Residual Gas Saturation in Gas Reservoirs

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Abstract: The value of residual gas saturation to water influx (Sgr) is a critical property when estimating recoverable reserves in gas reservoirs overlaying active aquifers, or natural gas storage reservoirs. It is customarily assumed that when a gas reservoir is overlaying an aquifer, water will imbibe into the gas-saturated zone with the onset of gas production. The process of gas displacement by water will be forced imbibition in areas of high drawdown and spontaneous imbibition in the areas of low drawdown. Early work in the 1950s and 1960s established that Sgr was not going to be as low as 10-15% PV, as was commonly expected at the time. But now, published values of Sgr vary between 15 and 80%. The mechanism of trapping is not clear, some factors that may has important effect on Sgr does not study very well and there is not clear reason for some phenomena that occur in gas saturated plugs. There is no relationship that could estimate Sgr as function of reservoir characteristics. The results with different authors, sometimes is quite different. So this subject deserves further investigation. This paper summarizes some work done on the subject of residual gas saturation and this paper will provide a good reference for researchers who are interested in investigating residual gas saturation in water drive reservoir.

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1.Introduction:

Numerous papers have been written on the subject of residual oil saturation from imbibition, but fewer on the subject of residual gas saturation of imbibition. The common conception is that many of the principles that cover oil and gas reservoirs are the same.

Early work in the 1950s and 1960s established that Sgr was not going to be as low as 10-15% PV, as was commonly expected at the time. But now, published values of Sgr vary between 15 and 80%.

Many studies have attempted to understand gas-trapping mechanisms according to various research axis: First, Geffen et al. (1952) established that residual gas saturation measured in the laboratory on core samples is the same as in a gas reservoir. Later results (Crowell et al.(1966), Delclaud, Katz et al.(1966), Mc Kay (1974) and Chierici et al.(1963)) proved that simple experimental conditions may be representative of gas trapping in reservoirs. The effect of water flooding rates on Sgr was found to be negligible (Geffen et al, Crowell et al, Delclaud) . Katz showed that the residual gas saturation left behind the moving water front remains constant and equal to that obtained during the measurement of capillary pressure. Several authors demonstrated that Sgr obtained by water flooding and spontaneous imbibition are very close (Geffen , Crowell and Mc Kay), provided the reduction in Sgr due to diffusion is disregarded (Delclaud). The effect of the type of displacing liquid was also found to be negligible (Geffen, Kyte et al. (1956) , Jerauld (1966)). The same Sgr values were obtained whatever the pressure and temperature prevailing during the core test (Geffen, Chierici et al., Delclaud, Mc Kay).

Geffen *et al.* investigated some factors, which effect the residual gas saturation, such as flooding rate, static pressure, temperature, sample size and saturation conditions before flooding. They found that water imbibition on dry plug experiments was different from water flooding experiments with connate water.

They also concluded that at reservoir conditions of temperature and pressure and reasonable rates, the effect of water flood rate on the efficiency of gas displacement is negligible. And this is the answer of essential questions that whether or not residual gas saturation indicated from small core relative permeability tests at atmospheric pressure and room temperature are representative of the residual gas saturations which could be expected after water flood of natural reservoirs!

Keelan and Pugh (1973) concluded that trapped gas saturation exists after gas displacement by wetting phase imbibition in carbonate reservoirs. Their experiments showed that the trapped gas varied with initial gas in place and it was a function of rock type.

Fishlock *et al* .(1988) investigated the residual gas saturation as a function of pressure. They focused on the mobilization of residual gas by blowdown. The trapped gas apparently did not become mobile immediately as it expanded. The gas saturation had to increase appreciably to a critical value for gas remobilization.

Chierici *et al.* (1963) tested whether a reliable value of reserves can be obtained from reservoir past production performance or not, by analyzing results from six gas field experiments. They concluded that different gas reservoir aquifer systems can show the same pressure performance in response to a given production schedule.

Pow *et al.*(1999) addressed the imbibition of water in fractured gas reservoirs. Field and laboratory information suggested that a large amount of gas be trapped through fast water imbibition through the fractures and premature water breakthrough. The postulation was made that such gas reservoirs would produce this gas if and when the bypassed gas was allowed to flow to the production intervals under capillary controlled action. The issue was raised on whether the rate of imbibition could enhance the production of this trapped gas. Preliminary experiments in full diameter core pieces showed that the rates of imbibition were extremely slow.

