HYDROCARBON MOVEABILITY FACTOR (HCM): NEW APPROACH TO IDENTIFY HYDROCARBON MOVEABILITY AND TYPE FROM RESISTIVITY LOGS

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Resistivity data is normally used to evaluate water saturation using porosity values from porosity logs (neutron and density). Determination of initial oil (gas) in place is based on hydrocarbon saturation, porosity and thickness obtained from openhole logging data for a given drainage area. It is important not only to determine the initial hydrocarbon in place, but also to define the existing hydrocarbon moveability, indicating the recoverable hydrocarbon and its type. This paper presents a new approach of hydrocarbon moveability factor (HCM). This factor is derived from shallow and deep resistivity data. The relation \( F = \frac{a}{\phi^n} \) is correct in water saturated zone. In partially saturated zones this relation becomes invalid and it will give the apparent formation resistivity factor (Fa). Based on this idea the hydrocarbon moveability factor (HCM) has been derived. With scale goes from 0.0 to 1.0, it is found that, for HCM greater than 0.75, the hydrocarbon is moveable and for HCM less than 0.75, the hydrocarbon is immovable. When HCM is less than 0.25, the moveable hydrocarbon is gas and for HCM greater than 0.25 and less than 0.75, the moveable hydrocarbon is oil. Field examples have been analyzed with the HCM factor. These field examples demonstrated the contribution of HCM in the field of hydrocarbon type identification and determination of hydrocarbon moveability from openhole resistivity logging.

1. INTRODUCTION

One of the most important functions of the reservoir engineer is the periodic calculation of the reservoir oil and gas in place and recovery anticipated under the prevailing reservoir mechanism(s) and conditions. Oil recovery is a reflection of the mobility of hydrocarbons through porous media. This mobility is controlled by reservoir rocks and fluid properties, and pressure gradient. Oil in place is calculated either by the volumetric method or by material balance equations. The recovery factor is determined from displacement efficiency studies or from correlations based on statistical studies of particular types of reservoir mechanisms. This study presents new concept of determining the recovery factor from resistivity logs. Recovery factor calculated from resistivity data can be used to foresee the final recovery factor after compiling all petrophysical, reservoir fluids and geological data [1-3]. Field examples have been analyzed in order to test the applicability of the resistivity derived recovery factor and oil mobility factors. It is found that, resistivity derived recovery factor can predict the recovery factor in a given well, that may be extended to the related reservoir. Meanwhile, oil mobility factor indicates the mobility of the hydrocarbon in place under normal conditions.

2. THEORETICAL BACKGROUND

The idea behind this technique of calculating the hydrocarbon recovery factor is based on the concept of the tendency of the fluid to move away due to the mud invasion. The invasion profile is controlled by two factors 1) drilling fluid condition and 2) Fluid and rock properties. The effect of drilling fluids become more or less effective depending on the type of drilling
fluids and mud pressure. Among fluid and rock properties affecting the fluid invasion, fluid viscosity, rock permeability and effective formation porosity are the most important factors [4-6].

Normal invasion profile contains the flushed zone, where the main saturating fluid is the mud filtrate and virgin zone where the main saturating fluid is the fluid(s) filling pore spaces; oil, gas and water.

In clean formation there is always residual oil in addition to free water in the flushed zone in clean formation. In shaly formation there is bound water effect. The volume of this bound water depends on formation water chemical composition, clay minerals type and shale volume [7, 8].

2.1 Clean Formation
In clean formation, water saturation, Sw and flushed zone saturation, Sxo are determined from clean formation water saturation model, Archie formula. Water saturation, Sw is calculated as:

\[ Sw = \left( \frac{F_{rw}}{R_{t}} \right)^{0.5} \]  

Flushed zone saturation, Sxo is calculated as:

\[ Sxo = \left( \frac{F_{mf}}{R_{xo}} \right)^{0.5} \]  

The determination of recovery factor from resistivity logs makes use of shallow log reading in flushed zone and deep log reading in virgin zone.

2.2 Fully Saturated Formation
In case of fully water saturated formation, formation resistivity factor (F) is a rock property; relates rock electrical property to its porosity and cementation factor. Formation resistivity factor is a rock property and independent of saturating conditions.

For \( Sw = 100\% \)

\[ F = \frac{a}{\phi^{m}} = \frac{R_o}{R_w} \]  

Ro is rock resistivity fully saturated with formation water and formation water resistivity, Rw. In a given rock, this equation is correct provided that pore spaces are fully saturated with water.

2.3 Partially Saturated Formation
In case of partially saturated rock, the calculated formation resistivity factor will change from the value if the section is 100\% saturated with water.

In virgin zone

\[ F_d = \frac{R_d}{R_w} \]  

Fd is the apparent formation resistivity factor, Rd deep log reading and Rw is formation water resistivity.

