-

covery is reduced at smaller range of capillary pressure ;while as the water wettability reduce to neutral or even oil-wet, the final oil recovery is enhanced or reduced to some extent,manifestly. Those are determined by the gravity to capillary pressure ratio and boundary condition.

- Scaling time against recovery profile also verify that the conclusion from 'interplay section'. Gravity effects is increased with ratio to capillary pressure, either reducing or improving the oil recovery and recovering rate, meantime or separately, in specific wettability and boundary condition.

Contents

Chapter 1

Introduction

Aroused by the various recovery of Naturally Fractured Reservoir, the relevant deriving mechanism of that has been studied in detail. Gravity drainage(GD) and spontaneous imbibition(SI) are marked as the concentration of this paper. Through the literature view, studies on SI and GD have been highlighted. Realize that relative few studies on the interplay of capillary pressure and gravity force under the different wettabilities. Character of both force working independently or interactively would be examined and summarized with regard to wettability status and boundary conditions. Besides that,how parameters that influence the above mechanisms have been concluded.

1.1 Background

Saidi [29] mention that 25-30% of total oil in-place in Middle Eastern is preserved in the fractured reservoir .Petroleum [28]conduct a statistical survey in terms of oil reserve distribution , 47.7% proven oil reserves is possessed by Middle East. Based on those oil resource contained in fractured reservoir is then range from 11.90- 14.30 % roughly.

Allan et al. [2] conduct a statistics study on around 100 fractured reservoir. With the comparisons of the rock property, they categorize the fractured reservoir into 4 different groups and plot the crossing-plot of oil ultimate recovery regarding to the attributes of matrix and fracture, mainly the porosity and permeability.

1. High storage capacity and obvious less resistance flow in fracture.

2. Matrix stores the oil partly, the fracture transport the oil efficiently.

3. Oil possessed by the matrix mostly and the fracture is still the main flow path.

4. Oil storage and flow is mainly contribute by the matrix while the fracture only improve the permeability.

According to the collecting data, 20% is characterised as the type 3. The ultimate oil recovery of behaviour of it are more scattered[Fig 1.1].The distribution of oil recovery draw our attentions on studying the underlying mechanism which control the recovery. With the fundamental understanding of that, the improved oil recovery methods could be applied to such category.

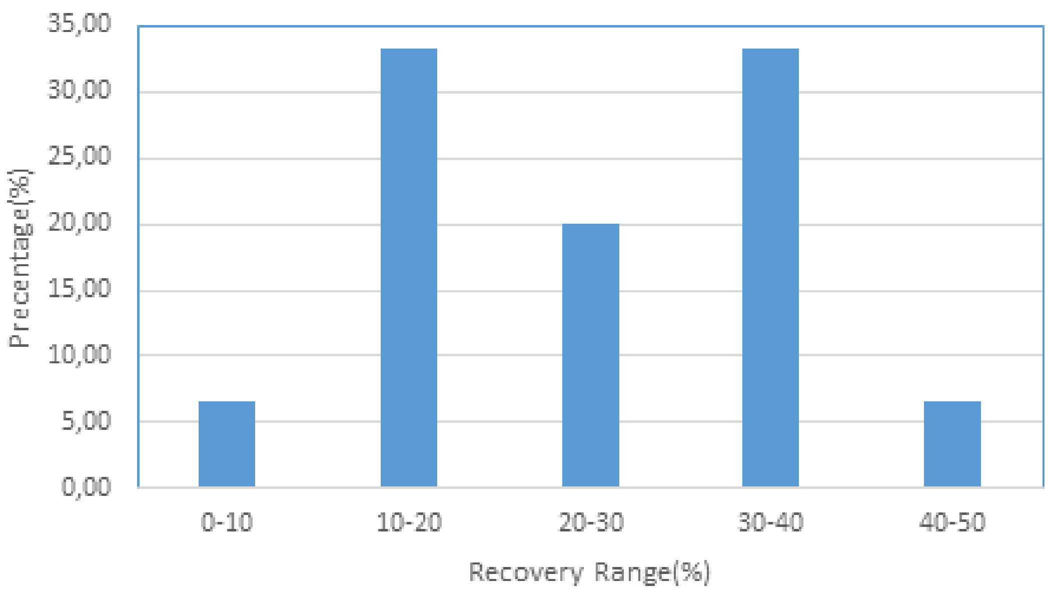


Figure 1.1: Distribution of ultimate recovery factor for Type III fractured oil reservoirs

Problem Formulation

Regarding the researches on driving mechanisms, there are two different stages, nature depletion and furthermore improving oil recovery stage.During the primary recovery section, Firoozabadi et al. [13]states that the expansion of the fractured rock and fluid is the initial and key deriving mechanism of production. The oil recovery of this step would be mainly depended on the magnitude of total compressibility coefficient of the reservoir. Once the depletion pressure reach under the saturation pressure, the solution gas drive would take control of that. Lemonnier and Bourbiaux [21] mentioned that gas solution drive is treated as ineffective recovery process for fractured reservoir regularly. One of the exception is tight, viscous and oil-wet reservoir where the mechanism is controlled by the spontaneous imbibition and gravity drainage is almost negligible.

Generally, water flooding is the most worldly applicable injection option for improved recovery methods. Bourbiaux et al. [7]point out that three main mechanisms would be involved in water displacement, namely 1) spontaneous imbibition; 2) viscous displacement under the pressure gradient generated by fracture flows; 3) gravity effects due to the water-oil density difference. Experimental studies have testified that spontaneous immbibition is the principal mechanism determined the recovery factor provided the water-wet condition, while for intermediated wet to oil wet, the oil recovery also relies on roles played by other mechanisms.

Therefore, it is crucial to understand how the interaction of different mechanism related to the characteristics of reservoir.This paper would address some basic concern on how the GD and SI interplay with each other in various reservoir conditions.

1.2 Objectives

Through this work, the role played by the gravity and capillary force would be inspected on core scale while water imbibes into the matrix spontaneously. Govern parameters of GD and SI would be explored and drawn out. To be more specific, the following questions would be discussed and addressed as the main topic.

1. The influential parameters to the GD process would be examined by assumption of without attendance of the capillary pressure. Core height, absolute permeability , wettability,viscosity of oil are the involved ones.

2. The characters of SI process without the gravity force and controlling factors of that,for example, interfacial tension and wettability.

3. Influences of boundary conditions to GD or SI,separately and assumed only one of force existed.

4. On the section of interacting of GD and SI, wettability, boundary condition,as well as IFT would be examined on how they influence the interaction of capillary pressure and gravity force.

1.3 Limitations

In literature view , the effects of wettability to the gravity drainage has not been deeply explored. Another important assumption during the numerical study is that same initial water saturation have been assumed for different wettabilities, which is one of important factors that influence the oil recovery and rate of imbibition[4].Additionally,relative permeability function has been assumed to be stable for varying interfacial tension,though studies have shown that relative permeabilities change with decreasing IFT[18]. Meanwhile, when computing the $R_c g$, which is gravity to capillary ratio, the magnitude of $J^{'}|_{S_w=S_w^*}$ is hard to determine accurately; but the applicable number used in this thesis does show the relative trend of that.Finally, the scaling time show disturb profile in case of TSO[Fig4.23], the reason is not clarified about yet, but it does show the generally trend ,correctly.

1.4 Approach

Based on the objective of this work, the implement could be initiate as question setting as the core immersed into the water completely. Firstly the construction of water and oil mass balance equation would be build. Then dimensionlize height term and time term with assistant of scaling operation. Powered by the IORCoresim developed by IRIS, the simulation cases are run to explore the role played by the gravity and capillary force. First, The GD process would be simulated without the attendance of capillary pressure. Parameters, such as core height,oil viscosity,peremeability and wettability, would be main parameters to examine. For example, when exploring the relationship between the oil recovery character and peremeability, other parameters would be fixed, only the permeability would vary in some range.Then this rule applies to other simulation cases. Then the case of without gravity, the spontaneous imbibtion process would run for two main factors, wettability and IFT. Finally, the interplay of gravity and capillary, boundary condition, wettability and IFT are the key factors that running for the simulation.

The role played by the capillary pressure or gravity force is determined by comparing with the cases with and without one of them .For example, when we try to analyse the role of gravity in top-opened boundary condition, the cases of with and without gravity would be compared with in same wettability settings.

1.5 Structure of the Report

Literature view would be presented as the Chapter 2. SI due to capillary pressure and DG due to gravity force would be the starter. Then previous research on the parameters which affect the SI and DG would be discussed as well as the time-scaling formulation.

Chapter 3 would focus on the building the mathematical modelling and scaling. The question settings, the assumption, initial and boundary condition, are introduced. 1D case scaling equation be proposed as considering the gravity and capillary force.

Chapter 4 Numerical study on GD or/and SI cases are presented this chapter. Wettabilities, IFT and boundary conditions as well as the properties of fluid and rock are the main discussing parameters which can determine the role played by gravity force and capillary pressure to GD or/and SI mechanism.

Chapter 5 conclusions and further study recommendation would be summarize, in regarding to gravity drainage and/or spontaneous imbibition.

Chapter 2

Literature Survey

2.1 Introduction to SI and GD

In the process of spontaneous imbibition (SI), wet fluid displaces non-wetting resident fluid. While the drainage process is the non-wetting phase compelling the wetting phase out[4]. The main driving force involved are gravity and capillary force[7].Capillary pressure is given by Laplace's equation[12] and Leverett et al. [22] define it empirically.

$$P_c = P_o - P_w = \sigma(\frac{1}{r_1} + \frac{1}{r_2}) \tag{2.1}$$

$$P_c = J(S_w)\sigma(\frac{\phi}{k})^{\frac{1}{2}} \tag{2.2}$$

In whichP_c is the capillary pressure, P_o and P_w are separately oil and water pressure in contact surface;σ is the interfacial tension(IFT),$J(S_w)$ is the J function which is characterise the capillary pressure to water saturation,S_w, ratio for specific rock with constant porosity,ϕ and permeability,K. With the assistant of it, capillary pressure could be computed for various water saturation,wettabilities[22].

Hammond and Unsal [16]describe deriving force of spontaneous imbibition is the capillary pressure. Anderson et al. [4] summarize that parameter which could influence the capillary pressure are including wettability,pore structure,and saturation history. .Permeability of the rock, the viscosity of the imbibing and displaced fluids, and the initial water and oil saturation of the rock and IFT [19], to some extent , affect the spontaneous imbibition behavior.

Hagoort et al. [15] state that gravity drainage(GD) is a recovery process in which gravity acts as the main driving force and where gas replaces the voidage volume. While for the water displacing oil case,other parameters than density difference, such as rock permeability and boundary condition, also to some extend influence the gravity drainage[15] .

2.2 Spontaneous imbibition

Considering the role of capillary pressure on spontaneous imbibition process, the previous studies on this topic would be reviewed. According to the formulation of the capillary pressure , wettability and IFT would be the main parameters to examine the variation of SI process.Wettability is demonstrated as the vital factor of determining the oil recovery behaviour. It is stated that the oil recovery is higher as the water wettability improved. Reduced IFT can slow the oil recovery rate but without influence to the final oil recovery in negligible gravity cases. The effects of boundary condition to spontaneous imbibion would be also discussed in this section.

Wettability

[3]In regard to the characteristics of the wettability, the Amott Wettability is defined as the ratio of saturation change by spontaneous imbibition, $\Delta S_i m, w$, to the total saturation change by both spontaneous imbibition and forced displacement, $\Delta S_w f$. The Amotte wettability index to water, I_w, can then be expressed as

$$I_w = \frac{\Delta S_{im}, w}{\Delta S_{im}, w + \Delta S_{wf}} \tag{2.3}$$

Similarly,the Amott wettability index to oil I_o is defined as

$$I_w = \frac{\Delta S_{im}, o}{\Delta S_{im}, o + \Delta S_{of}} \tag{2.4}$$

The difference between I_w and I_o define the Amott-Hrvey wettability index. For water-wet, it is range from 0.3 to 1.0. In case of the neutral wet, it is varying from -0.3 to 0.3. In terms of the oil-wet, the minimum Amott-Hrvey index is -1.0 and maximum is -0.3[3].

Zhou et al. [39] perform a series experiment study of spontaneous imbibition and drainage process with various wettabilities but similar porosity and peremeability of Berea Sandstone. Different wettability rock samples are obtained by range of aging time. The Amott Wettability Index are varying from 0.23 to 0.84, i.e passing from oil-wet until water-wet. The relationship between the wettability are summarized as that the rate of the SI is highly sensitive to the wettability.The ultimate oil recovery reach an peak an very strongly water-wet condition and decrease with the reducing water wetness[Fig 2.1].

