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Gravity Drainage – A Main Pillar in the Tertiary Oil Migration in Abandoned Reservoirs I. Basic Concepts

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Abstract

After an oil reservoir is abandoned, a chaotic saturation distribution is formed throughout the reservoir. The new position of fluids is highly unstable due their inappropriate hydrostatic placement. They will tend to migrate in a normal gravity position. Gravity drainage is the main parameter that acts towards the repositioning of the fluids, and itself is a part of processes entitled tertiary migration that ultimately leads to a new and redistributed saturation state which becomes economically attractive. A study on gravity drainage is presented in which the main parameters are examined and field examples are given to show that gravity drainage can be a very important constituent for extended times of production.

Key words: *gravity drainage, abandoned reservoirs, phase distribution, tertiary migration, saturation restoration*

Introduction

Gravity drainage is the main factor which acts in the redistribution of fluid phases inside a hydrocarbon reservoir, after the production of oil ceases and the reservoir is abandoned. This fluid redistribution is called a *tertiary migration* and stands at the basis of production resumption of abandoned oil reservoirs. After a primary production, recovery factors rarely reach values of 30-40 %, and an important quantity of oil is left behind. What is characteristic for an abandoned oil reservoir is the maximum disorder of phase displacement due to the different Darcy velocities of each phase which moves through the pore space towards the producing wells. Depending on the rates with which the wells produced and on the type of reservoir (active/inactive aquifer, presence/absence of initial gas cap), in the primary production stage, gas phase has a tendency to move downwards and water has a tendency to move upwards, thus *conning* appears and oil is bypassed. Extending the image to a larger scale, zones of gas and water will be formed in the middle layer around the producing wells. This shows an abnormal positioning of the fluid phases, given their densities and their correct hydrostatic position. On the other hand, even in the production stage, the phases tend to migrate to their rightful position, gas in the upper layer, oil in the median-layer and water in the lower layer.

The process is continuing after the reservoir abandonment. This migration takes place over decades with the result of oil and gas being redistributed and a high chance of having an economic production rate again. This is the case of many Romanian reservoirs which have produced in their primary stage and have been abandoned afterwards. Production resumption has been made and was successful on fields in Romania. The purpose of this paper is to present the main aspects regarding gravity drainage which is a very important factor in the tertiary migration process, as well as other factors which favor or disfavor the tertiary migration.

Basic Elements Concerning Gravity Drainage

Balance of forces

In the process of tertiary migration, recent studies [27] have pointed out four major aspects that govern fluid redistribution: (1) a movement from higher pressure zones to lower pressure zones, (2) a movement towards a normal gravitational setting (3) a movement so that there will be the smallest number of fluid interfaces and (4) repositioning at micro-scale level so that wettability equilibrium will be reached. Based on this classification, gravity drainage would be composed of the first two types of movement. In trying to view gravity drainage with the help of a balance of forces, three major forces can be identified: gravity, interfacial and friction. The papers [1], [4], [18] and others referred to an additional *buoyancy* and *viscous* forces. They also used the interfacial force under the name of *capillary force*, but capillarity requires small spaces and is a consequence of the interfacial force. Given the uneven distribution of the fluid phases, these forces will not be in balance and so the tendency would be towards equilibrium between them. In numerous works, two dimensionless numbers have been used as a criterion to evaluate the equilibrium of these forces: *Bond number* which is the ratio between gravity and capillary forces and *Capillary number* which is the ratio between the viscous forces and the capillary forces, but these two dimensionless numbers cannot alone guarantee a complete understanding of the migration. For our explanation of gravity drainage, from hereon we will use only the three forces mentioned. When speaking of gravity drainage, the force of gravity has a notable influence alongside the other two, but it will never be grater that any of them nor have a proportion comparable to the other two. Practically, gravity drainage is present in every reservoir but its effect is in geological time. Further on, we will discuss certain aspects that indicate a favorable fluid redistribution with the help of gravity drainage in human time.