In flushed zone

\[ F_s = \frac{R_s}{R_{mf}} \]  

Fs is an apparent formation resistivity factor, Rs shallow log reading in flushed zone and Rmf is mud filtrate resistivity.

2.4 Hydrocarbon Moveability
In water zones, it is found that \( F = F_s = F_d \). This is based on the fact in water zone Rt may be considered equal to Ro, then \( F = F_d \) from Eq. 1. In the flushed zone there is no residual oil (\( Sxo = 100\% \)), under this condition \( F_d \) equals to \( F \) from Eq. 2. In oil bearing formation, \( F_d \) and \( F_s \) values are greater than \( F \) value. The oil is considered immovable if the relative distribution of oil, water has not been changed after mud filtrate invasion, e.g. \( Sxo = Sw \). This fluid saturation condition is expressed as \( F_d = F \). In case of hydrocarbon moveability, \( Sxo \) will be greater than \( Sw \) e.g. \( F_d \) is greater than \( F_s \) factor. The degree of hydrocarbon moveability is expressed by hydrocarbon moveability factor (HCM) which equals to \( Sw / Sxo \) or the ratio between \( Fs \) and \( F_d \). The quantity of moveable hydrocarbon can be expressed per unit volume as the difference between flushed zone saturation and water saturation (\( Sxo - Sw \)) and the recovery factor can take the form of ratio between the moveable oil and initial oil (1-\( Sw \)). It will take the form

\[ RF = \frac{(Sxo - Sw)}{(1-Sw)} \]  

Then

If \( F = F_s = F_d \), it is water section

If \( F < F_s \) and \( F_s = F_d \), it is hydrocarbon section, but it is immovable

If \( F < F_s \) and \( F_d > F_s \), it is hydrocarbon section and it is moveable

Using \( F \) values recovery factor (RF) defined in Eq. 6 can take the following form

\[ RF = \left[ \frac{1}{F_d^{0.5}} - \frac{1}{F_s^{0.5}} \right] / \left[ \frac{1}{F_d^{0.5}} - \frac{1}{F^{0.5}} \right] \]  

The ability of hydrocarbon to move from one point to another can be identified by looking at flushed zone and virgin zones fluids saturation. Hydrocarbon movement ability can be defined using hydrocarbon moveability factor, (HCM).

Hydrocarbon mobility Factor (HCM) = \( (Fs/Fd)^{0.5} \)  

The ratio (Fs/Fd) is good indicator of hydrocarbon moveability. This ratio goes from 0.0 to 1.0. From experience, it is found that if HCM is less than 0.75, the hydrocarbon is moveable. When the value of HCM is less than 0.25 the moveable hydrocarbon is either gas or light hydrocarbon. In case of HCM value is between 0.25 and less than 0.75, the moving hydrocarbon is oil. When HCM is greater than or equal to 0.75, the existing oil is immovable. This HCM factor is helpful to define the ability of hydrocarbon movement, well productivity and the type of moveable hydrocarbon.
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2.5 Assumptions

This technique of predicting hydrocarbon recovery factor and oil movement by defining oil mobility factor from resistivity logs is subjected to two assumptions:

1- There is no significant change in rock petrophysical properties; permeability and porosity in the area around the borehole due to mud invasion. This is with reference to formation porosity and permeability at time of production.

2- Fluids flow regime during mud invasion where formation fluids are flushed away is similar to fluid flow regime during production, where formation fluids are moving toward the wellbore.

2.6 Benefits

The proposed technique of determining hydrocarbon recovery factor and oil mobility from resistivity logs provides the petrophysicist with the following benefits:

1- At early stage of the well life, resistivity derived recovery factor (RF) might be a good indicator for further action required especially in case of water drive reservoir.

2- Hydrocarbon moveability (HCM) is an excellent indicator of mobile hydrocarbon during well tests.

3- Values of oil mobility is very helpful in selecting the perforation intervals

2.7 Limitations

Recovery factor, RF and hydrocarbon moveability (HCM) technique is applicable in water base muds. In case of oil base mud drilling fluid and depleted reservoirs, this method requires further study.

1- In case of thin laminated shaly sand layers, the values of recovery factor and oil mobility may become inconclusive.

2- This technique has limited applications in case of thin layers, where the resistivity tools suffer from vertical resolution problems.

3- This technique has limited application in the cases of dissolved gas reservoirs and gas cap reservoirs. This is because of the driving mechanism in these reservoir is gas/ liquid displacement mechanism which is different from the mud filtrate/ water/ oil viscous displacement mechanism.