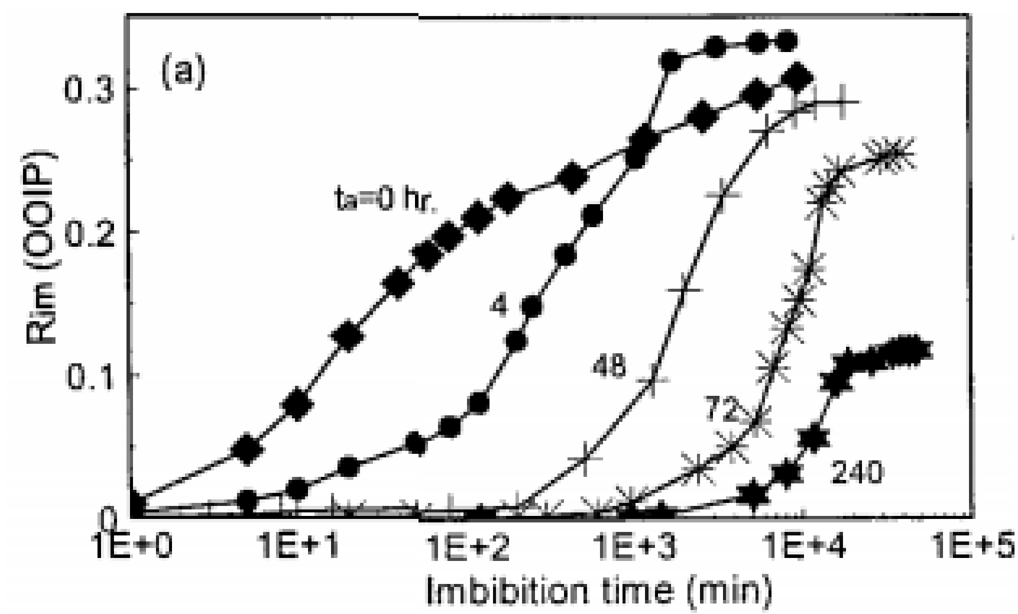


Figure 2.1: Oil recover by imbition vs imbibition with different aging time[39];final oil recover is positive to the water wetness

Hamon et al. [17] present experimental study on various wettabilities pores and conclude that strongly water-wet sample gives higher oil recovery generally.It is confirmed by Chen et al. [8] who conduct an SI experiment study on oil-wet and water-wet sample. It also shows that oil recovery is related to the index of water wettability[8].

Austad et al. [5]conduct experimental study on the imbibition process undergoing with different wettability of total-open rock sample. For the case of the oil-wet, there is no noticeable oil emerged within 14 days. Even though, only 10 % of oil has cumulated after 83 days. It could be explained by the literature survey on relation of capillary pressure and wettability accomplished by Anderson et al. [4], which is that there is no imbibition process happening under certain contact angle.When the surfactant solve added into the imbibing water, the oil produced exponentially growing and approaching to 65% in 10 days[5].

Austad et al. [5] explain that the enhanced imbibition rate is due to the surfactant modifying the wettability condition towards to water-wet.Hammond and Unsal [16] states that the surfactant solutions might enable the spontaneous imbibition processing through their effect on the modification of contact angle.

IFT

Another effect of the surfactant is that the capillary pressure be lowered by reducing IFT. Mathematically, [30] higher IFT,σ,associated with oil/water introduce a correspondingly high capillary pressure which, in turn, provides bigger driving force for spontaneous imbibition into matrix blocks.While the 1FT is reduced, the time required to recover a given fraction of the oil increases under the condition of capillary-dominated[30].

Cuiec et al. [9] perform experimental studies on outcrop chalk samples at variable IFT. He observe that reducing 1FT result in a decrease of imbibition rates but without changing the final oil recovery.

Boundary effect

Bourbiaux et al. [7]conduct an experimental and simulation study by using the good homogeneity of water-wet core sample. They observed that cocurrent production rate is much higher than countercurrent imbibition, although the ultimate oil recovery of that is slight bigger than the countercurrent case.

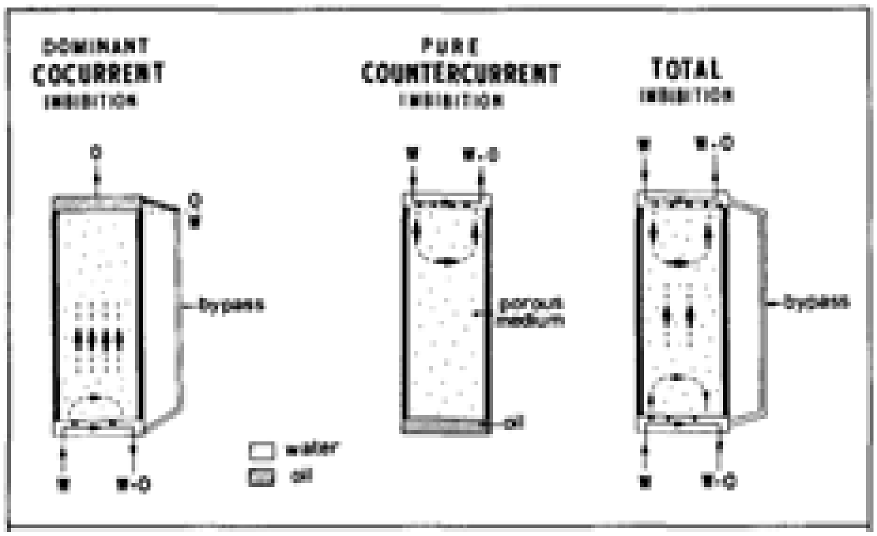


Figure 2.2: Diagram for the countercurrent and cocurrent imbibition[7]

Cuiec et al. [9] discuss the influence of the one-opened and two-opened sample to the oil recovery rate. It is doubled for the case of latter than the former because independent countercurrent occurs at the both opened-side instead of one-sided opened case. The difference of the one-side opened case to the cocurrent imbibition [7] is that the opposite side of opened side is sealed from contact of oil which is the boundary condition of latter.

2.3 Gravity drainage

In this section, the studys on gravity drainage(GD) would be reviewed. Dake [10] mention it is a vertical displacement of water/oil due to the density difference. Zendehboudi et al. [37] gives the formulation of the gravity drainage time scaling:

$$t^{'} = \frac{tK\Delta\rho g}{\mu_o H} \tag{2.5}$$

where $t^{'}$ is the dimensionless time. This section would review the study on the relevant parameters.Such as height and permeability as well as the viscosity, would be the main reviewing parameters.

Height

Hamon et al. [17] conduct experimental study to determine the effects of height in oil recovery. The rock sample is strongly water-wet. They observed that the shorter the sample, the faster oil recovery.

Permeability

Adibhatla et al. [1] perform experiment study on the surfactant-aid gravity drainage process and conclude that the rate of oil recovery is decreasing with the reduced core permeability. Zendehboudi et al. [37] also observe the similar result by conducting the experiment study.Hagoort et al. [15] states that the shape of oil relative permeability is one of vital factors to final oil recovery.

Viscosity

Zendehboudi et al. [37] design the free-fall gravity drainage and conclude that the lower viscosity of fluid prompt the drainage rate, the final oil recovery is same for different viscosity,approximately.

2.4 Interplay of gravity drainage and spontaneous imbibition

In water wet condition, Schechter et al. [30] design an experiment on the effects of IFT to the gravity drainage and spontaneous imbibition for varying permeabilities. As for the boundary condition,the sample is totally immersed into the water. The results show that oil recovery is increased at lower IFT, though the oil recovery rate is slowing down. They explain that higher permeability and lower IFT could enable the gravity force to overcome the capillary pressure. Besides that, they proposed three different regime of imbibiton: capillary-dominated, gravity-dominated and transition period. Moreover, they argue that the magnitude of IFT to reach the gravity dominate is also determined by the matrix permeability. Cuiec et al. [9] also observe the similar result that reducing the 1FT causes a decrease of imbibition rates but improve the final oil recovery.

For oil-wet condition, Adibhatla et al. [1] perform an experimental study about the effects of surfactant on the oil-wet sample. The IFT has been reduced to the range of 10^{-2}, the capillary pressure is reduced significantly. oil recovery is improved, they states that the improvement of that is due to gravity drainage. While for higher IFT at oil-wet setting,Morrow et al. [27] mention that with the negative capillary pressure override the gravity, the spontaneous imbibition would not be triggered.

In order to understand the interplay of gravity force and capillary pressure,Schechter et al. [31] introduce inverse Bond number N_B^{-1} :

$$N_B^{-1} = C_t \frac{\sqrt{\frac{\phi}{K}}\sigma}{\Delta \rho g L} \tag{2.6}$$

in which, C_t is the convection factor of units. They also conclude that the corresponding value for capillary and gravity dominated as well as intermediate cases. $N_B^{-1} << 1$ or $N_B^{-1} >> 5$ are separate representative for the gravity and capillary dominance, while other value indicates that the gravity and capillary are both the important factors affecting imbibition process.

Other factors

Regarding the relation between the geometry structure and the capillary pressure,Mohanty et al. [26]build an network model for simulating the multi-phase transport through porous media. The model combine the structure of the medium, pore level fluid displacement mechanisms, and saturation history to calculate new pore-level distributions of fluids. Then conclude that capillary pressure is determined by the pore body radii. Besides, the wider radius distribution, the lager body -to-throat aspect ratio and higher initial non-wetting saturation conduct the greater non-wetting residual saturation.

2.5 Scaling rule

Schmid and Geiger [32] mention that scaling groups are essential in any context where SI needs to be understood. Besides that it is also used to characterize the influence of key parameters on SI. Mattax et al. [24] proposal a scaling equation with the assumption of that: (1) the sample shapes and boundary conditions are identical; (2) the oil/water viscosity ratio is duplicated; (3) gravity effects can be neglected; (4) initial fluid distributions are duplicated; (5) the capillary pressure functions are directly proportional; and (6) the relative permeability functions are the same. Their equation is expressed as

$$t^{'} = C_t \sqrt{\frac{k}{\phi}} \frac{\sigma}{\mu_w L^2} \tag{2.7}$$

in where μ_w is the water viscosity. To compensate the influence of the boundary condition and the shapes of the matrix, Kazemi et al. [20] introduced the concept of the shape factor F_s:

$$F_s = \frac{1}{V_{ma}} \sum \frac{A_{ma}}{D_{ma}} \tag{2.8}$$

in where, A_{ma} is the opened surface area of matrix sample; D_{ma} is the diameter of the surface.

Corresponding to that, the characteristics length,L_c, is defined as

$$L_c = \sqrt{\frac{1}{F_s}} \tag{2.9}$$

Ma et al. [23] modified the scaling time based on the no-flow boundary during the counter-current imbibition process.

$$t^{'} = C_t \sqrt{\frac{k}{\phi}} \frac{\sigma}{\mu_w L_c^2} \tag{2.10}$$

in which, L_c is defined the distance between the flow surface and the imbibition boundary and computed as

$$L_c = \sqrt{\frac{V_b}{\sum \frac{A_b}{L_{ci}}}} \tag{2.11}$$

in where, V_b and A_b are the bulk volume and surface area, separately. Hamon et al. [17] conclude that neglecting the sample heterogeneity can lead to erroneous recovery rate predictions. Usual "scaling laws" do not take into account the effect of the core heterogeneity.

Shouxiang et al. [33] consider the effect of viscosity ratio between the wetting and non-wetting phase during the imbibition process and propose an modifying scaling group Eq.2.12.

$$t' = C_t \sqrt{\frac{k}{\phi}} \frac{\sigma}{\sqrt{\mu_w \mu_o}} \frac{1}{L_c^2} \tag{2.12}$$

Zhou et al. [38] derive a time scaling by considering the effects of the viscosity. The corresponding dimensionless time express as Eq.2.13

$$t' = t \sqrt{\frac{k}{\phi}} \frac{\sigma}{L_c^2} \sqrt{\lambda_{rw}^* \lambda_{nw}^*} \frac{1}{\sqrt{M^*} + \frac{1}{\sqrt{M*}}} \tag{2.13}$$

where λ_r^* represent the characteristics mobility for the wetting and non-wetting phase and M^* is the corresponding mobility ratio.

Above all, the scaling group mentioned is mainly focused on the water-wet condition ,the gravity effects on the spontaneous imbibition has been neglected.

Morrow et al. [27] discuss the gravity effect on the condition of weakly water wet and propose the representative scaling group include the gravity effect[Eq.2.14].

$$t'(c+g) = t \frac{K/\phi}{L_c^2 \sqrt{\mu_w \mu_o}} (P_c f(\Theta) + \frac{\Delta \rho g L_c^2}{H}) \tag{2.14}$$

where $t'(c+g)$ is the dimensionless time for imbibition that contains capillary and gravity force,P_c is the representative imbibition capillary pressure, $f(\Theta)$ is a wettability factor and H is the vertical height of sample.

Standnes [34] scale the time group from solution of Washburn equation[14].

$$t' = 1 + W(-e^{-1-t\sqrt{\frac{K}{2\phi}} \frac{\sigma}{\mu_g L_c^2}}) \tag{2.15}$$

In which,W(x) is Lambert's W function expressed by inverse exponential function:

$$x = W(x) e^{(W(x))} \tag{2.16}$$

Schmid and Geiger [32] derive the normalized volume scaling group from analytical solution of countercurrent spontaneous imbibition. It is also applicable for case include the gravity and capillary force.

$$t^{'} = (\frac{2A}{\phi L_c})^2 \tag{2.17}$$

2.6 What Remains to be Done?

With the intensive study on the spontaneous imbibition process on the strongly water-wet condition, the parameters that influence the interaction of gravity force and capillary pressure,for example, IFT and permeability, have been discussed. The inverse Bond number gives a quantifying criteria for determining the whether gravity or capillary dominant conditions.In case of oil wettability, most of the experimental studies are on the effects of the surfactant. The significant role played by the gravity drainage has been experimentally testified.

However, there is few paper focus on the interplay relationship between the gravity force and capillary pressure with various boundary condition. Besides that, the inverse Bond number criteria for the determination of dominance of gravity and capillary does not contain the parameter reflecting the wettabiity status.

Therefore, this paper would focus on the gravity effects on different boundary settings as well as the gravity effects on different wettabilities and proposal the criteria for inspecting the dominance mechanism.

