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New Methodology for Gas Migration Prediction after Oilwell Cementing

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Abstract

Many challenges have been presented in the oil well drilling including preventing gas migration after cementing operations. The phenomenon is potentially dangerous since the gas can migrate to the surface causing the annular pressurization or lead to a blowout with catastrophic results and loss of the well.

The well cementing involves several parameters evaluation: the fluid density definition, the top of cement to be reached, the displacement efficiency optimized in terms of density hierarchies and friction losses, the cement paste, washers and spacers design, pipe centralization, among others. Even if all these parameters are controlled and optimized yet the gas migration may occur due to hydrostatic pressure loss during the cement slurry transition period.

The static gel strength development associated with fluid-loss and chemical shrinkage are the main factors responsible for this hydrostatic pressure loss. If the hydrostatic pressure in front of the gas zone becomes less than the pressure in this zone the gas will invade the well.

The objective of this work is to present a comprehensive methodology to evaluate the gas migration after cementing operations taking into account the critical static gel strength concept associated with time dependent viscosity behavior. A mechanistic model based on a force balance acting on the gas bubble was proposed to predict the bubble displacement through the cement slurry while it gels and evaluate if the hydraulic isolation will be affected allowing project operation changes to ensure well construction safely.

Introduction

The cementing operation is very important for the well construction and if it is not successful may require corrections which in many cases is difficult to solve. One of the main functions of the cement slurry is the hydraulic isolation between zones containing fluid. This is achieved when the annular space between the casing and formation is completely filled with cement slurry with optimized properties.

To improve the displacement efficiency is necessary good casing centralization and drilling fluid treatment to reduce its rheological properties improving its removal. Other actions that help to remove and can be implemented are: pipe movement, either by rotating or reciprocating (alternating cycles of vertical movement); usage of rubber plugs inside the casing to separate mechanically the fluids involved and the pumping of chemically compatible and optimized fluids to separate the drilling fluid from the cement slurry avoiding its contamination.

If the drilling fluid displacement by cement slurry is not efficient it will create a fluid channel formed by the remaining fluid that intercommunicate two zones damaging the hydraulic isolation as shown in Fig. 1.

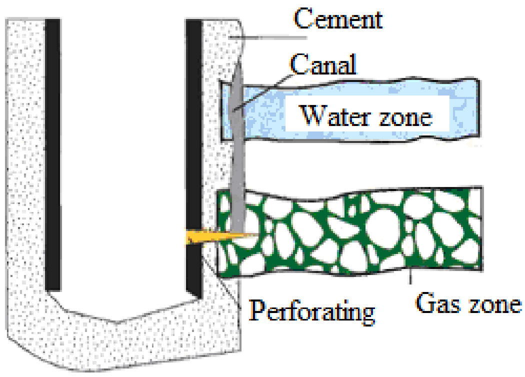

Fig. 1- Canalization generated by inefficient displacement of drilling fluid (modified from Nelson and Guillot 2006).

The hydraulic isolation is important to ensure not only the produced fluid control but also the injected one. If the hydraulic isolation is deficient during well stimulation the flow can be redirected to another zone and in most drastic situations promote the casing collapse, trapping all the tools that are below this collapsed point and consequently lead the loss of the well.

Even if all the casing positioning procedures and annular space cleaning through efficient drilling fluid removal have been made there are other processes that take place during the cement setting that can influence the perfect hydraulic isolation.

Changes that occur in the cement slurry

The cement slurry physical state progresses from a liquid immediately after its positioning in the well transmitting its hydrostatic pressure and gelling after a certain time under static conditions. Cement particles create cohesive structures that support part of their weight getting the initial fluid hydrostatic pressure trapped within the cement pores matrix.

The main factor controlling the pore pressure of the permeable interval becomes pore pressure within the cement matrix and as this pressure is greater than the pore zone (e.g., the gas zone) this gas will not be able to invade this structure. However, the pore pressure within the cement matrix is a function of its water volume and its reduction corresponds to the pore pressure reduction allowing the gas invasion. The fluid-loss can occur in two main ways: the cement hydration and the fluid-loss to the zone (Cheung and Beirute 1985).