3. FIELD EXAMPLES

This section is devoted to test the applicability of HCM and RF technique. Six field examples from Western desert fields, Egypt have been analyzed. The goal of this analysis is to investigate the contribution of the proposed technique for improving the accuracy of the analysis and increasing the amount of information from any given logs.

3.1 Field Example 1

This field example presents a case of a well encountered limestone formation known as A/R formation, Western Desert, Egypt. Fig. 1 shows logging data with interpretation. Tracks 1-4 are log data. Track 5 shows that interval 2611-2626 m is
3.2 Field Example 2
This is another example of hydrocarbon immovability in A/R F formation, Western Desert, Egypt. Water saturation values in track 6, Fig. 2 indicate that A/R formation has oil section interval 2500-2515 m. HCM factor illustrated in track 5 m shows oil section is moveable in the interval 2507-2515 (HCM is the range of 0.58), while the interval 2500-2507 has immoveable oil (HCM is greater than 0.80). Oil immaturity in the upper interval and maturity in the lower interval indicates that this well was drilled in an area where A/R F started to move from source rock formation to a producing formation. This conclusion has been confirmed after drilling well in nearby area and A/R F formation was tested in oil producing.

3.3 Field Example 3
This example shows log data in a well producing from sandstone reservoir, lower section of the A/R G formation, in Western Desert, Egypt, Fig. 3. Flushed saturation Sxo and water saturation Sw curves in track 7 indicate hydrocarbon interval 3507-3512 m. Track 8 shows HCM factor values which are in the range of 0.39 and 0.60. This range indicates that this is moveable hydrocarbon. Recovery factor, RF, in track 8 shows a good predictive recovery factor (range of 0.23-0.47) with an average of 0.35. Well test of this interval has shown oil section well oil rate has increased from 150 BOPD to 600 BOPD after perforating this interval.

3.4 Field Example 4
This is a field example of sandstone reservoir Bahariya formation, Western Desert, Egypt, Fig. 4. Logging data show that depth interval 3682-3693.5 is a hydrocarbon interval, track 7 shows Sw and Sxo curves. Hydrocarbon moveability factor HCM shown in track 8 was in the range of 0.3-0.42 with an average of 0.36. This low value indicates that either the hydrocarbon is light or there is gas associated with the oil production. Well test of this interval has given 1.7-2 MMSCF/D of gas and oil rate of 650 BOPD. It is obvious that the prediction of HCM factor was confirmed by the test results.

3.5 Field Example 5
Figure 5 shows a field example from Western Desert, Egypt. This well produces oil from two intervals; 3552-3557 has moderate permeability and porosity & 3566-3571 has higher porosity and permeability than first interval, as shown in tracks 5 and 9. These intervals are hydrocarbon bearing as depicted by Sw and Sxo curves in track 6. HCM curve in track 7 indicates that lower interval (Average HCM = 0.27), is better than upper interval (Average HCM = 0.57). Recovery factor in lower interval is about 0.48 and in
Figure 3. Log of moveable oil in sandstone reservoir (Example 3), Western Desert, Egypt.

Figure 4. Log of moveable oil in sandstone reservoir (Example 4), Western Desert, Egypt.
Figure 5. Log of moveable oil in sandstone reservoir (Example 5), Western Desert, Egypt.

Figure 6. Log of moveable gas in sandstone reservoir (Example 6), Western Desert, Egypt.
upper interval is about 0.24. This derived recovery factor was confirmed by the dynamic model results after putting this well on production.

3.6 Field Example 6

This is a field example of a gas well which produces from sandstone reservoir, A/R G formation, Western Desert, Egypt, Fig.6. Intervals 2637-2639 and 2640-2644 have hydrocarbon potential based on logging data analysis; track 6 shows Sw and Sxo against these intervals. Hydrocarbon moveability factor HCM shown in track 7 has values of 0.17 and 0.21; these values indicate that this is gas producing intervals. Well test confirmed that intervals flowed with 12.8 MMSCF/D of gas and 570 BOPD.

4. CONCLUSIONS

From the above analysis, the following points are concluded:

- Hydrocarbon moveability factor HCM reflects the hydrocarbon movement under normal conditions.
- HCM factor can help in identifying type of saturating hydrocarbon (oil or gas).
- Recovery factor determined from resistivity logs may be considered as primary recovery factor in case of water drive reservoir and as indicator for other types of reservoirs.
- The use of RF and HCM are good factors describing the performance of the well-drained area of the reservoir.
- HCM & RF technique has limited applications in oil base mud wells

5. NOMENCLATURES

- a tortousity factor
- m cementation factor
- n cementation exponent
- F formation resistivity factor
- Fd formation resistivity factor, deep
- Fs formation resistivity factor, shallow
- HCM hydrocarbon moveability factor
- RF recovery factor
- Sw water saturation
- Sxo flushed zone saturation

6. REFERENCES