Chapter 3

Theoretical Review

3.1 Mass balance equation

Considering the 1D2Phase spontaneous imbibition and gravity drainage process, the illustration could be shown as following (Fig 3.1).The conservation of water volume without convection(no internal sink or source) could be formulated as B.16[11]. The derivation of it is shown by Appendix.

$$\phi\frac{\partial(S_w)}{\partial t}+\frac{\partial}{\partial x}[K\frac{\lambda_w\lambda_o}{\lambda_T}(\frac{\partial p_c}{\partial x}-(\rho_w-\rho_o)g)]=0 \tag{3.1}$$

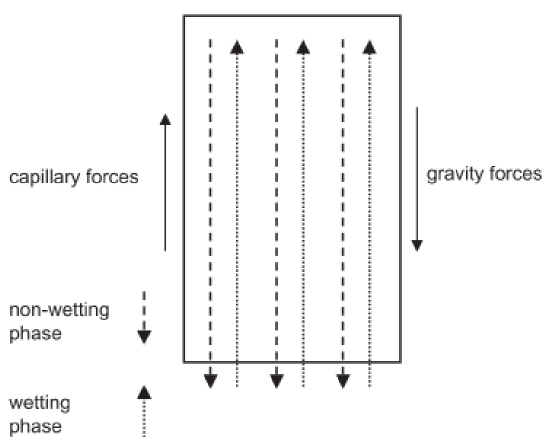


Figure 3.1: Illustration of spontaneous imbibition and gravity drainage process[35]

3.2 Scaling time and length

Introduce the dimensionless length and time

$$x^{'} = \frac{x}{L} \tag{3.2}$$

$$t^{'} = \frac{t}{\tau} \tag{3.3}$$

Then

$$\frac{\partial}{\partial x} = \frac{\partial}{\partial x^{'}}\frac{1}{L} \tag{3.4}$$

$$\frac{\partial}{\partial t} = \frac{\partial}{\partial t^{'}}\frac{1}{\tau} \tag{3.5}$$

From now on until Equ 3.11 , the derivation is based on the work of Tavassoli et al. [35]. The difference is the way of computing the dimensionless time τ.

Substitute Equ3.4 and Equ3.5 as well as Equ2.2 into equB.16 and rearrange it

$$\frac{\partial S_w}{\partial t^{'}} + \frac{\tau K}{L^2\phi}\frac{\partial}{\partial x^{'}}(\frac{\lambda_o\lambda_w}{\lambda_T}[J^{'}\sigma\sqrt{\frac{\phi}{K}}\frac{\partial S_w}{\partial x^{'}} - (\rho_w - \rho_o)gL]) = 0 \tag{3.6}$$

Mirzaei-Paiaman et al. [25] state that Equ3.6 is a highly non-linear and no exact solution has been proposed;while the approximation solution can be integrated from 0 to 1with respect $x^{'}$.

$$\frac{\partial \overline{S_w}}{\partial t^{'}} = \frac{K\tau J^{'}}{L^2\phi}\frac{\partial}{\partial x^{'}}(\frac{\lambda_o\lambda_w}{\lambda_T}[\sigma\sqrt{\frac{\phi}{K}}\frac{\partial S_w}{\partial x^{'}} - (\rho_w - \rho_o)gL])_{x^{'}=1}^{x^{'}=0} \tag{3.7}$$

Rearrange the Equ 3.7 and get,

$$\frac{\partial \overline{S_w}}{\partial t^{'}} = \frac{\tau J^{'}|_{x'=0}}{L^2}\sigma\sqrt{\frac{K}{\phi}}(\frac{\lambda_o\lambda_w}{\lambda_T})|_{x'=0}[\frac{\partial}{\partial x^{'}}(\frac{\partial S_w}{\partial x^{'}}|_{x'=0} - \frac{(\rho_w - \rho_o)gL\sqrt{\frac{K}{\phi}}}{J^{'}|_{x'=0}\sigma})] \tag{3.8}$$

In special cases, without consideration of the gravity force and consider the characteristic length[Equ2.11], the scaling time for the capillary pressure term,τ_c, is formulated as,

$$\tau_c = \sqrt{\frac{\phi}{K}}\frac{L^2}{J^{'}|_{x'=0}\sigma\frac{\lambda_o\lambda_w}{\lambda_T}|_{x'=0}} \tag{3.9}$$

Similarly, assuming there is no capillary pressure then the gravity scaling time,τ_g, is

$$\tau_g = \frac{\phi L}{K\Delta\rho g \frac{\lambda_o\lambda_w}{\lambda_T}|_{x'=0}} \tag{3.10}$$

In where, $\Delta\rho = \rho_w - \rho_o$.

Furthermore the scaling ratio for the gravity to capillary, which is to measure the relative scale of gravity to capillary force.

$$R_c^g = \frac{\Delta\rho g L_c^2}{H\sigma J'|_{x'=0}}\sqrt{\frac{K}{\phi}} \tag{3.11}$$

The water saturation at $x^{'} = 0$ is assumed reaching the residual water saturation, S_w^*,Mirzaei-Paiaman et al. [25], then Equ3.11 is transformed to

$$R_c^g = \frac{\Delta\rho g L_c^2}{H\sigma J'|_{S_w=S_w^*}}\sqrt{\frac{K}{\phi}} \tag{3.12}$$

For convenient, the coefficient is denoted as R_c^g which corresponding to the quantified ratio of gravity to capillary effects during the spontaneous imbibition process. It include the parameter that is not counted in the Inverse Bond number,wettability, inside the ratio of gravity to capillary pressure.

3.3 The characteristics behaviour of recovery

The water saturation profile could be describe as the quadratic form before the water front reach the no-flow by integrating Equ3.8 from inlet until before reaching the flow boundary(at flow boundary $S(x^{'}, t) = 0$)[25].

$$S^{'}(x^{'}, t) = S^* - A(t)x^{'} + B(t)x^{'2} \tag{3.13}$$

In which $S^{'}$ is the dimensionless water saturation,$S^{'} = \frac{S_w - S_{wi}}{1 - S_{wi} - S_{or}}$.

Tavassoli et al. [35] gives that early time solution for the cases of the capillary-dominated or gravity-dominated and states. They conclude that average saturation is dominated by the capillary pressure regardless of the gravity force.

$$\overline{S(t')} = S^* \sqrt{4t'/3} \tag{3.14}$$

In where, S^* is the water saturation after the imbibition process.Early time refer to that the function of time , u, meet with the expansion:$ln(1-u) \approx u - u^2$[35].

For the later time profile of oil recovery,Tavassoli et al. [35] found that is characterized as the exponential behaviour.

Mirzaei-Paiaman et al. [25] gives the full solution for the spatial average saturation based on the Equ 3.13.

$$\frac{N}{N_p} = \frac{1}{R}[1 + W(-e^{-1-6t'})] \tag{3.15}$$

In where, N and N_p are the recovery at time t' and the final oil recovery,respectively. They argue that the solution solve the issue of estimating over or under to the early or later time oil recovery.

$$t' = \alpha R^2 t \tag{3.16}$$

In where, α, rate constant and R, ratio of capillary to gravity force,are separate ratio of gravity force to capillary pressure and rate constant. They are expressed as Equ 3.17 andEqu 3.18 in Mirzaei-Paiaman et al. [25].

$$R = -\frac{1}{S^*(1 - S_{wi} - S_{or}})\frac{\Delta\rho g L}{2\sigma J'}\sqrt{\frac{K}{\phi}} \tag{3.17}$$

$$\alpha = -\sqrt{\frac{K}{\phi}}\frac{\sigma}{L^2}(J'\frac{\lambda_o\lambda_w}{\lambda_T})|_{x'=0} \tag{3.18}$$

Chapter 4

Simulation Study

Through this chapter, the affecting parameters to the spontaneous imbibition and gravity drainage would be discussed by the assistance of the IORCoresim. The interplay of them would be would be discussed base on the Equ 3.12. In addition to that, the boundary condition would also be explored in terms relationship to SI and GD.

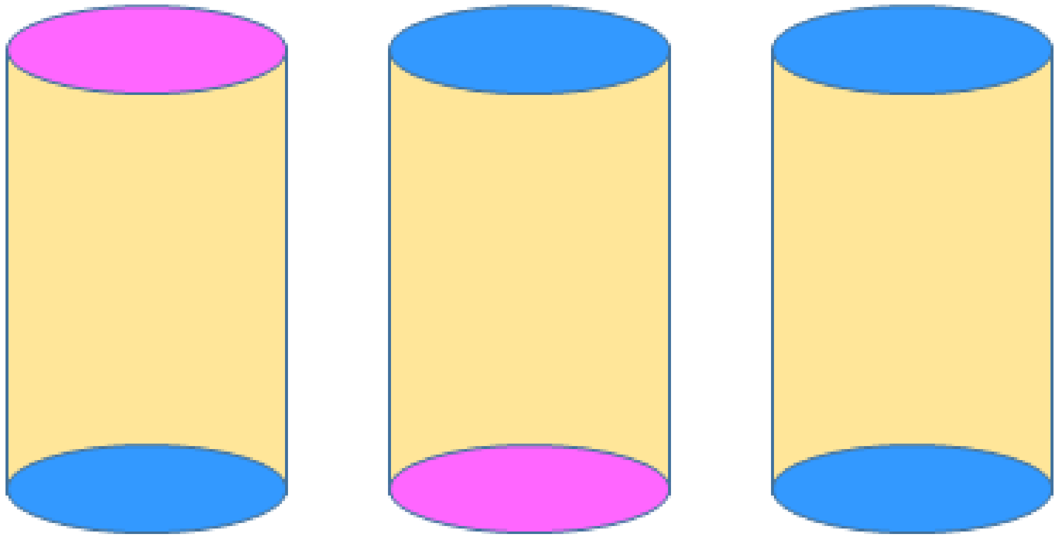
Regrading to the cases of identifying the characteristics of spontaneous imbibition, wettability and IFT would be the corresponding involved factors. The gravity force is neglected by the assumption of density of water and oil is equal.

while in case of gravity drainage, the core height, absolute permeability,viscosity and wettability would be the involved factors. Similarly, in this section the capillary pressure would be assumed to be zero.

Finally, based on the previous simulations on spontaneous imbibition and gravity drainage, the interplay of them would be discussed on varying wettabilities and IFTs as well as boundary conditions.

4.1 Model declaration

The model shapes cylindrical. The diameter is fixed as 3.80cm,the height is varied. Three boundary condition would be discussed, bottom-opened(BO) and top-opened(TO),two surface opened(TSO). The opened face is communicating with water, while the closed face is sealed without contact with oil or water. Fig4.1 illustrate the three boundary condition .



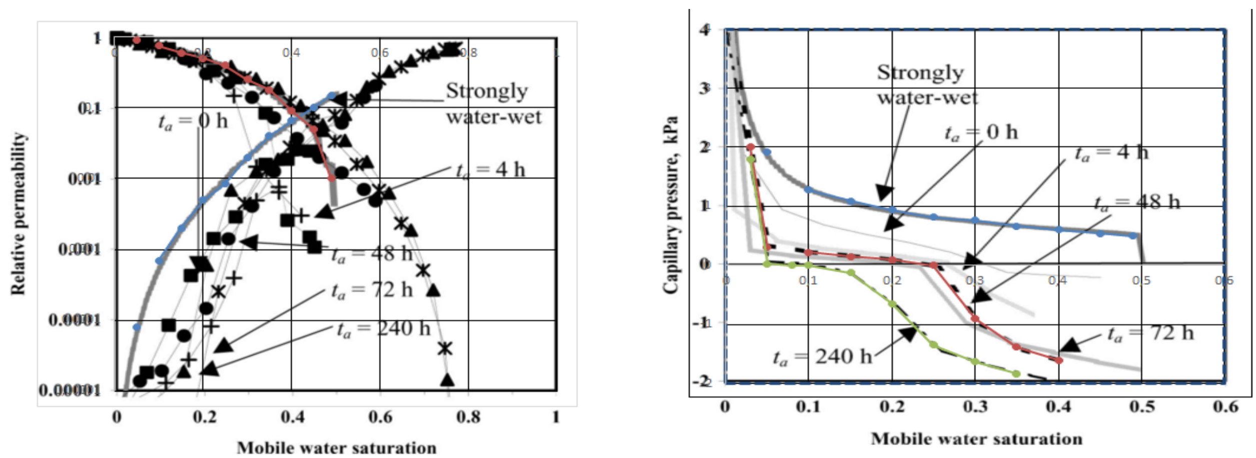
(a) Bottom-opened(TO) (b) Top-opened(BO) (c) two surface opened(TSO)

Figure 4.1: Various boundary condition in simulation cases

Rock permeability and porosity is homogeneous. The detail simulation data and relative permeability function are based on the pore scaling modelling of Behbahani et al. [6], including the relative permeability curve[Fig4.2a] and dates could be found in 4.1. Accordingly, the aging time correspond to the different initial saturation and wettablity condition. The neutral wetness(NW) is the effect of the aging time 48 hour. while the oil-wet(OW) is the result of the aging time 240 hour, the strongly water-wet(SWW) relative permeability data is from Valvatne and Blunt [36].Another assumption is that the initial water saturation is identical for the wetness conditions. It is defined as separately in the data file instead of the initial water saturation in the relative permeability function.