One domain that uses gravity drainage to study the downward migration of fluids is ecology, where hydrocarbon pollution deteriorates the ground water. It is the so called nonaqueous phase liquids migration or simpler NAPL migration. This type of migration is based almost solely on gravity drainage, where oil-based fluids that are not recycled accordingly and are thrown on the soil move to the ground water and make it unusable. A comprehensive study [39] is made on this topic and it is observed that from the balance of forces standpoint, NAPL's gravity drainage process is based on the same parameters as the tertiary migration's gravity drainage process. Given the fact that a lot of funding is given to this domain, tertiary migration could be updated with data from NAPL migration. However, two major drawdowns occur in the two gravity drainage process comparisons: one would be that in the case of NAPL, the hydrocarbon-based fluids were never in equilibrium with the collector rock (soil), and a lot of changes occur during NAPL gravity drainage, like volatilization, solubilisation in passing ground water, rapid composition changes in the fluids due to reaction with the solids. The other issue would be that shales act as zones of fractured rock with preferential pathways and because of shale's property of high ionic exchange, the balance of forces would be distorted severely. Shales that are present in reservoir collector rock as impermeable bands are true barriers in the way of tertiary migration and greatly hinder the process, whereas in NAPL migration, they favour the process.

Phase fragmentation and regeneration

During oil production, predominantly will always be the interfacial-friction forces: far away from the wellbores, fluids will move more under the interface force and closer to the wellbore, friction forces will be predominant. During production, phase fragmentation occurs. It firstly develops around the wellbore and it is amplified with higher rates of production. One study made by *Terwilliger et al.* [5] showed the influence of increasing flow rates on gravity drainage. Gas breakthrough would occur much faster at high rates compared to low rates, thus leaving a lot of badly swept oil areas. At micro-scale, small volumetric entities arise such as droplets, bubbles, clusters or ganglia. Phase continuity will be diminished and the Jamin effect will be strong enough to stop the flow. The small entities will have several types of distribution such as pendular, funicular or ring and will position themselves in the micro capillary traps. Rocks that have a high degree of heterogeneity regarding pore size distribution will be able to better capture the fluid phases.

After the reservoir is abandoned, pressure distribution is uneven in the whole reservoir. Due to multiple factors such as production rate, skin factor, well interference and increased rock heterogeneity, pressure differences of tens of bars can exist between reservoir areas. The types of reservoir energy that were in the primary production stage are also very important to the pressure redistribution, for instance if there was a very active aquifer, water/oil contact moved upwards, gas would be dissolved in a higher proportion in the oil and thus it would have higher mobility and phase rearrangement through gravity drainage would be much easier. In this particular case, one disadvantage would be that the oil is very easily bypassed because of a higher mobility of the water.

Through coalescence, the small volumetric clusters will increase in size and the number of phase interfaces will drop and fluids will be able to reposition themselves easier in their corresponding place. At micro-scale level four types of flow are identified: homogenous flow, interface flow, droplet flow and annular flow. They are strongly dependent on the phase distribution, which was mentioned earlier, pore structure, and pressure gradients. Given the Jamin effect, gravity drainage will be hindered in the cases of interface and droplet flow. Maximum efficiency will be in the cases of homogenous and annular flow because of smaller pressures required to move the phases. Despite the enormous flow rates of the non-wetting phase in annular flow, this type of flow is the most unstable due to high interface area and in consequence, a very high free surface energy. A flow like this is very susceptible to degenerate in droplets. The homogenous flow also has a short duration of time, because it implies migration of a single fluid phase at a time through the pores. Given the phase distribution at reservoir abandonment, it is very unlikely that gravity drainage will be able to move significant amounts of volumes in this type of flow.

