A New Formula for Evaluation of Severity of Aqueous Phase Trapping in Oil Reservoirs

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Abstract
Aqueous phase trapping (APT) in many of the oil and gas reservoirs is a significant mechanism of formation damage during drilling, completion, work over, and stimulation operations. APT which occurs as introduction of water filtrate and retention of that in the porous media, can limit the productivity of the well to a high extent, especially in low permeable gas formations. Predicting the sensitivity of reservoir to APT is of great importance where the reservoir is susceptible to APT. During the last fifteen years, limited number of predictive formulas has been proposed to evaluate the potential severity of APT in the reservoir. Most of these formulas are so simple and do not include many effective parameters on the severity of APT, therefore they cannot precisely evaluate the true potential severity of APT in reservoir and may gives a wrong evaluation on the extent of APT. In this paper common predictive formulas for APT are reviewed and a new predictive formula for evaluation of APT is presented in such a way that all effective parameters on APT are lumped into one single parameter, CAPT (coefficient of aqueous phase trapping).

Keywords: *Formation damage; aqueous phase trapping; water filtrate.*

1- Introduction
Introduction of filtrate of drill in fluids into the near wellbore reservoir rock is commonly associated with several types of formation damage. [1] These types of formation damage are described in literature. [2-10]
Among different types of formation damage caused due to introduction of drill in water filtrate into the near well bore formation, very little has been recorded regarding damage induced by aqueous phase trapping (APT), despite it has a tremendous effect on productivity reduction. APT in many of the oil and gas reservoirs is a significant mechanism of formation damage during drilling, completion, work over, and stimulation operations and can limit the productivity of the well to a high extent, especially in low permeable and sub-irreducible gas formations (i.e. formations in which the initial water saturation is lower than the irreducible water saturation). [11-19]
Evaluating reservoir's potential for APT is of great importance where the reservoir is susceptible to APT, since well productivity can be improved through proper evaluating and consequent attempts to reduce associated formation damage. This can be done using laboratory tests on reservoir rock samples. But, since reservoir rock is hundreds to thousands of meters below the surface of the earth, therefore direct observation and sampling of the damaged zone is highly restricted. Hence, alternative approach is

followed which is use of predictive formulas. During the last fifteen years, limited number of formulas has been proposed to evaluate the reservoir's potential for APT. In addition, an appropriate predictive formula can be used to adjust water filtrate properties in order to minimize associated formation damage. In continuation, these formulas, their advantages, and limitations will be described.

2- Reviewing Current Methods to Evaluate APT

Generally, current formulas for evaluating the tendency of reservoir to APT are classified in two categories. First category is where formulas are obtained from results of regression analysis of experimental data pertaining to parameters affecting APT and realizing a relation between these dependent variables (parameters) and an independent variable. In such approach, some effective parameters may not be included, since only recognized parameters are investigated. Two evaluating formulas of this category which one of them is a more rigorous form of another one are presented by Bennion et al. (1996) [11]. These formulas will be presented in the next sections of this paper.

Second category is where evaluating formulas are obtained by investigating the parameters available in current formulas related to invasion of water filtrate into near well bore formation and spontaneous imbibition phenomenon. Of course, since one source of APT is water retention, therefore, some additional parameters affecting APT may be included or adjusted. An example of such a formula is presented by You and Kang (2008) [12].

Each of the above two categories formulas which give results more close to laboratory results of investigating APT can be used to evaluate the potential severity of reservoir to APT and can has practical applications. A comparison between the evaluations made by these formulas and the laboratory results will be presented in the next sections.

2.1 Permeability Damage Ratio

In this approach permeability of hydrocarbon, K_i, is measured at the initial water saturation condition of core in the laboratory. Then after full saturation of core with water filtrate (i.e. imbibition process), the drainage process is started and final irreducible water saturation in the core is established. In this condition, again, permeability of hydrocarbon, K_d, is measured and permeability damage ratio due to APT, D_{pt}, is calculated according to Eq.1. We should not that all measurements should be done at reservoir conditions.

$$D_{pt} = 1 - \frac{K_d}{K_i} \qquad (1)$$

Value of D_{pt} can be used to evaluate potential for APT. Values of D_{pt} are interpreted as shown in Table 1.

Table 1- D_{pt} values and comments on potential for APT

D_{pt}	$D_{pt} < 0.05$	$0.05 \leq D_{pt} < 0.3$	$0.3 \leq D_{pt} < 0.7$	$0.7 \leq D_{pt} < 1.0$
Damage potential	None	Weakly	Medium	Intensely

The predictions made by other tools should be validated with the permeability damage ratio which is actual APT test in the laboratory.

2.2 Index of APT

Bennion et al. (1996) [11] proposed a simple equation to evaluate potential for APT. This equation is based upon results of regression analysis of a large number of APT tests. For the first time, he defined the index of APT, APT_i; using only two parameters (see Eq.2).

$$APT_i = 0.25\log_{10}(K_a) + 2.2S_{wi} \quad (2)$$

Where K_a is the average air permeability in mD, and S_{wi} is initial water saturation in fraction. The value of APT_i for a given reservoir evaluates the severity of APT in that reservoir as shown in Table 2.