Additives for oil well cementing

The cement slurry should be designed to provide optimized physical and chemical properties both in the liquid and solid state. In the liquid state the cement slurry should have density and rheological properties that meet the operational window and the drilling fluid replacement requirements. Also present thickening time long enough to complete the pumping operation to the desired position in the well and the resistance development within the time required to resume operation. In addition, the cement slurry must have fluid-loss control and be resistant to fluids migration such as water and gas. In the solid state have low permeability and be resistant to pressure and temperature downhole conditions (Rocha, 2010).

The additives aim to modify the cement slurry properties according to well conditions. They are classified into various roles based on performance, such as, accelerators, weighting agents, lost circulation prevention agents, antifoam, dispersants, extenders, fluid-loss controller, retarders, gas migration controller, among others.

Cement slurry without proper fluid-loss control can not transmit the hydrostatic pressure in its entirety even before the start of setting. Moreover the application of differential pressure at the beginning or end of the setting may result in microcapillaries that can allow the gas migration. Therefore the cement slurry project should include maximum fluid-loss control to minimize gas migration. Field results have indicated that values of approximately 50cc/30min have shown success in combating gas migration (Christian et al., 1976).

The gas migration can be avoided in many ways. The first step is to optimize the removal process and in parallel to optimize the cement slurry properties. There are some additives that act by preventing the entry of formation fluids after placing the cement slurry blocking the cement slurry matrix in the setting process; or by creating cement slurry volume expansion due to gases release chemical reaction; or by foam generating if gas get in cement slurry matrix.

The most common additives are the waterproofing / blockers which are usually typical polymeric microemulsions as latex styrene / butadiene or polyvinyl alcohol. In addition formulations should have fluid-loss control, retarders and dispersants that help in obtaining the other required properties. The migration control can also be achieved by the additives incorporation during the cement slurry preparation that generate in-situ hydrogen gas bubbles through chemical reactions or through the blocking process using very fine particles (e.g., as microsilica) (Nelson and Guillot 2006).

Rheology

The cement slurry rheological behavior is crucial to oil well cementing operations design. Cement slurry are solid suspensions of solid / liquid formed by uniform particles through a liquid medium without significant dissolution of the particulate material as a function of time.

The main factors affecting the viscosity are: solids volumetric concentration; liquid characteristics (viscosity, density, etc.) and temperature. When the solids concentration is very low, the collisions frequency between particles is relatively low and the suspension still behaves as a Newtonian fluid. When the solids concentration is greater interaction begins to occur between the particles and the rheological behavior is no longer Newtonian. In this case other characteristics also affect the rheology: particle physical characteristics (size distribution, density, shape, specific surface area, roughness, etc.) and type of interaction between particles (repulsion and attraction).

The concentration of dispersant in the liquid medium, chemical composition, molecular weight and thickness of the adsorbed dispersant layer around the particles should be evaluated (Oliveira, 2000).

Parameters that influence the cement slurry rheological behavior

The main parameters that influence the cement slurry rheological behavior are listed below (Dubois, 1999).

Water content

The increased amount of water acts on the cement grains dispersion reducing the intergranular friction which in turn reduces the cement slurry viscosity. The water also serves to lubricate the grains. There are practical limits to the upper and lower water content that can vary from a very viscous to an unstable cement slurry with solids sedimentation.

Cement characteristics

Chemical composition, specific surface and particle size are one of the most important characteristics of the cement that affect the cement slurry rheology. The higher the content of C3A (Tricalcium Aluminate) the more reactive is the cement and may require higher dispersant concentrations. Colloidal forces and gravity which are functions of nature and size of grains also affect the rheological behavior.

Temperature and pressure

The temperature has a greater effect on the cement slurry rheology than the pressure. Influences the hydration rate of cement components and an error in its determination can result in premature set or thickening time extension. In the first with the risk of the operation be interrupted before completed its positioning. In the second it promotes the delay in drilling continuity with the risk of fluids migration into the well due to the longer cement slurry exposure causing its contamination.