Rock wettability

One very important parameter that acts favorably towards a repositioning of fluid phases through gravity drainage is the rock wettability. Given the mineralogical composition of the rock and the chemical composition of the oil, the reservoir can have a preferential wettability by water, oil or have an intermediate wettability in which both phases wet the reservoir rock in an equal proportion. After abandonment, in an oil reservoir all three phases will be present. Another parameter which is important for the gravity drainage is the *spreading coefficient*. Details about the spreading coefficient are given elsewhere [26]. At micro-scale level, there can be identified two types of flow: one *bulk flow*, in which oil flows through relatively large volumes and one *film flow*, where oil flows as very thin layers on the surface of water. Observations on the three-phase flow have been made by *Kantzas et al.* [12] and *Chatzis et al.* [13] where they illustrate phase positioning and phase flow in an inert gas injection process. A very interesting study is given by *Vizika and Lombard* [19] in which they present a study of the gravity drainage through the point of view of rock's preferential wettability and spreading coefficient. They reach the conclusion that gravity drainage is very efficient in the case of positive spreading coefficient and when the rock is preferentially wetted by water or has an intermediate wettability. The key for successful gravity drainage is to maintain phase continuity. During production, saturation of oil decreases and its continuity deteriorates. This translates into droplets which due to Jamin effect become more and more difficult to move and end up being immobile. Having a positive spreading coefficient, hydraulic continuity of the oil phase is maintained and a repositioning of the fluid phases will produce much more freely. In the case of oil wet rocks however, water cannot form thin layers on the surface of the oil, hence water cannot film flow on the oil surface. In this case gas is going to be separated from the water by an oil layer and moving the residual droplets of water is not going to be the same as moving the residual droplets of oil. The gas phase is very little affected by the wettability of the rock. Due to their higher mobility, gases which are in excess will migrate very easy to the upper layer via the pores that have large dimensions. The interfacial tension between oil and gas is smaller than the interfacial tension between gas and water, so in oil-wet rocks the gas phase should migrate more easily. This advantage that oil wet rocks would have is compensate by the long periods of time which are needed in order for the fluids to reposition through gravity drainage.

Another important aspect for efficient gravity drainage would be the macro-scale rock wettability variation. Due to mineralogical variation of the rock and the pore size distribution, wettability will have sometimes strong variations. This points out to zones that will have different sweep efficiencies. Some zones will be well swept, others totally bypassed. Thus, small portions of the reservoir will have isolated zones with high oil saturation. They will act as local reservoirs in the process of saturation regeneration and a more uniform redistribution of the phases can be obtained.

Gravity drainage mathematical model

Tertiary migration is a very complex phenomenon and still needs a more thoroughness approach. The defining results in this case should be a velocity of the migrating fluids, and a time in which a given volume of fluids rearrange. At the present time, there is no mathematical model to determine the two parameters or to try to simulate the process itself.

For gravity drainage, many mathematical models exist in the literature. Out of them, we would like to point out the models of *Sahni et al.* [21], *DiCarlo et al.* [22] and *Pedrera et al.* [23] in which attention is focused on oil saturation variation. Having all three phases present in the pores, gas phase will tend to migrate upwards, whereas oil phase will tend to go downwards. Because of pore structure and micro capillary traps, above the gas/oil contact will be a small saturation in oil which is immobile. A study that shows the influence of pore size distribution index and the volume of oil trapped is made by *Li and Horne* [24]. In the lower zones, an *oil buildup* is formed in which in which oil saturation increases fast. Given the fact that gas is non-wetting phase to the rock in respect to oil, a similar process can be imagined between the oil and water, where oil is the non-wetting phase to the rock with respect to water. The mathematical model applies as well to the cases where oil is the preferentially wetting phase. From the mathematical models of gravity drainage, two extremely valuable parameters are obtained: the relative permeability towards the oil phase and gas phase or towards the oil phase and water phase. Also, the time in which gravity drainage takes place on small core samples is very important when extrapolating to reservoir scale. Direct observations on the relative permeability helped better understand the fluid redistribution. For instance, in water-wet rock samples compared to oil-wet rock samples and given the chemical nature of both water and oil, water occupies the smallest pores, corners, grooves, crevices and gas occupies the larger pores whereas for the oil-wet rock both water and gas race for the larger pores. This results in a more pronounced phase fragmentation so a lesser relative permeability towards the phases. A first indication would be that gravity drainage is expected to work better in water-wet reservoirs that in oil-wet reservoirs. Measurements of absolute permeability on rock samples cannot alone assure a successful gravity drainage, and also an increased value of absolute permeability does not mean a favorable condition for easier fluid migration.