It must be noted that several attempts have been made in the past to group data from different reservoirs or conditions and quantify the value of residual gas saturation (Agarwal 1967-Crowell *et al* 1966 , Batycky *et al* 1998).

Crowell *et al.* (1966) discussed the efficiency of gas recovery by water imbibition. It was shown that gas recovery is a strong function of the initial gas saturation and that the maximum recovery is obtained at zero initial water saturation. They observe slight increase in gas recovery with a reduction of interfacial tension. They concluded that the effect of permeability seemed to be rather convoluted when different sandstones were employed. Finally, for the fluids they tested, there was consistent behavior of the gas recovery efficiencies irrespective of the fluid (water, brine or oil) used.

Katz *et al*. (1966) studied how water displaced gas from porous media. A method of predicting residual gas saturation behind an advancing waterfront was obtained. They found that residual gas saturation at the base of a porous bed appeared to be the same as that of gas saturation on a relative permeability curve at zero relative permeability. It was also concluded that only a very general relationship existed between gas saturation and porosity and no relationship was found with permeability.

Kantzas *et al*. (2000) discussed the effect of core conditioning on residual gas saturation and found that rate of imbibition, wettability and production history seemed to play an important role on the final value of residual gas. They conclude from their experiments that initial wettability and the brine salinity of the system strongly affected the gas recovery. Core that did not go through the repeated cleanup cycles had significantly higher residual gas saturation. They also found that semi-empirical models such as the Land model to be accurate for a limited number of samples.

The experiments done by researcher reveal that the mechanism of water influx in a gas reservoir is quite complicated. Production history and saturation affect the results of gas recovery. It is apparent that the rate of imbibition (i.e., the speed by which water invades the pore space) also varies with initial conditions and production history. (Kantzas et al. 2001) observation of experiments show that residual gas saturations sometimes are quite similar while they are quite different in other cores; however, no significant difference exists in the procedures and other parameters.

The experiments done by researchers are quite sporadic. Sometimes we see the result and conclusions is quite different. So in this paper, I tried to use the results of work done by researcher, based on two factors: first, the number of experiments that done by the researchers and second number of time that other authors referenced to that researcher.

2.Literature review:

Behaviour of residual gas saturation:

It is observed two trends in the relationship between gas saturation and production time:

- the first step, with a steep slope, corresponds to the advance of the liquid front through the sample by capillary rise.
- the second step, with a smaller slope, occurs after the liquid front has reached the upper face ; it denotes a trapped gas diffusion process.

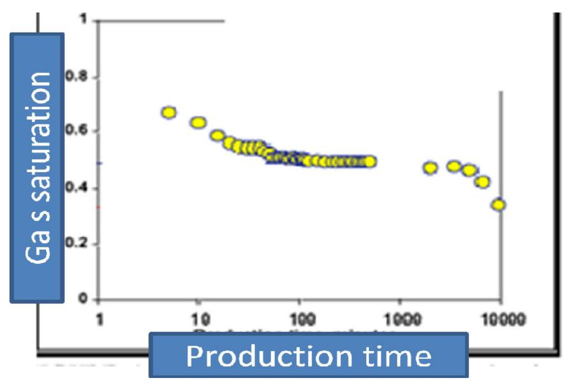

Figure 1 : residual gas saturation behaviour.(Ding and Kantzas)

The intersection point of the two steps allows to determine the maximum residual gas saturation SgrM. Delclaud has observed that the exchange in second step is inversely proportional to $\sqrt{P\,abs}$ Therefore; we can anticipate that the diffusion phenomena will be of small importance at reservoir conditions.

Study of reservoir characteristics effects on Sgr:

Many studies have tried to correlate trapped gas saturation to reservoir characteristics (Geffen (1952), Crowell et al.(1966), Delclaud, Katz et al. (1966), Mc Kay (1974), Chierici et al.(1963),Keelan (1976) and Jerauld (1968)). Katz et al. have underscored a relationship between SgrM and porosity: as porosity increases, SgrM decreases. Following authors have confirmed this single but scattered trend (Delclaud, Katz et al.(1966), Mc Kay (1974), Chierici et al.(1963),Keelan (1976) and Jerauld (1968)).Suzanne et al.(2001) and Hamon et al (2001) have presented a new trend SgrM-porosity; and they have shown the influence of microporosity and pore size on SgrM values. Chierici et al presented the first and the larger Sgr results with 251 measurements on small samples of different lithological types: but they failed to correlate Sgr values with porosity, permeability or irreducible water saturation. Attempts to correlate Sgr with distribution of pore entry radius and several combinations of porosity and permeability were also unsuccessful.