Table 4.1: Relative permeability function for the strongly water-wet(left four columns),neutral wetness(middle 4 columns)and oil-wet(right 4 columns)

Sw	Krw	Kro	Pco	Krw	Kro	Pco	Sw	Krw	Kro	Pco	
0.25	0,00	1,00	10,00	0,162	0,000000	1,00	8,00	0,16	0,00	1,00	5,00
0,30	0,00	0,90	1,92	0,212	0,000015	0,9	0,30	0,28	0,00	0,92	1,80
0,35	0,00	0,75	1,28	0,262	0,00002	0,7	0,22	0,21	0,00	0,87	0,03
0,45	0,01	0,50	0,94	0,312	0,00006	0,5	0,15	0,32	0,00	0,83	0,00
0,50	0,01	0,40	0,82	0,362	0,00015	0,3	0,10	0,26	0,00	0,77	0,00
0,55	0,02	0,25	0,76	0,412	0,001	0,2	0,00	0,36	0,00	0,50	-0,65
0,60	0,04	0,18	0,67	0,462	0,004	0,15	-0,90	0,41	0,01	0,40	-1,35
0,65	0,07	0,09	0,60	0,512	0,009	0,08	-1,38	0,46	0,01	0,30	-1,63
0,74	0,15	0,01	0,50	0,562	0,02	0,04	-1,60	0,56	0,03	0,12	-5,35
0,75	1,00	0,00	0,00	0,762	0	1	-10,00	0,91	1,00	0,00	-15,00



(a) Duplication of relative permeability function (b) Capillary pressure function for various wetness

Figure 4.2: Relative permeability function and the capillary pressure function[6]

4.2 Spontaneous imbibition

SI is driven by the capillary pressure and based on the Equ2.2, $\frac{1}{tau_c}$.The involving parameters are mainly the IFT and the permeability as well as the wettability. Equ3.9 represents the time scaling group. The porosity is assumed as constant for this study, thought it has positive relationship with the permeability. Effect of permeability to the capillary would be discussed in gravity drainage section. In this section, importantly, the gravity is assumed to be absent.

Generally, imbibition rate of capillary force is much faster than the gravity drainage process.

Within 0.1$hour$,[Fig4.3 VS Fig4.6] shows that the capillary pressure has imbibed into significant amount of water than the solely gravity acting. For example, the highest water saturation of the former has rose to 0.75 comparison to that, 0,256,of gravity drainage process[Fig4.6]. It is also matched with conclusion of the Tavassoli et al. [35], the very early time of the imbibition process is contributed only by the capillary pressure instead of the gravity.

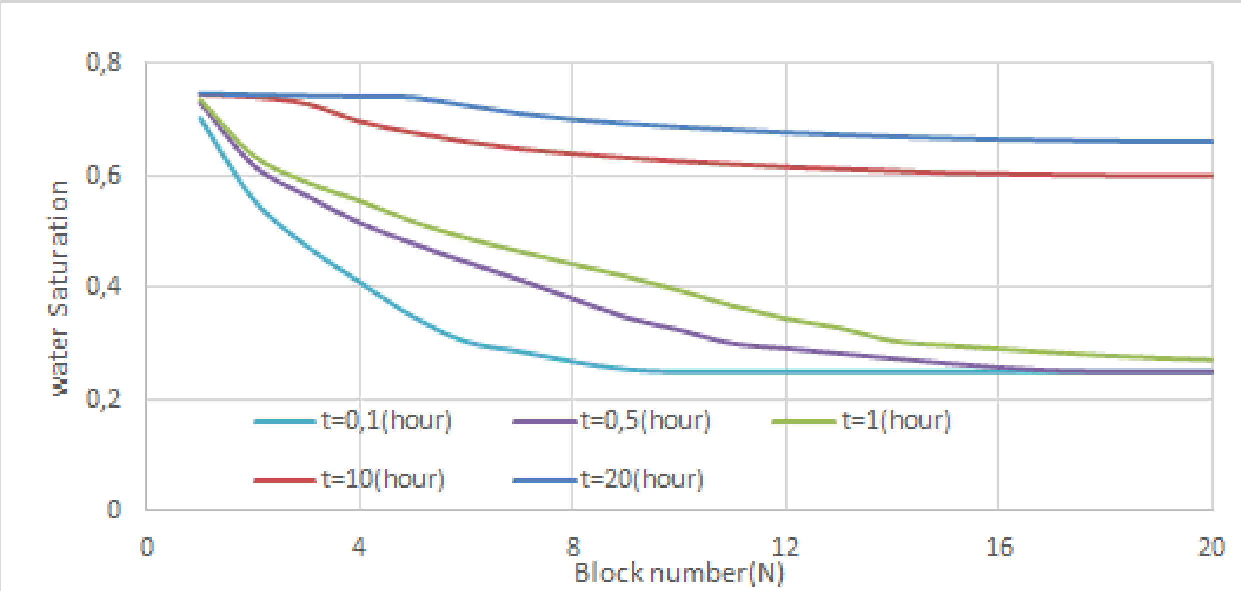


Figure 4.3: Water saturation distribution at different time of sample length=10cm;block 1 is the top surface contact with water

Wettability

As mentioned before, wetness is mostly discussed factors that affect the spontaneous imbibition process. It is well established that the water wettability improve the final oil recovery and imibibition rate[Fig 4.4]. It is matched with study of Zhou et al. [39].Comparing with the affects of GD individually[Fig4.8b], the SI of neutral wet and oil-wet give less oil recovery, which verify that reducing in water wettability impairs oil recovery.

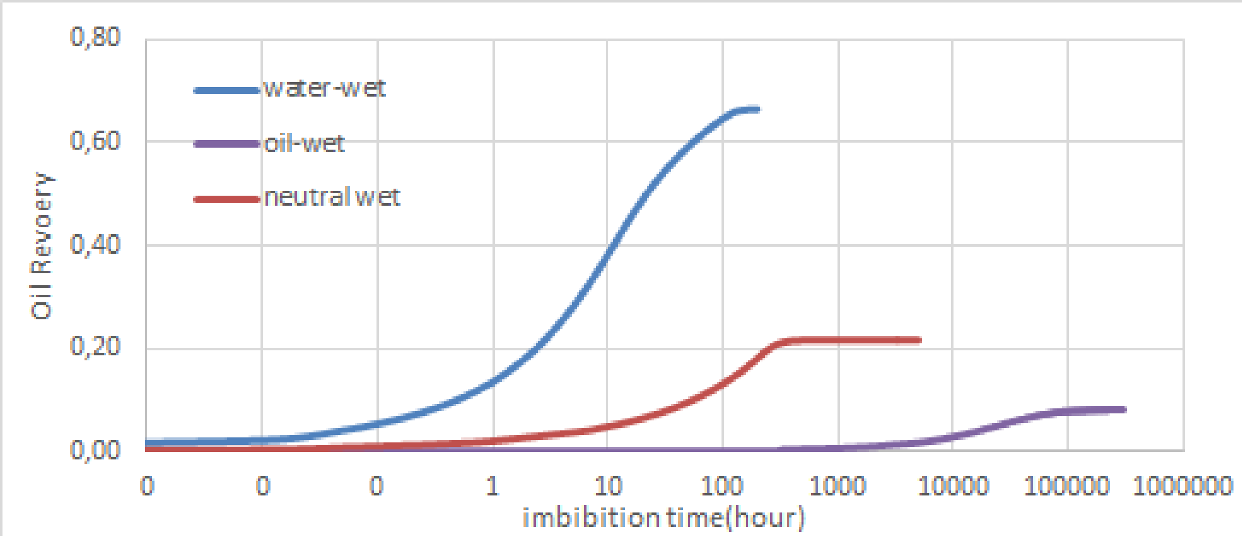
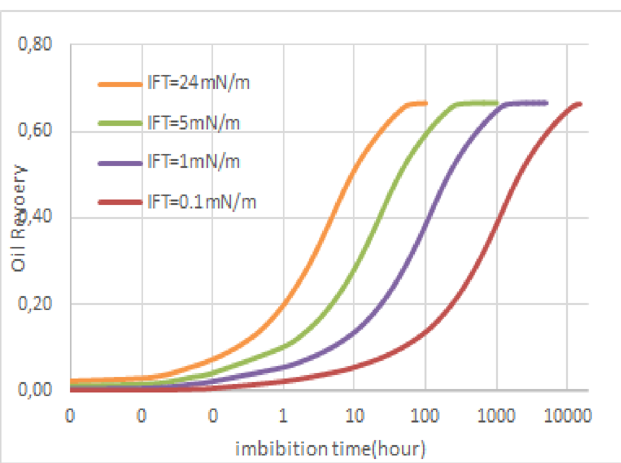


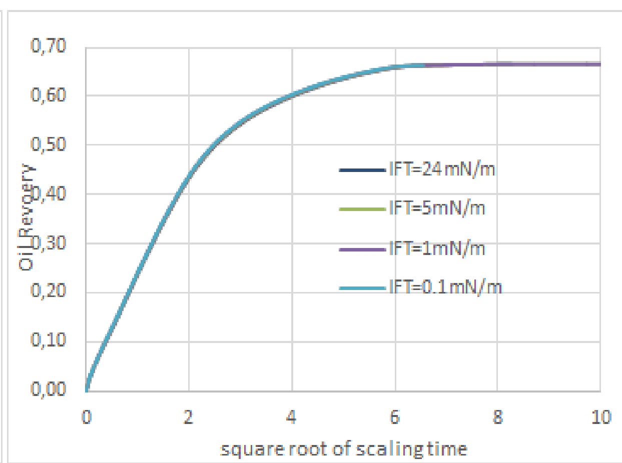
Figure 4.4: wettabiity effects to the oil recovery and recovery rate in the condition of TO (and BO) without gravity when IFT=10mN/m

IFT

IFT variation is directly related to the capillary force, it could be noticed that reduction on the IFT slow down the spontaneous imbibition rate [Fig4.5a]. It is coordinating with the observation of Schechter et al. [30],the final oil recovery is not influential by the IFT magnitude with the negligible gravity.



(a) Effect of IFT to the recovery profile



(b) Oil recovery vs. square root of scaling

Figure 4.5: Effect of IFT to spontaneous imbibition process with TO (and BO) in strongly water-wet without gravity

4.3 Gravity Drainage

Within this section, capillary pressure is assumed zero,GD process would be simulated and discussed under various height and wetness conditions as well as the permeabilities. The scaling time is based on Equ3.10, $\frac{1}{\tau_g}$.

In general,while in the absence of the capillary pressure,Hagoort et al. [15] states that there would be shock in front water saturation which also is observed in simulation [Fig4.6].

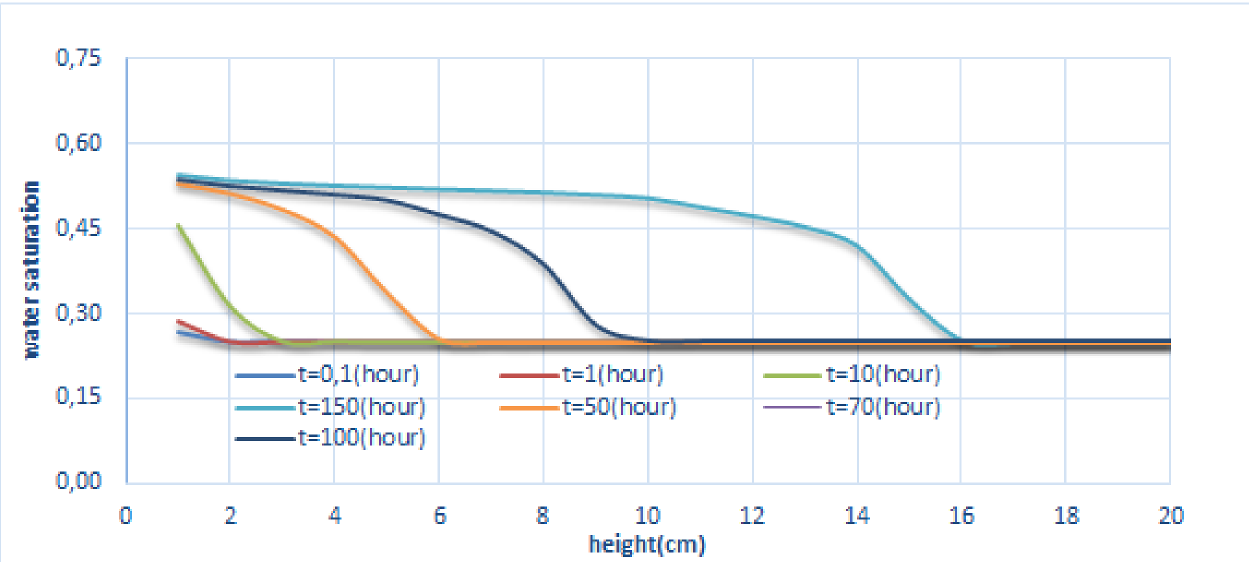
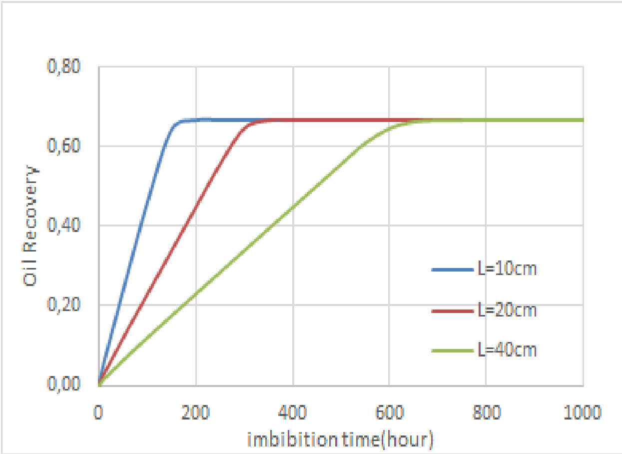


Figure 4.6: Water saturation distribution of sample at height=10cm(top block is 0) for TO condition without capillary pressure

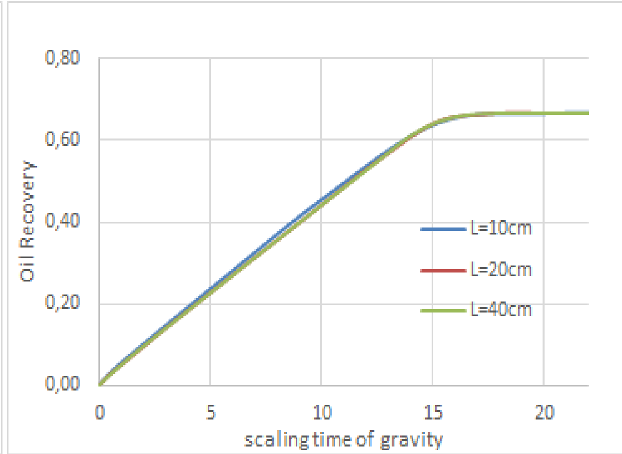
Height

Three different height models varying from 10cm to 40cm is simulated. Regarding to the boundary condition, TO case would be the setting consumption to get basic understanding about the parameter to affect the gravity drainage process.