Table 2- Criteria for interpreting values of APT_i

APT_i value	Prediction
$APT_i \geq 1.0$	Reservoir unlikely to exhibit significant permanent sensitivity to aqueous phase trapping
$0.8 \leq APT_i \leq 1.0$	Reservoir may exhibit sensitivity to aqueous phase trapping
$APT_i < 0.8$	Reservoir will likely exhibit significant sensitivity to aqueous phase trapping

The idea for linear form of Eq.2 is not mentioned in the original work, but it can come from correlations between the end point saturation (in this case irreducible water saturation) and permeability. As shown by Collins (1961) [23], the irreducible water saturation decreases linearly with increasing logarithmic permeability in sandstone. Thus, irreducible water saturation can be approximated by Eq.3.

$$S_{wirr} = a_j - b_j \log_{10}(K) \quad (3)$$

Where S_{wirr} is irreducible water saturation, K is permeability and a_j and b_j are some empirically determined parameters. And since one of the parameters affecting severity of APT is the difference between irreducible water saturation and initial water saturation therefore term of S_w can be subtracted from right hand side of Eq.3 to get a formula in the form of Eq.2.

2.3 Modified Index of APT

Bennion et al. (1996) [11] proposed a more rigorous evaluation of APT_i with taking in account more parameters, as Eq.4. We call this formula as modified APT index.

$$APT_i = 0.25\log(K_a) + 2.2(S_{wi} - RP_a - IP_a + PR_a) \quad (4)$$

In the above equation RP_a, IP_a and PR_a are relative permeability adjustment factor, invasion profile adjustment factor, and reservoir pressure adjustment factor, respectively. These adjustment factors are defined as Eqs. 5-7.

$$RP_a = 0.26(\log(x - 0.5)) \quad (5)$$

$$IP_a = 0.08(\log(I_d + 0.4)) \quad (6)$$

$$PR_a = 0.15\log(P_r) - 0.175)) \quad (7)$$

In which x is relative permeability shape factor varying from 0 to 8, I_d is invasion depth in cm, and P_r is reservoir pressure in MPa. The interpretation of the new APT_i is just the same as two parameters APT_i (see Table 2).

2.4 Percent of Bulk Volume Water

Another predictive formula was proposed by Davis and Wood (2004) [13]. In this approach only two parameters are used to determine the percent of bulk volume water, BVW. The value of %BVW will be used to predict APT potential in a given reservoir. %BVW is determined using Eq.8.

$$\%BVW = S_{wi}.\varphi \times 100 \quad (8)$$

In which %BVW is percent of bulk volume water, S_{wi} is water saturation in fraction, and φ is porosity in fraction. The interpretation of %BVW for a given reservoir is as per Table 3.

Table 3- Criteria for interpreting values of BVW

%BVW	Prediction
%BVW≥3.5	Reservoir unlikely to exhibit significant permanent sensitivity to aqueous phase trapping
2.0≤ %BVW≤3.5	Reservoir may exhibit sensitivity to aqueous phase trapping
%BVW < 2.0	Reservoir will likely exhibit significant sensitivity to aqueous phase trapping

3.5 Phase Trapping Coefficient

You and Kang (2009) [12] proposed a relation to evaluate reservoir's potential for APT. In their study, the coefficient of phase trapping (PTC), Eq.9, was proposed which is characteristic of integrating the geology and engineering factors.

$$PTC = e^{-\sqrt{\frac{K}{\varphi}\frac{\Delta P.\mu_{hc}}{\sigma\cos(\theta).\mu_w}.\frac{S_{wi}}{S_{wirr}}}} \quad (9)$$

Where PTC is coefficient of phase trapping and is dimensionless, K is air permeability in μm^2, φ is porosity in fraction, ΔP is the difference between reservoir pressure and the capillary pressure (i.e. P_r-P_c) in kPa, μ_w and μ_{hc} are water and hydrocarbon viscosity, respectively, σ is interfacial tension between trapping fluid and oil or gas in mN/m, θ is contact angle, S_{wi} is initial water saturation in fraction, and the S_{wirr} is irreducible water saturation in fraction. Criteria for interpreting PTC values are shown in Table 4.

Table 4- Criteria for interpreting values of PTC

PTC	PTC<0.05	0.05≤PTC<0.3	0.3≤PTC<0.5	0.5≤PTC<0.7	PTC≥0.7
Damage severity	None	Weakly	Weakly to medium	Medium to intensely	Intensely

3. Proposing a New Predictive Formula

A new formula to predict the true sensitivity of oil reservoir to APT is developed based on a parameter study and experimental work and is called CAPT or coefficient of aqueous phase trapping. This formula is obtained by proper arrangement of the parameters in such a way that values of CAPT give the predictions close to perditions made by values of permeability damage ratio. CAPT is per Eq.10 and is interpreted as the same as PTC shown in Table 2.

$$CAPT = e^{\frac{-\sqrt{\frac{K}{\phi}}\Delta P.\mu_{hc}}{(\rho_w-\rho_o)(S_{wirr}-S_{wi})\mu_w\sigma\cos(\theta)I_d^2}} \quad (10)$$

In which K is in μm^2 or Darcy, ρw and ρ_o are water and oil density in kg/m3, respectively, ΔP is in kPa, and I_d is in meter.

4- Conclusion and Results

Different current formulas used for evaluating reservoir's potential for APT were reviewed. A new formula for evaluating tendency of oil reservoirs to APT was proposed; CAPT, coefficient of APT. In the new proposed formulas, which all affecting parameters have been included, relation between damage by APT and collection of affecting parameters is exponential.

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