Other properties such as fluid-loss, rheology, free water, stability and compressive strength development are also influenced by temperature.

Methodology

The methodology developed in this work comprises the following steps and is represented by Fig. 2.

a) Determination of the equation that relates the gas bubble position as a function of fluid viscosity and temperature which are time dependents among others fluid and particle parameters;

b) Experiment to evaluate the rheological model and the time dependent fluid viscosity behavior;

c) Experiment to determine the critical time, i.e. time required to reach critical static gel strength from which the gas invasion occurs;

d) Determination of the model to representative equation from the time dependent fluid viscosity behavior and use it in the item "a)".

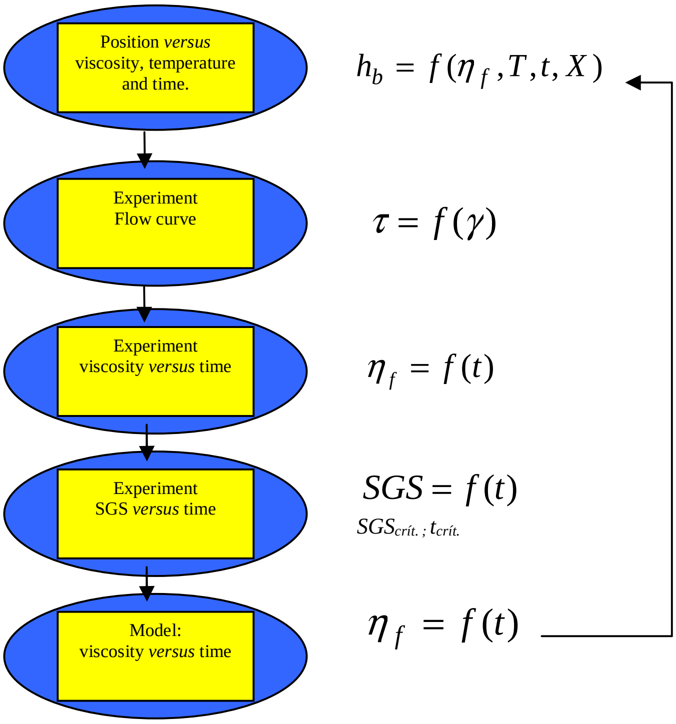

Fig. 2 - Gas migration evaluation methodology.

The details to obtain the equations are described below.

Gas bubble expansion

The hydrostatic pressure exerted by the fluid in a given depth is expressed by Eq. 1.

$$p_h = \rho_f . g . h_f \quad \text{.......(1)}$$

Where:
p_h = hydrostatic pressure;
ρ_f = fluid density;
g = gravity acceleration;
h_f = vertical depth.

For a spherical bubble at a given depth, there is an interface between the bubble and the fluid that generates a capillary pressure resulting from the interfacial tension. The capillary pressure (Pellicer, 1999) can be defined by Eq. 2:

$$p_c = \frac{2.\sigma}{r_b} \quad \text{.......(2)}$$

Where:
p_c = capillary pressure;
σ = surface tension;
r_b = bubble radius.

And the total pressure inside the bubble would be according to Eq. 3:

$$p_t = p_h + p_c \quad \text{.......(3)}$$

For the application to which this methodology deals the capillary pressure did not influence significantly the total pressure when comparing with hydrostatic pressure (deep wells) and in this case will be neglected. In addition, on cement slurry composition antifoam additive is used that reduces the surface tension further reducing the influence of this factor.