Jerauld (1996) studied Prudhoe Bay sandstone and conglomerate. He concluded that the maximum trapped gas saturation depends primarily on porosity, grain sorting, and microporosity. He also found a significant decrease in Sgrm with rising clay content. Conglomerates have, on average, a lower level of trapped gas at a given porosity level than sandstone. SEM photographs confirm the pore size to pore throat ratio as explanation of the gas trapping variation.

It is agreed that the main factors affecting trapping of the strongly non-wetting phase are pore-to-throat ratio, throat-to-pore coordination number, type and degree of heterogeneity and surface roughness (Wardlaw, 1978).

It is sometimes stated that Sgr is a function of Sgi only. (Skauge et al. (2002)).but wide range of experiments that done with Suzanne et al.(2003) show that Sgr values are function of both rock characteristics with porosity (or permeability) and microporosity content, and of initial gas saturation. Also, they conclude that microporosity does not trap gas and gas trapping takes place in the macroporosity. In the below we will see the relationship between Sgr and rock and fluids characteristics.

Initial saturation:

A starting point is the recognition of a relationship between the initial saturation of a phase and, following displacement, its residual saturation. The concept that increased residual saturations result when initial saturations are higher is described by many authors. (Craige et al (1971), Stegemeier (1977), Keushnig (1976)). The models for estimating the Sgr, that will be described later.

Initial imbibition rate:

Depiction of the residual gas saturation measured as a function of the estimated initial rate of imbibition, as obtained from the experimental data has a function as below:

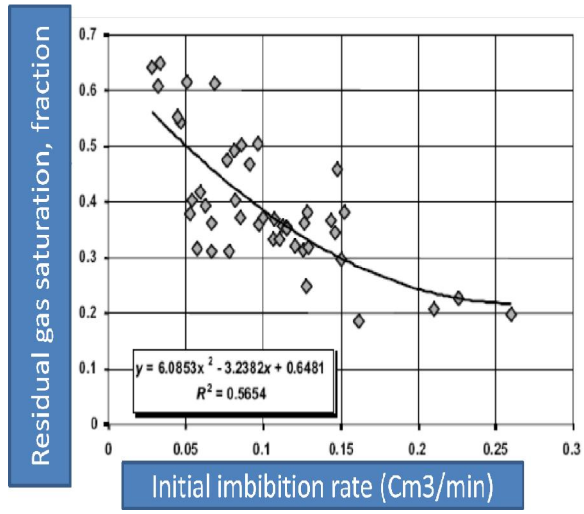

Figure 2: Residual gas saturation as function of initial imbibition rate
(Kantzas et al.(2001))

The imbibition rate was calculated from the slope of the gas-production volume curve with time for the first 10 minutes. High initial rates of imbibition imply that the water will rush inside the pore space and should be associated with strong water-wet conditions.

Wettability:

Wettability plays a very important role in the recovery of gas through the spontaneous-imbibition mechanism and by increasing wettability in this mechanism the amount of residual gas saturation will decrease (recovery increase). It is believed that this mechanism is the strongest driving mechanism in the reservoir away from the perforations, and this is why it is important to understand how it is related to residual gas saturation.

Ding and Kantzas (2002) show that concurrent imbibition test and counter-current imbibition tests have a significant difference in the initial imbibition rates. However, the residual gas saturations from counter-current imbibition tests are similar to co-current tests for carbonate and sandstone plugs. This indicates that the gas recovery will reach the same level after long time water influx.

Figure 3 show that the residual gas saturation after the long spontaneous imbibition test decreases with increasing waterwetness, whereas it increases after brine flooding with increasing water-wetness. Following authors have confirmed this

(Ding and Kantzas (2001), Kantzas et al.(2000), Zhou et al.(2000)). Amott Index to water is defined as a ratio of gas produced from spontaneous imbibition to gas produced from both spontaneous imbibition and forced imbibition.