From Fig 4.7a, the conclusion could be stated that the final oil recovery is not relevant to the height of sample, while it does impact the drainage rate. Height of 40cm halves the recovery rate to the core height 20cm. Fig4.7b, shows that the linear relation between the oil recovery and time scale.Distinctively, it is different to SI working individually case[Fig 4.5b].



(a) Influence of height to the recovery profile

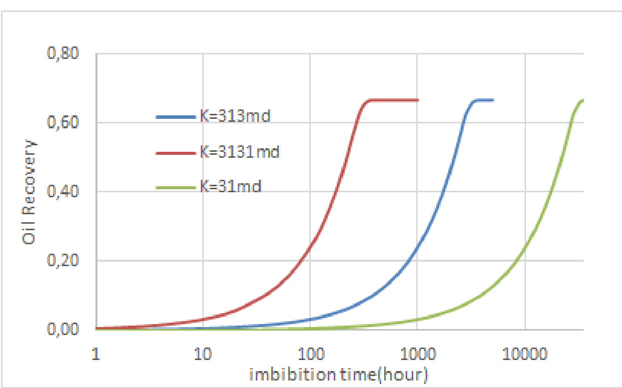


(b) Scaling time to oil recovery

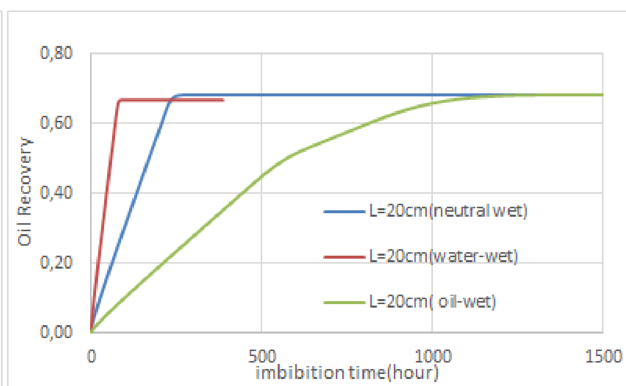
Figure 4.7: Effect of height to gravity drainage process for TO condition without capillary pressure

Permeability

Under this subsection, the impacts of absolute permeablity variation to GD would also be explored. Three different absolute permeabilities will be involved, separately 3131md,313md,31md. Besides that, the different relative permeability behaviour for the water and oil would also be examined; to be noted that the comparison of the relative permeability is achieved by the simulation on various wetness condition.



(a) Influence of permeability to the recovery profile



(b) impacts of wettability to the reocvery profile

Figure 4.8: Effect of wettability and permeability to gravity drainage for TO condition without capillary pressure

The oil recovery profile for variations on the permeabilities shows that higher permeability posses the highest oil recovery rate[Fig 4.8a] , thought the final oil recovery is same for range of permeabilities. Another feature is that the oil recovery rate is linear to the permeability value, the 3131md core elicit 10 times faster recovery rate than the 313md.In regarding to the various relative permeability function, the relevance between the oil recovery profile is shown by Fig4.8b .Strongly water-wet generate the highest oil recovery rate due to growing faster water relative peremability[4.2a].

Viscosity

The viscosity also influence the gravity drainage process. Various viscosity cases has been run for simulating, from 5cp to 39cp. The time to reach the stabilized of final recovery reaching is shorter in case of less viscous oil, the final recovery is equal for the various viscosity[Fig4.9].

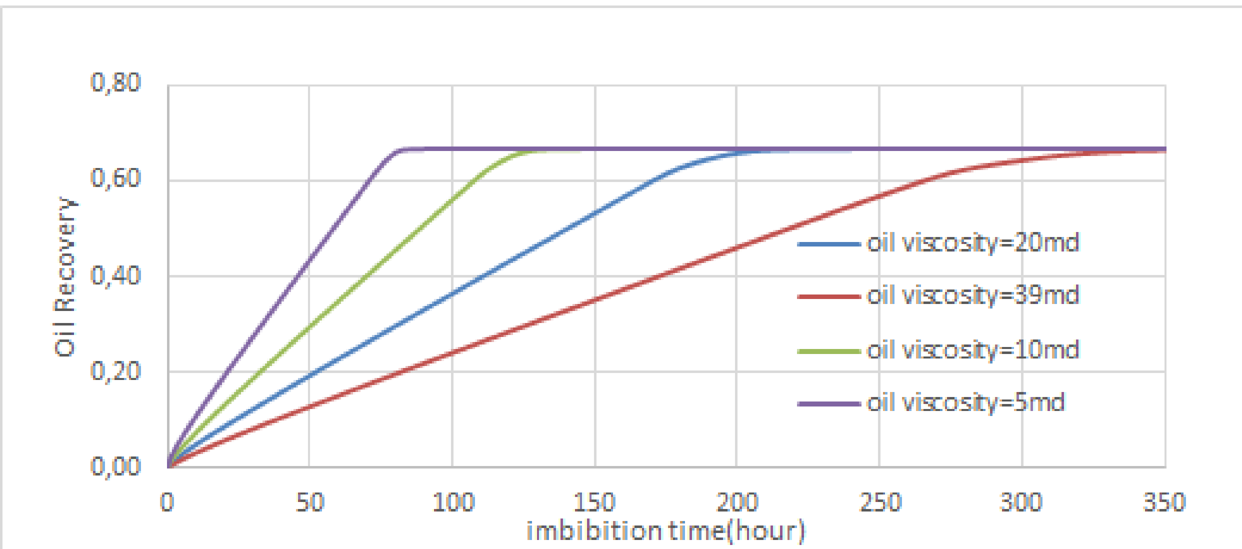
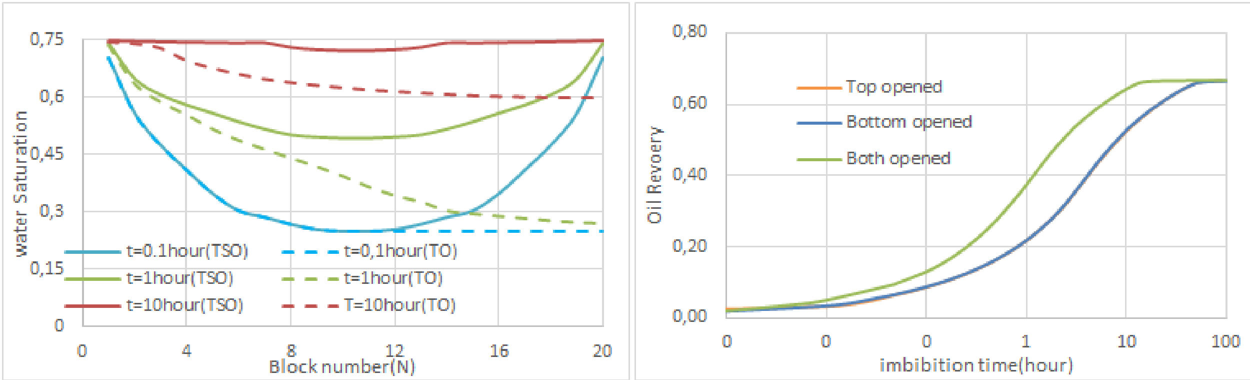


Figure 4.9: Viscosity effect to gravity drainage process for TO condition without capillary pressure

4.4 Boundary condition

In the model declaration section, three different boundary condition(BC) has been set, BO and TO, TSO. In this section, the principle effects of BC to the gravity drainage and spontaneous imbibtion would be simulated respectively.

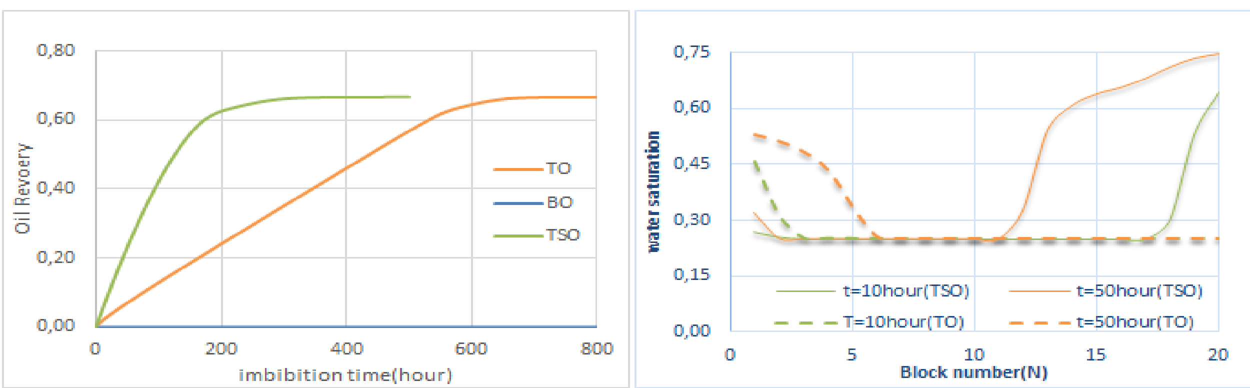


(a) Water saturation comparison for TSO and TO without gravity force at SSW

(b) Recoery profile for BO,TO and TSO without gravity force at SSW

Figure 4.10: Water saturation distribution and recovery profile for BO,TO and TSO without gravity at SSW

For the SI working individually, the TSO gives the higher recovery rate [Fig4.10a] than BO or TO [Fig4.3], since TSO has bigger imbibition area than only one side opened. BO and TO posses the same recovery profile for same wettability and IFT[Fig 4.10b]. In Cuiec et al. [9] work, the effect of boundary condition also studied as similar, the oil recovery rate of both sided opened case also double the one-side opened condition[Fig4.10b].



(a) Gravity drainage recovery profile for TO,BO and TSO without capillary pressure for SSW

(b) Water saturation at different time without capillary pressure for SSW

Figure 4.11: Water saturation distribution and recovery profile for BO,TO and TSO without gravity at SSW

In case of the GD , the BO could not trigger the gravity drainage, while TO elicit gravity drainage[4.11a]. For the case of TSO, the oil recovery rate is higher than the TO case[Fig4.11b].

4.5 Interplay of Spontaneous imbibition and gravity drainage

This part, the interaction of gravity force and capillary pressure under various conditions would be discussed .The interplay of them is defined by Equ3.12,R_c^g. in which,IFT is one of determining parameter influenced the interaction them, which is also easy to modified in practical case by adding surfactant.

Therefore, various ratio of gravity force to capillary pressure would be achieved by introducing the different IFT. For example Table 4.2 and 4.3 shows the IFT variation for different cases and R_c^g for TO and BO as well as TSO. $J'|_{S_w=S_w^*}$ are 250,10,3 respectively, for SWW,NW and OW.Rock properties and fluid density and viscosity would remain same for this section,while characteristics length[Equ2.11],L_c,change with the boundary condition. Each boundary condition would run for 2 cases, one for the same wettability, while the other would explore the effects of wettability.

Table 4.2: gravity force to capillary pressure ratio for TO and BO in various wettabilities and IFT

IFT(mN/m)	24,2	10	5	1	0,5	0,3	0,2	0,1	0,05
R_c^g(SWW)	0,00	0,00	0,01	0,04	0,08	0,14	0,20	0,41	0,82
R_c^g(NW)	0,04	0,10	0,21	1,04	2,07	3,45	5,18	10,36	20,71
R_c^g(OW)	0,14	0,35	0,69	3,45	6,90	11,51	17,26	34,52	69,05

Table 4.3: gravity force to capillary pressure ratio for TSO in various wettabilities and IFT

IFT(mN/m)	24,2	10	5	1	0,5	0,3	0,2	0,1	0,05
R_c^g(SWW)	0,00	0,01	0,02	0,08	0,16	0,27	0,41	0,82	1,63
R_c^g(NW)	0,09	0,21	0,41	2,07	4,14	6,91	10,36	20,72	41,44
R_c^g(OW)	0,29	0,69	1,38	6,91	13,81	23,02	34,53	69,07	138,14

Top-opened(TO)

Generally, the recovery rate is enhanced by the gravity force with TO condition,it is applicable for all the wettability cases. While in case of oil recovery, one exception case is happened at SSW, the oil recovery could not improved any more, since the residual oil saturation is interrelated with relative permeability function,peaked at 66%. However, oil recovery factor in case of *NW* and *OW* have been enhanced by gradually dominating gravity force.

For instance, in case of SSW[Fig4.12], the gravity acts as the accelerator of the recovery rate;the accelerating effects is increased with the reducing IFT, which arise growing positive effect from the downward gravity influence when the boundary condition is TO. Another characteristics is that the GD(dark-red line) and SI share the same final oil recovery[Fig4.12] for same wettability under TO boundary condition.