The relationship among the pressure, volume and temperature on gases kinetic theory gives Eq. 4.

$$\frac{P_0.V_0}{T_0} = \frac{P.V}{T} \quad \text{.......(4)}$$

Where:
P_0; V_0; T_0 = pressure, volume and temperature at initial time;
P; V; T = pressure, volume and temperature at final time;

The bubble volume is defined by Eq. 5.

$$V_b = \frac{4}{3}.\pi.r_b^{\ 3} \quad \text{.......(5)}$$

The air pressure inside the bubble is the pressure due to fluid column. If we assume that the air is an ideal gas we have substituting and solving Eq. 1 and 5 in 4 the Eq. 6.

$$\frac{\rho_f . g . h_{b0} . \frac{4}{3}.\pi.r_{b0}^{\ 3}}{T_0} = \frac{\rho_f . g . h_b . \frac{4}{3}.\pi.r_b^{\ 3}}{T} \quad \text{.....(6)}$$

Being "r_{b0}" the bubble radius in depth "h_{bo}" when enters in the well both defined for a given initial condition. Rearranging the above equation we can determine how the bubble radius changes with depth and temperature according to Eq. 7.

$$r_b = \sqrt[3]{\frac{h_{b0}}{h_b} \cdot \frac{T}{T_0}} . r_{b0} \quad \text{.......................................(7)}$$

Figure 3 represents the bubble in its depths.

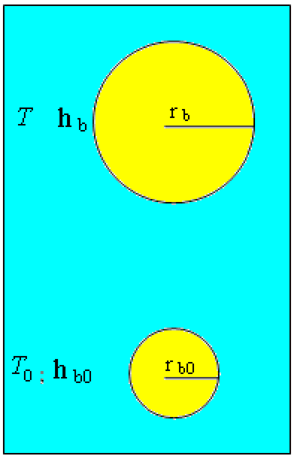

Fig. 3 - Change in bubble size with depth.

Forces acting on gas bubble

In the case of a bubble rising through a fluid it experiences a frictional force *"Fr"* which is proportional to the fluid density, particle projection area *"Sp"* and the square of the speed according to Eq. 8.

$$F_r = \frac{C_r}{2} . \rho_f . S_p . v_b^{\,2} \quad \text{...(8)}$$

Where:
Cr = friction coefficient or flow resistance.

For a small bubble with spherical geometry ascent rate is sufficiently slow so that the flow is laminar and Stokes law can be applied and friction coefficient is defined by Eq. 9:

$$C_r = \frac{24}{\text{Re}} \quad \text{...(9)}$$

Where:
Re= Reynolds number
In the laminar flow region it can make a correction in the Stokes law for non-Newtonian fluids (Kawase and Moo-Young 1986) through Eq. 10 and the friction coefficient becomes:

$$C_r = \frac{24X}{\text{Re}} \quad \text{..(10)}$$

Where:
X= factor deviation of friction coefficient, defined by Eq. 11:

$$X = 3^{(3n-3)^2}\left[\frac{-7n^2 - 4n + 26}{5n(n+2)}\right] \quad \text{..........................(11)}$$

Where:
n = index behavior for 0.75 < n <1. When n = 1 (Newtonian fluid), X = 1.

The friction force for a Newtonian fluid is defined by Eq. 12:

$$F_r = 6.\pi . r_b . \eta_f . v_b \quad \text{......................................(12)}$$

The correction proposed for non-Newtonian fluids gives Eq. 13:

$$F_r = 6.\pi . r_b . \eta_f . X . v_b \quad \text{.................................(13)}$$

The second force acting on the bubble is the buoyant force *"E"*. According to Archimedes' principle it is a vertical force from the bottom to up applied at the fluid volume gravity center displaced equal to weight of the volume of fluid displaced as defined by Eq. 14.

$$E = \rho_f . g . \frac{4}{3} . \pi . r_b^{\,3} \quad \text{..(14)}$$

Figure 4 illustrates the forces acting on a bubble.

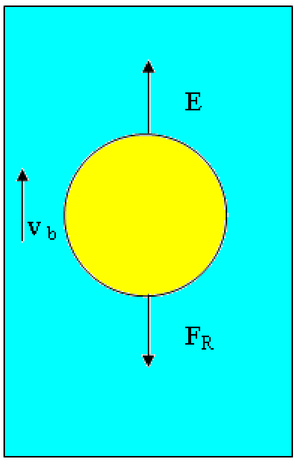

Fig. 4 - Forces acting on a bubble.