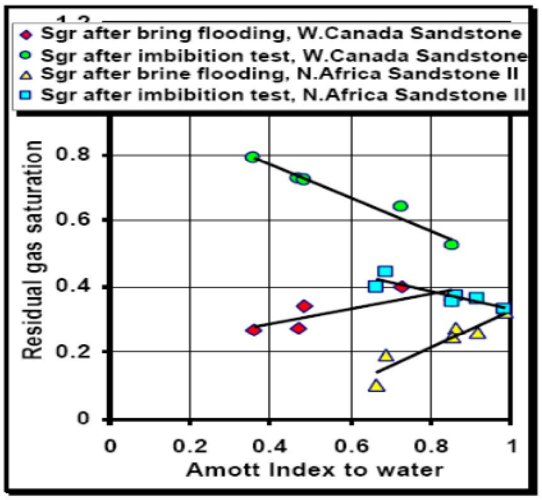

Figure 3: Relationship between residual gas saturation and wettability for sandstone plugs.(Ding and Kantzas, 2001)

Porosity:

Suzanne et al. do a wide range of experiments and also they use large sets of literature data to find a relationship between Sgrm and porosity and finally they conclude:

Sgrm versus porosity plots show three major trends(as we see in figure 4):

- Two very different but clear trends in the low to medium porosity range, i.e. below 14%. As porosity increases, Sgrm decreases for clay free sandstone whereas it increases for other shaly sandstones.
- Concerning the highest porosity values, i.e. above 14%, the two trends above merge around an average Sgrm of 25%.

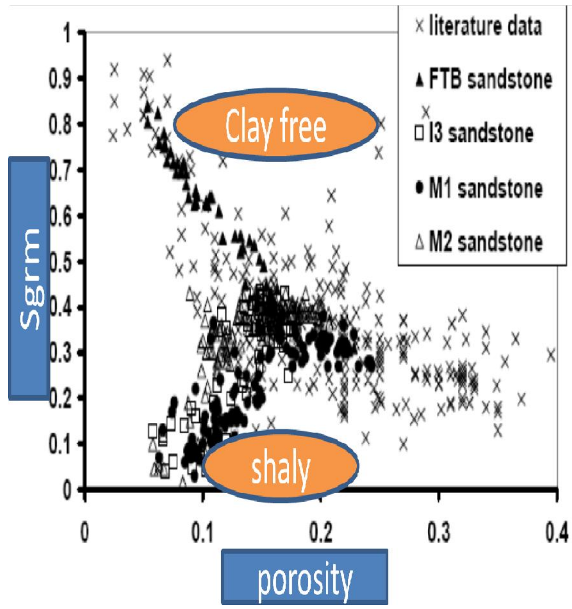

Figure 4: the effect of porosity and clay content on Sgrm.(Hamon et al.(2001))

Observations suggest that trapping mechanisms differ in the high and low porosity regions depending on the amount of clay and the pore network geometry.

Clay type influence:

Presence, type, structure and location of clays within the porous network are known to influence petrophysical characteristics such as permeability and irreducible water saturation (Wilson, 1977). different clay types: illite, smectite, illite/smectite, kaolinite and chlorite. Suzanne et al. conclude the amount of clay controls the Sgrm versus porosity relationship. Sgrm decreases as the clay content increases. Attempts to correlate Sgrm with any of the clay types were unsuccessful.

Influence of Microporosity:

Result of experiment done by Hamon et al. (2001) show that the presence of clay and microporosity controls whether a sandstone will belong to the uppermost or lowermost porosity/SgrM trends.

Permeability:

Very similar behavior was observed for Sgrm versus permeability trends by Hamon et al. (2001). as we see in below figure:

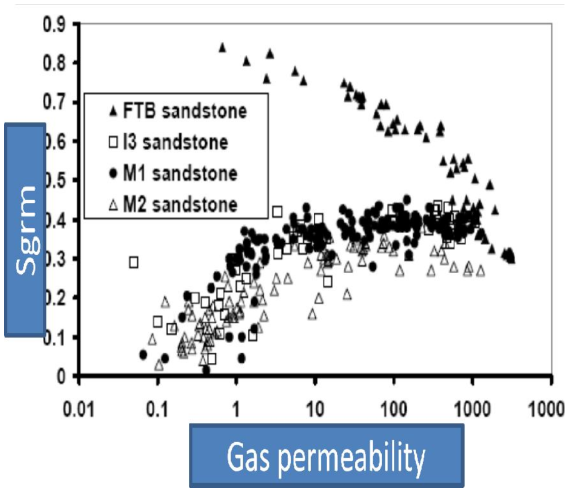

Figure 5: SgrM versus gas permeability (Hamon et al.(2001))

Some authors (Batycky (1998), Keelan and Pugh) stated that with increasing cementation and hence decreasing pore throat size and permeability, residual saturations increase. They stated for a single rock type the dependence of trapped gas saturation on permeability can be correlated by plotting trapped gas saturation versus log permeability at single initial gas saturation.