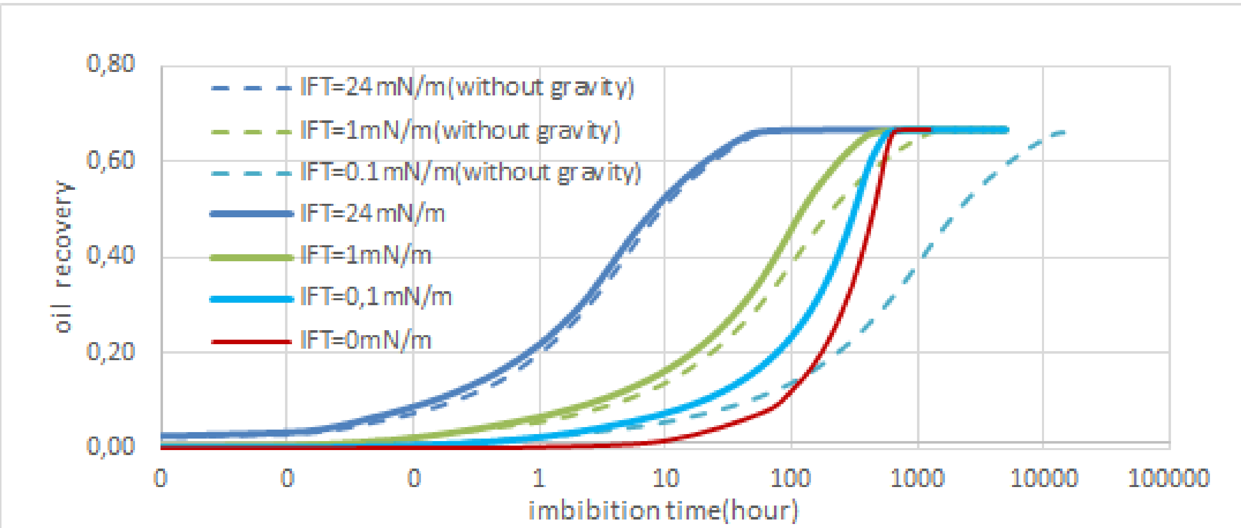


Figure 4.12: Gravity effects to oil recovery profile with TO in strongly water-wet for varying IFT; the legend which is not marked with "without gravity" imply that they are cases with gravity, and it apply to the following figures in this section.

Except for the speeding effect of gravity to oil recovery rate[Fig4.13],it also acts as enhancer of oil recovery. For instance, it stars to grow evidently once IFT reduces to $0.1 mN/m$. One extreme case is that IFT is $0 mN/m$, which is totally gravity drainage process, it posses the highest enhancement of oil recovery effect,which explains that the positive effect to recovery rate and final oil recovery is duet to gravity . Another striking character of recovery rate is that it cease to accelerating as the IFT reduce to $0.1 mN/m$.It could be signified as the initiating point of gravity dominating .Correspondingly, R_c^g reaches 10.36.

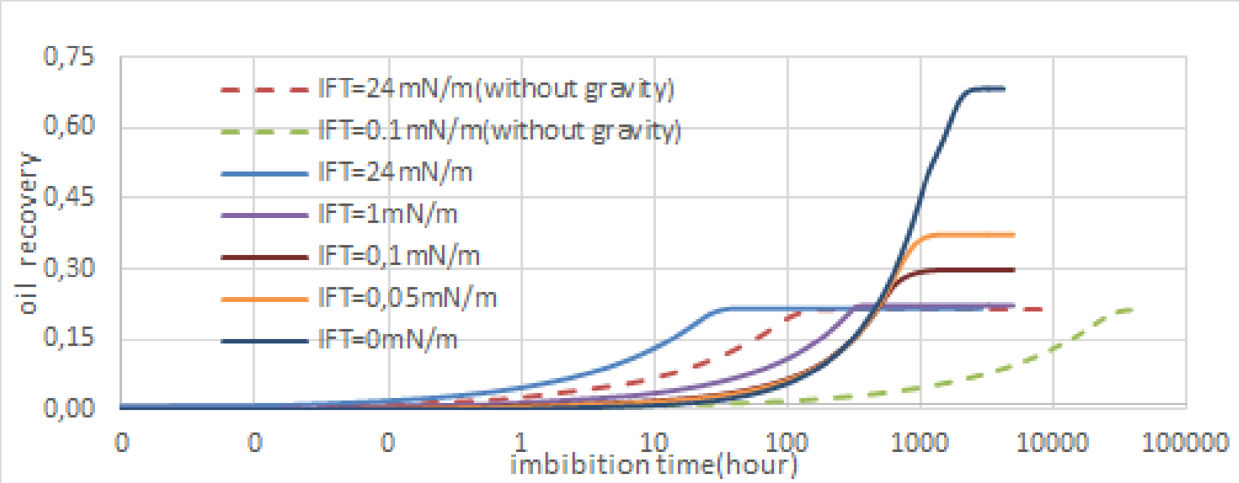


Figure 4.13: Gravity effects increases with reducing IFT in TO with neutral wet

Similar enhancing effect from gravity to ultimate oil recovery and recovering rate have been observed in case of oil-wet[Fig 4.14].For example, the oil recovery could reach 0.26 when IFT reduces to $0.1mN/m$ while in case of without gravity is only 0.08[Fig 4.14]. The R_c^g trigger this behaviour is range from 13.8 to 23.02. More accurate value of R_c^g could not given since lack of cases between $0.1mN/m$ and $0.5mN/m$ and the case for oil-wet is extremely time-consuming. It could be taken as further study.

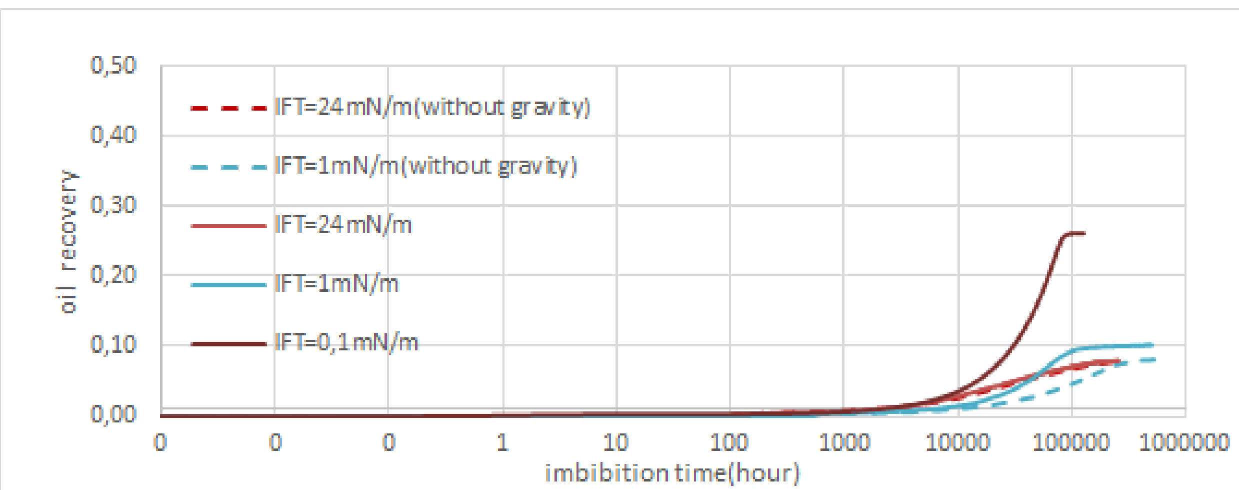


Figure 4.14: The effects of gravity increases reducing IFT in TO with oil-wet with gravity

Bottom-opened (BO)

Commonly, with BO boundary condition,for all wettability conditions recovered oil takes more time to be stabilized.Moreover the final oil recovery is even reduce obviously when IFT reach enough small range. it is due to the downward gravity is playing a anti-enhancing role comparing with the TO condition.

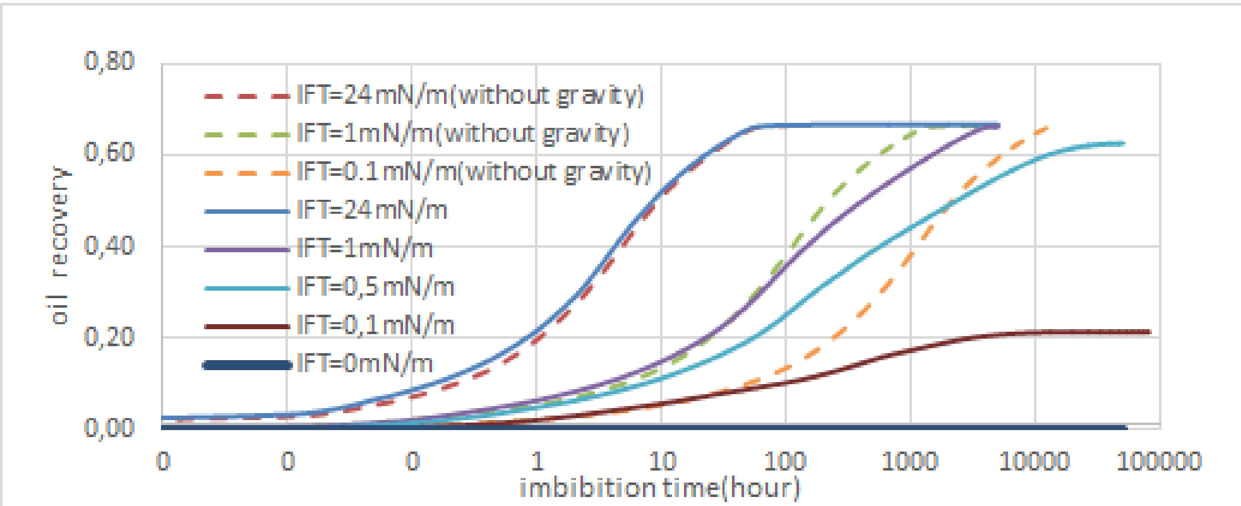


Figure 4.15: Gravity effects to recovery profile with BO in strongly water-wet for various IFT

In case of SWW[Fig4.15], the range of IFT triggering consequence of gravity force is around $0.5mN/m$, corresponding R_c^g is 0.082. Then it grows quickly when IFT lower to $0.3mN/m$,at which R_c^g is 0.14. The enlarged negative effect is from the growing effects of gravity force which result the reducing IFT. Extremely, gravity would hold the oil in initial saturation once the IFT reduces to $0mN/m$,which could also interpret as the negative influence from the downward gravity force.

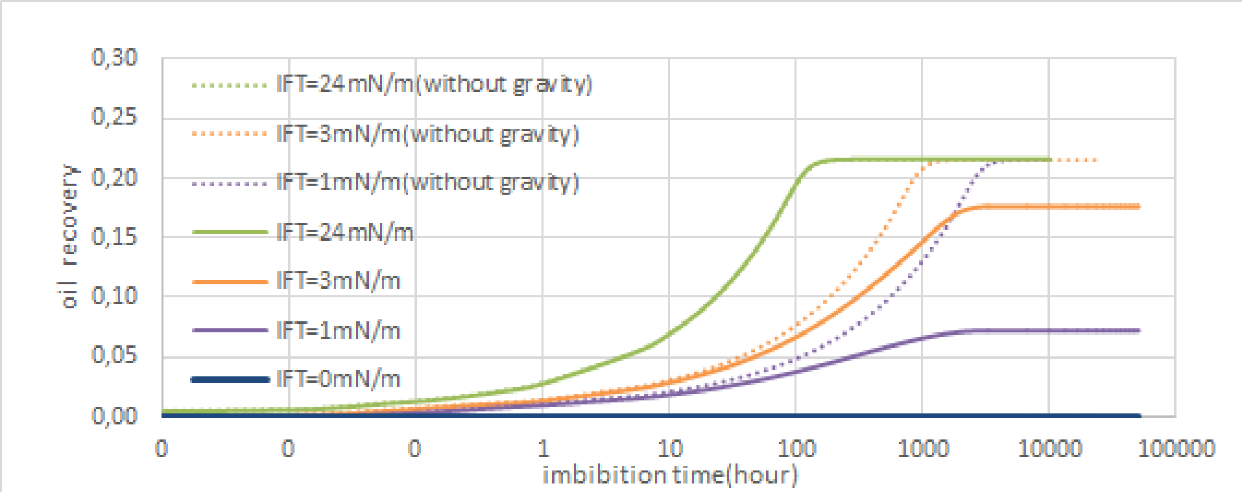


Figure 4.16: Gravity effects to recovery profile with BO in neutral wet for various IFT

when move to the NW case, gravity also play as harming the oil recovering rate and final oil recovery [Fig 4.16],but more evidently. At IFT is $1mN/m$, the oil recovery is already less than half of original recovery factor without gravity when the $IFT = 24mN/m$[Fig4.16];while in case of SSW [Fig4.15], the oil recovery is still same as original oil recovery,0.21. But it is hard to determine the initial vale of R_c^g which trigger the reduction on oil recovery and recovering rate in case of NW,since there is no abrupt change in oil recovery with reducing IFT in this study.