Equation of motion

The Newton's Second Law says that when a net force *"F"* is present in a particle it acquires an acceleration *"a_c "* in the same direction of force according to an inertial frame defined by Eq. 15.

$$F = m.a_c \quad (15)$$

Where:
m = particle mass

Considering the bubble weight negligible and the particle moves through a viscous fluid in laminar regime, after a time reaches a constant limit velocity and the resulting forces acting on this particle is zero. Assuming that the bubble remains at steady state the buoyancy and frictional force are nearly equal and opposite and the bubble reaches each time the limit speed although it changes with time (Vermillon, 1975) the forces acting on the bubble will be as Eq. 16.

$$E + F_r = 0 \quad (16)$$

Substituting and solving Eqs. 7, 13 and 14 in Eq. 16 it is obtained Eq. 17.

$$v_b = -\frac{2.\rho_f.g}{9.\eta_f.X}.\left(\frac{h_{b0}}{h_b}.\frac{T}{T_0}\right)^{2/3}.r_{b0}^{\;2} \quad (17)$$

Separating variables and integrating with the condition that it starts at time t = 0 the instant at which the bubble enters the well in depth "h_{b0}" it is obtained the Eq. 18.

$$\int_{h_{b0}}^{h_{bt}} h_b^{\;2/3}.dh_b = -\frac{2.\rho_f.g.r_{b0}^{\;2}}{9.\eta_f.X}.\left(\frac{h_{b0}.T}{T_0}\right)^{\frac{2}{3}}.\int_0^t dt \quad (18)$$

Solving the above equation it can determine how the bubble position changes with time by Eq. 19.

$$h_{bt} = \left[h_{b0}^{5/3} - \frac{0,37.\rho_f.g.r_{b0}^{\;2}}{\eta_f.X}.\left(\frac{h_{b0}.T}{T_0}\right)^{\frac{2}{3}}.t\right]^{\frac{3}{5}} \quad (19)$$

In the case of time dependent viscosity fluids like cement slurry it must determine a function that represents this behavior. This can be obtained through rheological tests and then evaluate a representative function for the model.

Considering that the gas will enter into the well only some time after the cement slurry placement, time related to a reduction in hydrostatic pressure that will allow the gas zone pore pressure overlaps the hydrostatic pressure of the well, a correlation between the cement slurry viscosity evolution with the gel strength concept will be made to determine the critical time, i.e. time that the cement slurry reaches a critical static gel strength from which any pressure decay in the well will allow the gas invasion. This time will be used to determine the initial viscosity of the model.

The temperature changes with well depth and time beginning at BHCT and tends to BHST. The circulation temperature in cementing operations is obtained using specific guidelines (API, 1997). In order to automate the test conditions determination there is a computer program that develops tables simulating the cement slurry heating and pressurization after placed in the well.

Hydrostatic pressure reduction of cement slurry during the transition time

After the cement slurry placement is noted a reduction in the hydrostatic pressure (Tinsley, 1980; Cooke, 1984 and Reddy, 2009). This is caused by the volume reduction due to filtration for the adjacent formations and the shrinkage resulting from the cement hydration reactions combined with the pressure restriction caused by cement slurry gelation.

The pressure drop resulting from the volume change depends on the compressibility of the medium "C" and is expressed by Eq. 20.

$$\Delta p_{an} = \frac{(V_h + V_f)}{C} \quad (20)$$

Where:
V_h = volume reduction by hydration;
V_f = volume lost by filtration.

The maximum hydrostatic pressure restriction is related to the resistive force development to cement slurry movement called static gel strength which increases gradually during the transition period. Eq. 21 shows this relationship (Sabins, 1982).

$$\Delta p_{an} = \frac{SGS.A_{an}}{A_H} \quad (21)$$

Where:
Δp_{an} = pressure drop in the annulus;
SGS = static gel strength of cement slurry;
A_{an} = annular space area in front of the cement slurry defined by Eq. 22.

$$A_{an} = \pi(D_{well} - D_c).h_{vert.slurry} \quad (22)$$

And:
A_H = hydrostatic area defined by Eq. 23.

$$A_H = \frac{\pi}{4}(D_{well}^2 - D_c^2) \qquad (23)$$

Where:
D_{well} = open hole diameter in front of gas zone;
D_c = casing diameter;
$h_{vert.slurry}$ = cement column height.