Field verification and examples

Gravity drainage is a process that acts not only after a reservoir is abandoned, but it present including when the reservoir is in production. In the first years of production gravity drainage cannot be observed. Depending on the main energy of the reservoir, gravity drainage shows a few particular signs: for instance, when an aquifer is active and oil continues to be produced with high water cuts for a long period of time. When cumulative of oil is plotted versus time, it has a small growth over a long time, similar to a tail. These long tales of production offer a good hint that after shut-in, fluids will have a good opportunity to redistribute more easily through gravity drainage. Another example is when an inclined reservoir with initial gas cap has wells drilled down-dip. A reservoir such as this would produce with relative small and constant production GOR over long periods of time. This would be another hint for effective gravity drainage.

In one study, three reservoirs have been pointed out for a good production under gravity drainage. *Dykstra* [9] showed that for these three reservoirs, the produced oil was in high proportion under the mechanism of gravity drainage. If a look is taken at the reservoir's characteristics, one can see that all three of them have a fair inclination, and the oil has reduced dynamic viscosity. This would mean that the oil has a higher mobility and could redistribute more easily. Unfortunately, the author did not mention anything about pore size distribution and the heterogeneity of the pore space. Also, no detail is given on the possibility of production resumption for these reservoirs nor on the idea that gravity drainage could work to restore the saturation state in a possible abandonment of the reservoirs.

Another field case study presented by *F. Minescu et al.* [27] shows two reservoirs which have been put into production over 70 years ago. They entered production with high oil rates, such as 50 Mtons/Day and have produced for about 25 years. The reservoir fluid characteristics are similar to those mentioned above. Because of the high production rates, rapid pressure decline occurred. Gravity drainage worked well in these reservoirs, because they were reopened approximately 20 years ago and gave low water cuts and fair production rates. Tertiary migration is a good example for these two reservoirs that fluids can redistribute to values that restore the economic interest of a reservoir. The minimum time in which tertiary migration would start to have an effect on saturation restoration would be 30 years, although this value is not a warranty for a successful process.

Conclusions

1. Gravity drainage can be viewed as equilibrium between gravity, interface and friction forces. Given the fact that both phase distribution and pressure gradient are very diverse in an abandoned reservoir, the fluids will tend to a stable state both from a hydrostatic point of view and from a wetting point of view.
2. Gravity drainage is very favored in homogenous type flow and in annular type flow. Specific for these flows would be a transfer of high fluid volumes in a short duration of time, hence a sharp saturation restoration. Unfortunately, these flow regimes have a very small timespan, the annular flow due to its high interface area and the homogenous flow because of the unlikely hood of a single phase to exist in the pore space for long distances.
3. Spreading coefficient is a very important parameter for the gravity drainage process. If it has a positive value, then oil can form very thin layers on the surface of water. If the value is

negative, both for water-wet rocks and oil-wet rocks, water cannot form the same thin layers on the surface of oil and droplets will form very rapidly, thus making gravity drainage a slower and more time consuming process. The key would be maintaining hydraulic continuity of the oil phase.

4. The mathematical model offers a solution for determining the relative permeability towards the fluid phases. This value is closer to a truer interpretation of the efficiency of the gravity drainage and could be used is computerized simulation for more accurate results.
5. If gravity drainage is known to have had a high influence for a certain abandoned reservoir, this could point to an efficient tertiary migration that could have taken place in a shorter period of time, thus resulting economically attractive saturation states. This could prompt the certain reservoir for a study on the production resumption potential.

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Drenajul gravițational – O componentă importantă a migrației terțiare a țițeiurilor în zăcăminte abandonate
I. Concepte de bază

Rezumat

După abandonarea zăcămintelor de țiței, distribuția saturațiilor fazelor fluide în cuprinsul zăcământului este una haotică. Noua așezare a fazelor fluide în spațiul poros este foarte instabilă datorită diferențelor de densitate dintre ele. Fluidele vor tinde spre o noua poziție de echilibru care va fi una normal gravitațională. Drenajul gravitațional este principalul factor ce acționeazăîn sensul redistribuirii fluidelor, și la rândul său este o componentă importantă a unui proces mai amplu denumit migrație terțiarăcare va avea ca finalitate o nouă stare de saturație cu hidrocarburi a rocii ce va motiva economic o nouă redeschidere. Un studiu asupra drenajului gravitațional este przentat în care se examinează parametrii principali ai acestuia și sunt prezentate exemple în care drenajul gravitațional a contribuit la o producție îndelungată a țițeiului.