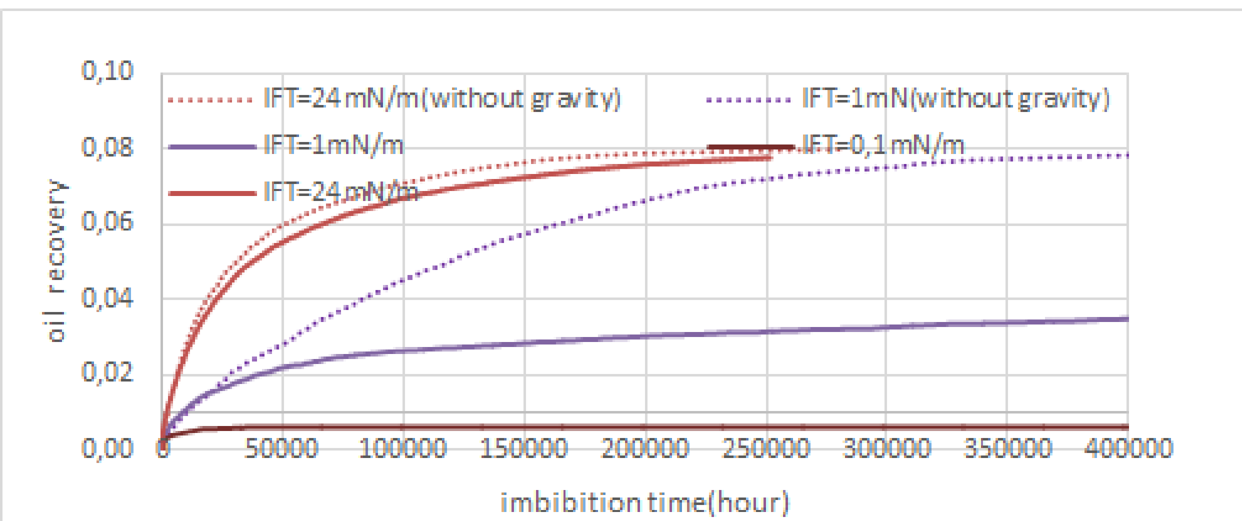


Figure 4.17: Gravity effects to recovery profile with BO in oil-wet for various IFT

With respect to the oil wetness, the gravity effects is more evident than the case of neutral wet. The oil trap consequence from the gravity is obvious, even though IFT is $24mN/m$, which give oil recovery less than 0.08[Fig 4.17]. Correlated R_c^g is 0.29 for $IFT = 24mN/m$. One extreme case happens at $IFT = 0.5mN/m$,which the oil recovery factor less than 0.01.

Two surface opened (TSO)

Similarly to the case of TO, gravity generally acts as the enhancer of oil recovery . Again, the enhancement of gravity force are only observed in case of neutral wet and oil-wet for the same reason of TO. Besides that, the magnitude of recovery increment is similar to the case of TO.

In the condition of SWW, the oil recovery is remain stable[Fig4.18]. It is also due to the relative permeability function for SSW.

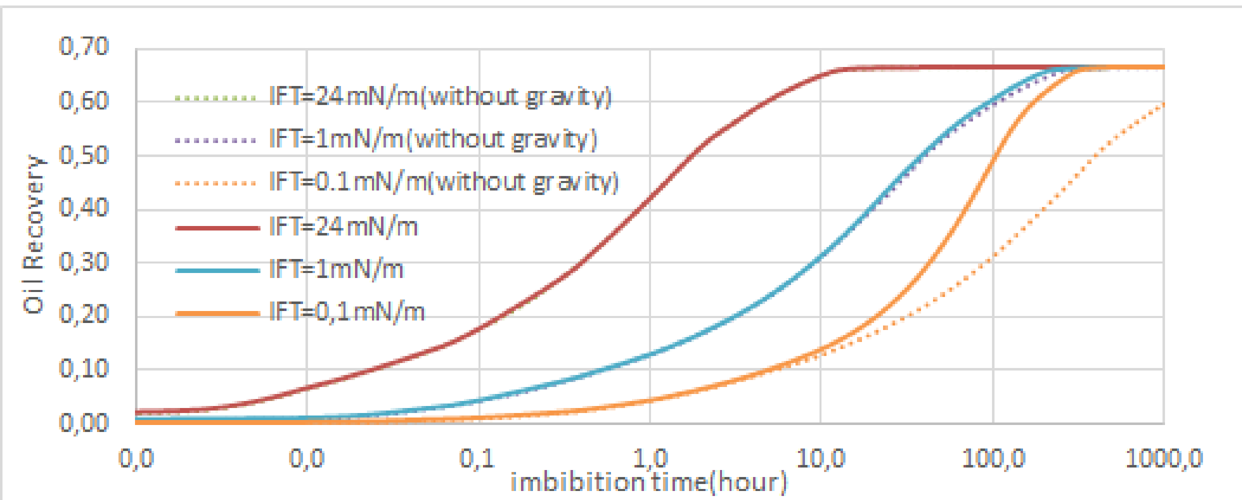


Figure 4.18: Gravity effects to recovery profile with TSO in strongly water-wet for various IFT

In the neutral wet, the gravity has the same effects which improve the oil recovery[Fig4.19]. For example, the oil recovery soar to 0.37 when IFT reduces to $0.1mN/N$ and $R_c^g = 20.72$, which is similar to the case of TO at $IFT = 0.1mN/m$. The different R_c^g is caused by different characteristics length,L_c.

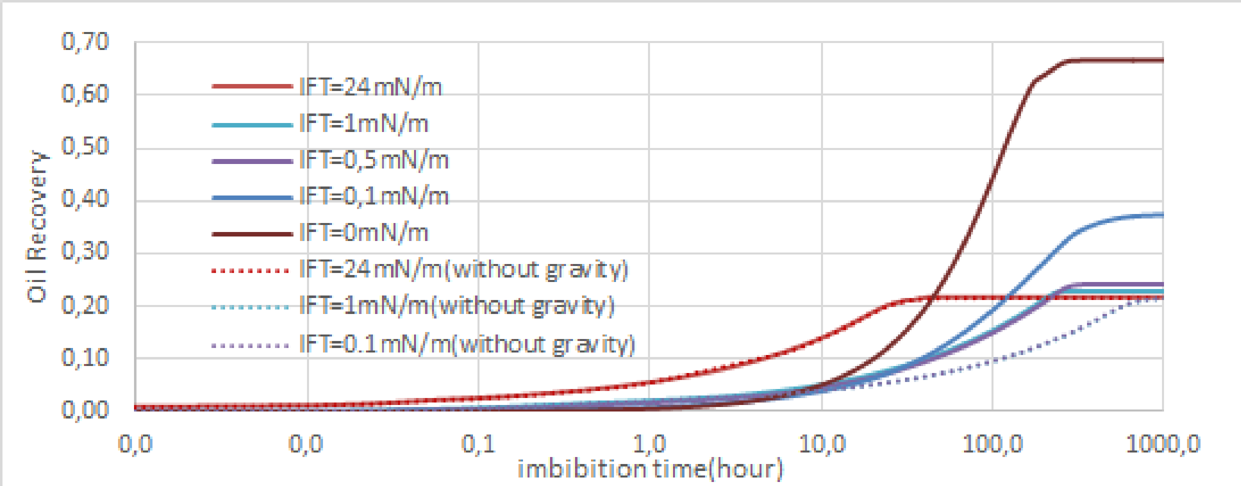


Figure 4.19: Gravity effects to recovery profile with TSO in neutral wet for various IFT

For oil-wet, it also experience same positive influence from the gravity force, the oil recovery jumps to 0.255, when the IFT decrease to $0.1mN/m$ and the corresponding R_c^g is 69.07.

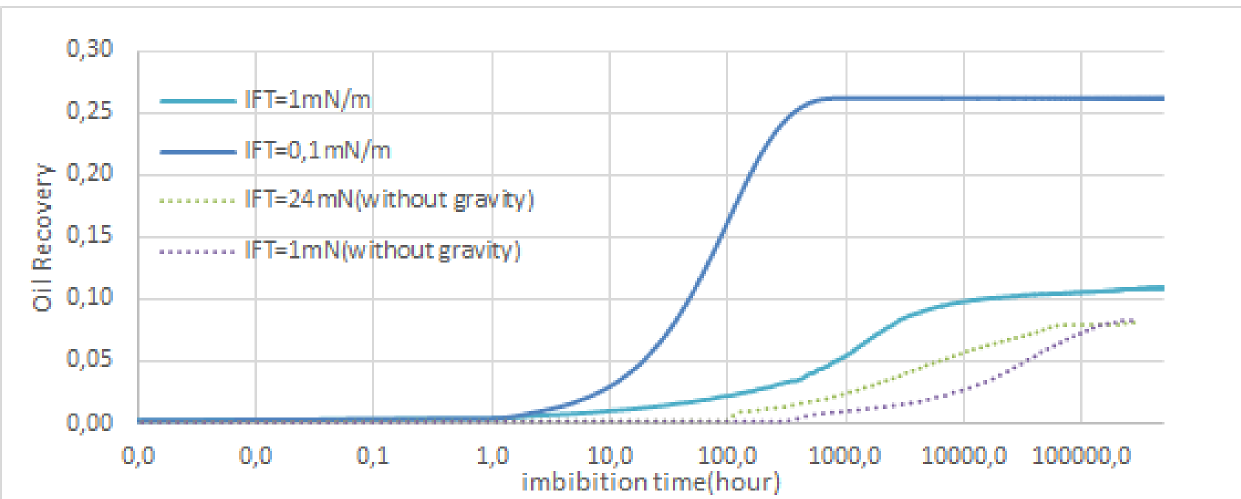


Figure 4.20: Gravity effects to recovery profile with TSO in oil-wet for various IFT

Scaling

In this section ,the interplay of gravity and capillary would be examined by the scaling time with relation to the recovery profile. The scaling time is defined as

$$t^{'} = t/(\sqrt{\frac{\phi}{K}}\frac{L_c^2}{J'|_{x'=0}\sigma\frac{\lambda_o\lambda_w}{\lambda_T}|_{x'=0}} + \frac{\phi H}{K\Delta\rho g\frac{\lambda_o\lambda_w}{\lambda_T}|_{x'=0}}\sqrt{\frac{K}{\phi}}) \tag{4.1}$$

From scaling on SSW condition, relative higher IFT(24mN/m) posses identical characteristics recovery profile[Fig 4.21], which is mentioned by Tavassoli et al. [35], which early time shows linear relation to the square root of time scaling [Equ3.14]and later time characterized as the exponential behaviour[Equ3.13]. while with reducing IFT which result in increasing gravity to capillary ratio, the separation of recovery profile cased by enlarging gravity effect are more obvious. For example, the reduction recovering rate and recovery rate is more evident for IFT=0.1mN/m than IFT=1mN/m in case of BO. while for case of TSO and TO, gravity force acts as the accelerator of recovering rate.

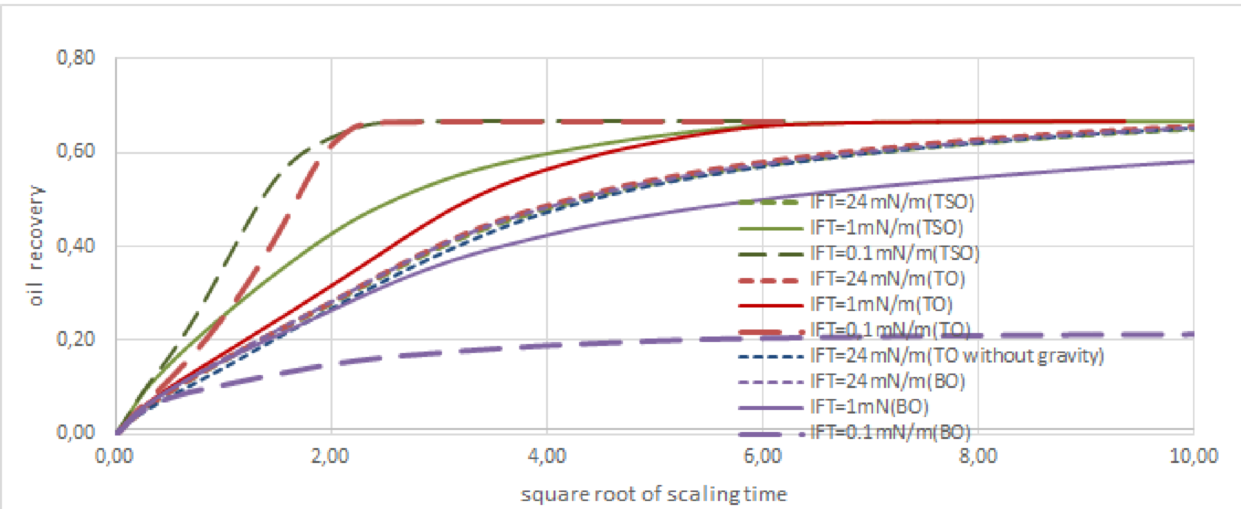


Figure 4.21: Recovery profile vs scaling time for Various boundary condition and IFT in strongly water-wet condition

Similar character for the increasing gravity to capillary ration have been observed in case of neutral wet[Fig 4.22] and oil-wet [Fig 4.23]condition when IFT is reducing. Gravity ratio increased,which results in IFT reducing in this study, then recovery rate and oil recovery is improved in case of TO and TSO, while it is the opposite consequence in case of BO. But there is disturbing profile for the TSO condition, the recovery profile is not matched with the BO and TO when the IFT is 24mN/m. This could be in the further study section.