Sgrm cannot be predicted a priori using porosity or permeability only, or any usual combination of the two.

Number of Phases Present:

Batycky et al (1998) stated when the liquid phase is not strongly wetting, such as when there is a connate saturation of a second non-displacing fluid or when contact angles are larger, viscous forces play a larger role. The net effect is a lowering of residual gas saturations when compared with situations in which spontaneous imbibition dominates.

The effect of other factors:

The results obtained by Delclaud, after a cumulative injection of 1 to 2 pore volumes of brine show that, Sgr is not affected by : the length of the sample, the injection rate and operating conditions: ambient and reservoir pressure and also negligible effect of surface tension. This result also is verified by Geffent et al.

There is no clear relationship between Sgrm and grain density, or formation factor, or cementation factor.(Hamon et al.(2001), Suzanne et al.(2001)) .

3. Models:

The criteria that I used to name the relationship are the number of experiment that authors done to reach these relationships and numbers of time that these relations are mentioned in papers.

Agarwal (1965) addressed the relationship between initial and final gas saturation from an empirical perspective. He worked with 320 imbibition experiments and segmented the database to develop curve fits for common rock classifications. The Agarwal's Model was given as:

$$S_{gr} = 0.1813 \times S_{gi} + 0.096071 \qquad equ.1$$

In 1968, Land proposed a hyperbolic law to estimate Sgr values from Sgi values, based on Swir and Sgr@Swir values. His aim was the calculation of end points of relative permeability curves. He has first proposed this law with six experimental relationships of the literature. Later, Land (1971) has validated this relationship with his own experimental data measured on two samples. Originally, the Land's law is limited from 0 to 1-Swir as below:

$$\frac{1}{S^*_{gr}} - \frac{1}{S^*_{gi}} = C = \frac{1}{Sgr@Swir} - \frac{1}{1-Swir} \qquad equ.2$$

C parameter is Land's coefficient which is assumed to be only rock dependent. Its value is defined by the end point of the Sgi -Sgr curve.

A simplified form of Land's law, based on real gas saturation, is commonly used:

$$\frac{1}{S_{gr}} - \frac{1}{S_{gi}} = C = \frac{1}{Sgrm} - 1 \qquad equ.3$$

If we rearrange it we will have:

$$S_{gr} = \frac{S_{gi}}{1 + \left(\frac{1}{Sgrm} - 1\right) S_{gi}} \qquad equ.4$$

Usually, a simplified form is used. But original Land's law gives a lightly better estimation of Sgr than simplified version does.(Suzanne et al., 2003) In this model, the only free parameter is the maximum observable trapped non-wetting phase saturation corresponding to Sgr (Sgi=1). This expression does not predict residual phase saturation, only how residual saturation scales with initial saturation.

Kleppe *et al.*(1997) suggested that the residual gas saturation could be obtained from a linear relationship, with the maximum residual saturation at the end of the complete imbibition curve.

$$S_{gr} = \frac{S_{gi}}{S_g^{max}} S_{gr}^{max} \qquad equ.5$$

Kantzas et al.(2001) conclude that when the data fit Land's model, they also fit Kleppe's model well. If the data fit a linear transformation of Land's model, they also will fit a linear transformation of Kleppe's model. They state that it does not appear that there is a preference for one model over the other. Also they state that a modified Land correlation or Land model seems to match well the experimental data for a reservoir.

Various empirical Sgr-Sgi relationships were proposed. Most of them are based on limited experimental results, and referred to Land's law. The various analytical relationship define a form of Sgr-

Sgi curves fitted on Sgr(Swir) and Swir or on Sgrm and 1. Two analytical are noticeable because of their form and number of experimental relationship that support: first, Aissaoui(1983) proposed a piecewise linear relationship as below:

$$If\ \ S_{gi} < S_{go}\ :\ S_{gr} = \left(\frac{S_{grm}}{S_{go}}\right) \times S_{gi}\ \ else\ S_{gr} = S_{grm} \qquad equ.6$$

Aissaoui's law Sgo parameter correspond to initial gas saturation at the breaking point between two straight lines segment of the Sgr-Sgi curves. As we see in below figure:

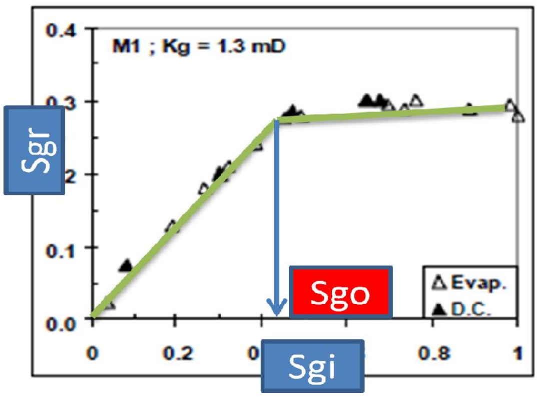

Figure 6: definition of Sgo in Aissaoui's law.(Suzanne et al. 2003)

Aissaoui has proposed a piecewise linear relationship with two parameters: Sgrm and Sgo. he has studied only Fontainebleau sandstone and estimated Sgo with Swir according to porosity samples:

$If\ \ \varphi < 0.10,\ \ S_{go} = 1 - S_{wir}$

$If\ \ \varphi > \ 0.13\ ,\qquad S_{go}\ is\ between\ 0.60\ and\ 0.70$

So the Sgo parameter is function of the porous media parameter, and more precisely of the microporosity content. Suzanne et al.(2003) show that Sgo was found to be dependent on the amount of microporosity and different of 1-Swir values.

Second, Jerauld (1996)`worked on fifty Berea and Prudhoe Bay sandstone plugs, the proposed relationship has hyperbolic form with a nil slope at Sgi equal to 1

$$Sgr = \frac{Sgi}{1 + \left(\frac{1}{Sgrm} - 1\right) * Sgi^{\left(\frac{1}{1-Sgrm}\right)}} \qquad equ.7$$

Suzanne et al. compare experimental relationship of Sgr-Sgi of authors who have published largest number of experiments and they conclude that the best relationship to describe Sgr-Sgi curves is the piecewise linear Aissaoui's law.

4. Results and Discussion:

From the literature it seems that the trapping mechanisms of gas as non-wetting phase in reservoir rocks is more complicated than trapping of oil, because of special properties of gas such as high compressibility and solubility. So the study of the gas trapping seems to be more complicated, but few works are done on this subject.

Measurements indicated that the value of residual gas saturation depends on many factors, including reservoir properties, the capillary number, experimental procedures, fluid properties and also very strongly depends on the gas solubility and compressibility.

Because of dependence of residual gas saturation on many factors finding a correlation that could predict the amount of residual gas saturation is very difficult. Since reservoirs are very different in their properties, the evaluated residual gas saturation is expected to be quite different. However, there are still some common correlations, even though very rough.

Predictive capacity of existing models is not generally applicable. Thus, testing of plugs for each reservoir can provide the data required to calibrate a Land's-type model for determining the expected residual gas saturation. Different authors suggest different models to estimate the Sgr, but it seems the Aissaoui's law is the best description of the behaviour of gas trapping and residual gas saturation. Another good model that could predict the Sgr, is modified Land method, in the form of $y = ax + b$ if we assumed equation 4 in the form of $y = x$, then the amount of a, b could be find from experiment of plugs for each reservoir.

5. Conclusions:

Some conclusions can be reached for this paper:

1. Predictive capacity of existing models that is not generally applicable, but we could use modified Land's model for different reservoir.
2. Models do not predict residual phase saturation, only how residual saturation scales with initial saturation.
3. There is no relationship that could estimate Sgr as function of reservoir characteristics. (multi parameter)
4. The mechanism of trapping is not clear, some factors that may has important effect on Sgr does not study very well and there is not clear reason for some phenomena that occur in gas saturated plugs, so this subject deserves further investigation.
5. This paper summarizes some work done on the subject of residual gas saturation and this paper will provide a good reference for researchers who are interested in investigating residual gas saturation in water drive reservoir.

Nomenclature:

Phi: porosity
C: Land's constant
Sgi: initial gas saturation

Sgr: residual gas saturation
S*gi: effective initial gas saturation $S_{gi}^{*} = \frac{S_{gi}}{1-S_{wir}}$
S*gr: effective residual gas saturation $S_{gr}^{*} = \frac{S_{gr}}{1-S_{wir}}$
Sgr@Swir: residual gas saturation of sample at Swir
Sgrm: maximum residual gas saturation
Swir: irreducible water saturation
PV: pore volume

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