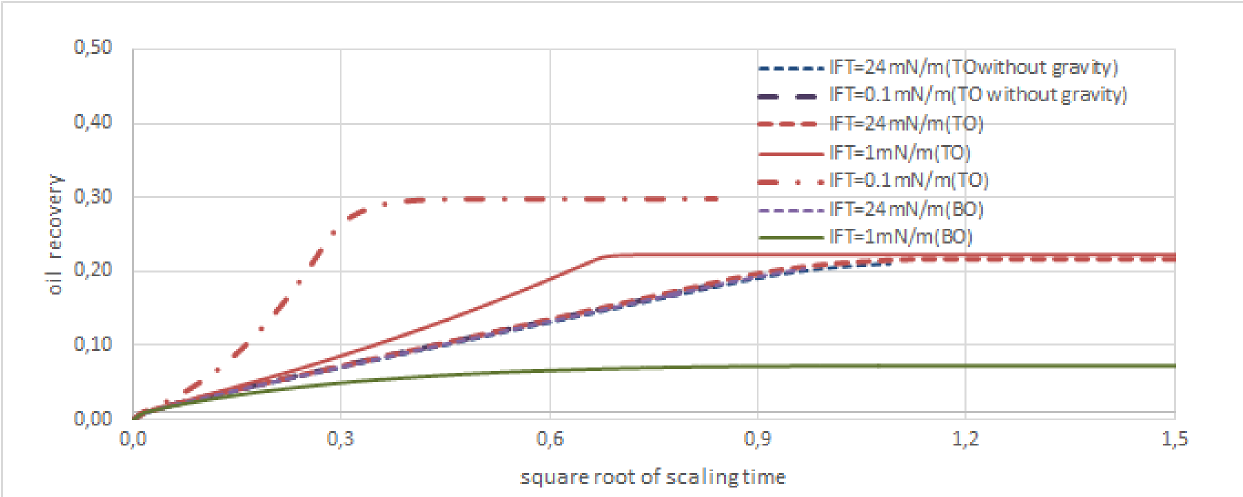


Figure 4.22: Recovery profile vs scaling time for Various boundary condition and IFT in neutral wet condition

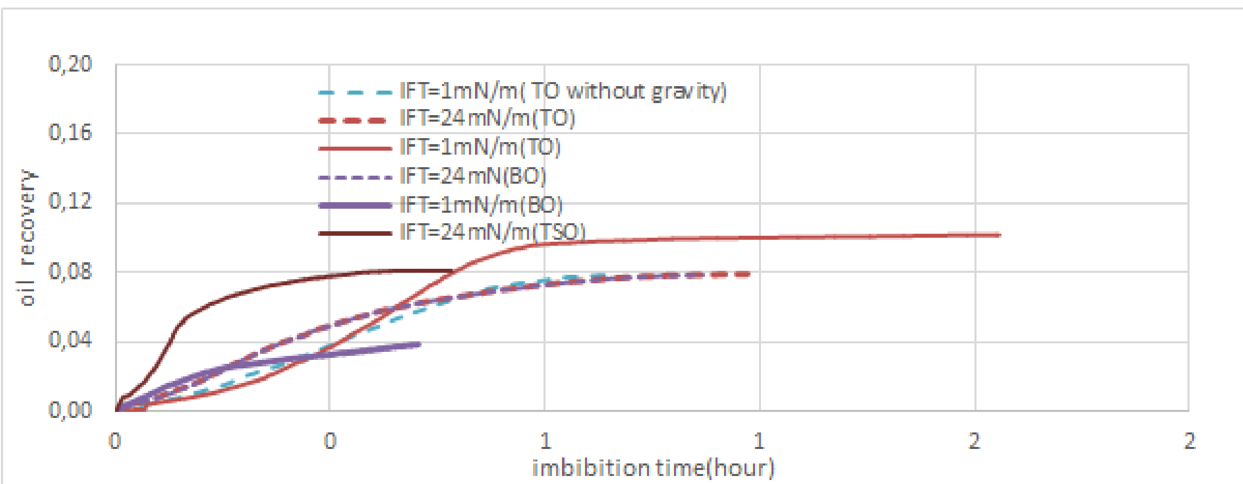


Figure 4.23: Recovery profile vs scaling time for Various boundary condition and IFT in oil-wet condition

Chapter 5

Summary and Recommendations for Further Work

5.1 Summary and Conclusions

Through the simulation and the literature study on the spontaneous imbibition and gravity drainage, the following conclusions on the interaction of them could be summarized:

- In case of spontaneous imbibition driving individually, recovery profile is highly determined by the IFT and the wettability. Stronger water wettability, higher oil recovery is reached[Fig4.4]. The IFT could influence the oil recovery rate. Higher IFT induce faster oil recovery[Fig4.5a]. The recovery shows linear relationship to the square root of scaling time[4.5b] .

- For Gravity drainage alone,the involving parameters, such as height,permeability as well as viscosity and wettability do not influence the final oil recovery. However, higher permeability and short sample has positive effects to the oil recovery rate[4.8a and Fig4.7a], while lower viscosity accelerate the drainage procedure[Fig4.9]. Moreover, the recovery rate is linear relation to the time scale[Fig4.7b].The wettabilities give the different profile of oil recovery[Fig4.8b].

- Top-opened boundary condition can trigger gravity drainage, while there is no oil producing in case of bottom-opened case[Fig4.11a]; TSO posses higher drainage rate than

TO[Fig4.11]. while for case of spontaneous imbibition, top-opened and bottom-opened possess the same recovery profile and final oil recovery[Fig4.10b]. However in case of both-surface-opened, the oil recovery rate has been accelerated[Fig4.10a].

- The interaction of gravity force and capillary pressure acts differently on varying of IFT, wettability and boundary conditions could be measured by R_c^g. The influence from the gravity is enlarged with increased R_c^g.

  1. For top-opened condition, gravity plays as enhancer of recovering rate[Fig 4.12]. In terms of final oil recovery, it could not improve in case of strongly water-wet[Fig 4.12]. While move to the neutral wet [Fig 4.13] and oil-wet [Fig 4.14], the enhancement oil recovery grow significantly when the IFT reduce to $0.1 mN/m$,correspondingly R_c^g are 10.36 and 34.52, respectively.
  2. In contrary, bottom-opened condition, the oil recovery rate is not influenced by the gravity, clearly . But the oil recovery rate is reduce by it evidently, when the IFT start reducing from $24 mN/m$, in case of water- wet[Fig4.16] to neutral wet [Fig4.16] until oil-wet[Fig4.17]. For example, when R_c^g are 0.41, the oil recovery already reduces to 0.20 in case of water-wet. In case of neutral wet, when IFT is $0.1 mN/m$, oil recovery reduces to 0.07, while the corresponding R_c^g is10.36.
  3. In case of both surface opened case, gravity acts similarly to the case of top-opened case in case of neutral wet[Fig4.19 Vs Fig 4.13] and oil wet[Fig4.19 Vs Fig 4.14] as well as strongly water-wet case[Fig4.19 Vs Fig 4.12].Namely, gravity plays as the accelerate in water-wet condition, while for neutral wet and oil-wet, the oil recovery as well as the recovering rate are both enhanced by increasing gravity effect which derive from the reduction of capillary pressure.

- Scaling time also confirm that recovery profile is same for the capillary dominated case while IFT is higher,it shows linear relation between the recovery profile to square root of scaling time at early time [Fig4.21 and Fig4.22 and Fig4.23];but as the gravity effects amplifying, which is caused by reduced IFT in this study,the influence from that is modifying the profile,evidently.

5.2 Recommendation for further work

The simulation result on effect of boundary condition,individually worked capillary pressure and gravity force has been verified. In regard to the interaction of gravity force and capillary working simultaneously, same result have been observed on case of strongly water-wet. However, on case of oil-wet and neutral, the corresponding R_c^g which could induce much higher oil recovery, have not been verified by experiment. Then further study could be used the relevant experimental data or performing related experimental test to verify or correct the threshold value of R_c^g to practical use of strategy for improving oil recovery. Other than that, the numerical simulation result has not closed against to the analytical solution,it also could be as for refining further study on this topic.

Appendix A

Acronyms

Abbreviation

BO bottom-opened

GD gravity drainage

NW neutral wet

OW oil-wet

SI spontaneous imbibition

SWW Strong water-wet

TO top-opened

TSO two surface opened

Greek Symbols

α rate constant

$\Delta\rho$ density difference, ML^{-3}

λ mobility $M^{-1}LT$

λ^*_{rw} wetting characteristics mobility,$M^{-1}L^T$

λ^*_{nw} non-wetting characteristics mobility,$M^{-1}L^T$

μ viscosity,$ML^{-1}T^{-1}$

σ interfacial tension, MT^{-2}

τ_c inverse of capillary pressure scaling term

τ_g inverse of gravity force scaling term

ϕ porosity

Roman Symbols

A crossing-area,L^2

A_b area of opened-surface,L^2

A_{ma} area of opened-surface for matrix,L^2

C_t unit convection factor

D_{ma} Diameter of opened-surface,L

F_s shape factor

$f(\Theta)$ wettability factor

g gravity acceleration constant,LT^{-2}

H Height,L

I_{of} saturation variation due to oil forced displacement

$I_{im,o}$ saturation variation due to oil sponataneous imbibition

$I_{im,w}$ saturation variation due to water sponataneous imbibition

I_o Amotte oil wettability

I_w Amotte water wettability

I_{wf} saturation variation due to water forced displacement

J J Leverett function

K absolute permeability, L^2

L length of the core, L

L_c characteristics length ,L

L_{ci} opened surface to the no-flow boundary ,L

M^* ratio of characteristics mobility

N_B^{-1} Inverse Bond number

p pressure, $ML^{-1}T^{-2}$

p_c capillary pressure, $ML^{-1}T^{-2}$

Q volume rate, L^3T^{-1}

N recovery at time $t^{'}$

N_P final oil recovery

r radius, L

R ratio of capillary to gravity force

R_c^g gravity force to capillary ratio

S saturation

S^* water saturation after imbibition

T total

t' time scaling

t time, T

t_c capillary time scaling

t_g gravity time scaling

u Darcy velocity,LT^{-1}

V_b bulk volume of matrix,L^3

V_{ma} bulk volume of matrix,L^3

W Washburn equation

x arbitrary length,L

subscription

o oil

w water

Appendix B

the derivation of mass balance equation and scaling

B.1 mass balance equation building

In the following 1D1Phase case, the mass balance equation is defined as

$$Au(x)\rho(x)\Delta t - Au(x+\Delta x)\rho(x+\Delta x) = A\Delta x[\phi(x,t+\Delta t)\rho(x,t+\Delta t) - \phi(x,t)\rho(x,t)] \tag{B.1}$$

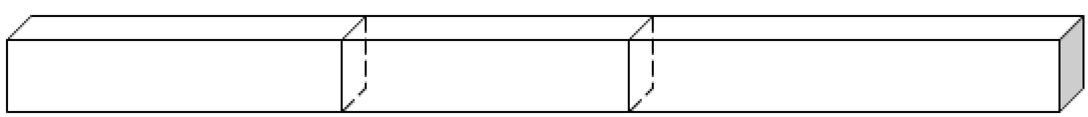


Figure B.1: 1D 1Phase Physical Model

Divided by $A\Delta x\ \Delta t$ and rearranged EquB.1,

$$\frac{\partial(\rho u)}{\partial x} + Q = -\frac{\partial(\rho\phi)}{\partial t} \tag{B.2}$$

Extend to 3D and 2 Phase(oil and water):

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho u)}{\partial y} + \frac{\partial(\rho u)}{\partial z} + Q = -\frac{\partial(\rho\phi)}{\partial t} \tag{B.3}$$

Consider the gravity force in Darcy equation, u is formulated as

$$u = -\frac{k}{\mu}(\Delta p - \rho g) \tag{B.4}$$

Assume the liquid is incompressible and the mass balance equation for the water and oil are

$$\frac{\partial(\phi S_w)}{\partial t} + \nabla \cdot [-\frac{KK_{rw}}{\mu_w}(\Delta p_w - \rho_w g)] = -Q_w \tag{B.5}$$

$$\frac{\partial(\phi S_o)}{\partial t} + \nabla \cdot [-\frac{KK_{ro}}{\mu_o}(\Delta p_o - \rho_o g)] = -Q_o \tag{B.6}$$

With the constrain equations

$$P_c(S - w) = P_o - P_w \tag{B.7}$$

$$S_w + S_o = 1 \tag{B.8}$$

and assuming the rock is incompressible. i.e the porosity, permeability are constant as well as the environmental temperature.

Add the equB.5 and equB.6

$$\nabla \cdot (u_o + u_w) = \nabla \cdot (u_T) = -(Q_w + Q_o) \tag{B.9}$$

in where

$$u_T = u_o + u_w = K[-\lambda_T \Delta p_w - \lambda_o \Delta p_c + (\lambda_w \rho_w + \lambda_o \rho_o) g] \tag{B.10}$$

$$\lambda_T = \lambda_w + \lambda_o \tag{B.11}$$

$$\lambda_w = \frac{k_{rw}}{\mu_w} \tag{B.12}$$

$$\lambda_o = \frac{k_{ro}}{\mu_o} \tag{B.13}$$

Assume that there is no convection, u_T is constant and with the initial condition u_o=0, then u_T=0.

Then derive the expression for Δp_w

$$\Delta p_w = \frac{-\lambda_o \Delta p_c + \lambda_o \rho_o g + \lambda_w \rho_w g}{\lambda_T} \tag{B.14}$$

Substitute into the equ.B.5 and get

$$\phi \frac{\partial (S_w)}{\partial t} + \Delta \cdot [K \frac{\lambda_o \lambda_w}{\lambda_T} (\Delta p_c - (\rho_w - \rho_o) g)] = 0 \tag{B.15}$$

Particulary, in 1D case, then

$$\phi \frac{\partial (S_w)}{\partial t} + \frac{\partial}{\partial x} [k \frac{\lambda_w \lambda_o}{\lambda_T} (\frac{\partial p_c}{\partial x} - (\rho_w - \rho_o) g)] = 0 \tag{B.16}$$

The initial condition is that there is no flow of oil or water and the initial saturation is expressed as

$$S_w(x,t) = S_{wi} \tag{B.17}$$

Different boundary condition could be involved

$$S_w(0,t) = 1; S_w(L,t) = 0 \tag{B.18}$$

$$S_w(0,t) = 0; S_w(L,t) = 1 \tag{B.19}$$

$$S_w(0,t) = 1; S_w(L,t) = 1 \tag{B.20}$$

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