Substituting Eqs. 22 and 23 in 21, Eq. 24 is obtained:

$$\Delta P_{an} = \frac{4.SGS.h_{vert.slurry}}{(D_{well} - D_c)} \qquad (24)$$

The volume loss in the bottom of the well causes the cement slurry movement downwards. In response to this motion a shear stress in the cement slurry against the casing walls is generated. Considering that there is enough movement the shear stress at the contact surface between the cement slurry and casing starts to support the cement column (Bonett and Patifis 1996).

Critical Static Gel Strength

It is the gel strength value that allows supporting pressure decay in the well equivalent to overbalance pressure until to equal the value of the gas pore pressure. With values above the critical static gel strength gas may invade the well. The behavior is defined by Eq. 25.

$$SGS_{crit} = \frac{\Delta p_{ob}(D_{well} - D_c)}{4h_{vert.slurry}} \qquad (25)$$

Where:
SGS_{crit} = critical static gel strength
Δp_{ob} = difference between the hydrostatic pressure and the pore pressure.

The smaller the value of critical static gel strength more critical is the possibility of gas invasion during the gelation process. With this critical static gel strength value it is possible determine the critical time by a gel strength experiment and then use that time to determine the initial viscosity of the rheological model.

Experimental Procedure

Cement slurry used

For this work were considered two types of cement slurry that represent different rheological characteristics affecting mainly the gel strength development: cement slurry A and B. The formulation includes the use of various additives especially the gas migration controller.

Rheology

Rheology test was performed to determine the rheological model and its parameters. The model parameters obtained will be used in calculating the deviation factor of the friction coefficient for non-Newtonian fluids.

Time dependent viscosity

The rheological tests should simulate real downhole conditions after the cement slurry placement being conducted at a strain low enough to allow gel growth without breaking it and the methodology should include a schedule and materials to minimize interferences, for example, use of grooved geometries to reduce sample slippage.

Dinamic oscillatory rheological tests were conducted to evaluate the time dependent cement slurry viscosity behavior. First it was performed a strain sweep test with 1 Hz frequency and strain scan of 10^{-4} to 10^2 s^{-1} to determine the linear viscoelastic region. The sample was replaced and held in rotational mode at 10 s^{-1} for 1 minute to break any gel and then evaluated the viscosity behavior in dynamic oscillatory mode over time with 1 Hz and 10^{-3} s^{-1}, rate low enough to allow gel formation. It was then possible to obtain a function that relates the viscosity over time to be used in the bubble position equation.

Gel Strength

Gel strength tests were performed in MACS II analyzer to evaluate the gel strength behavior along the time. With this test is possible to obtain the time required to the cement slurry reach critical static gel strength $SGS_{crít.}$ at which is considered the initial condition for the gas migration process as described before.

Results and Discussion

Rheology

The model characteristic of cement slurry was power law as shown by Figure 5. To adjust the model was made nonlinear regression and the behavior index (*n*) for cement slurries A and B was obtained.

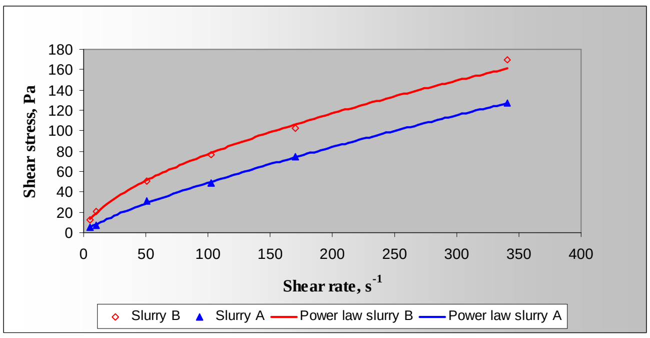

Fig. 5 – Rheological model for slurries A and B.

Time dependent viscosity

Figure 6 shows experimental result for time dependent viscosity behavior for cement slurries A and B.

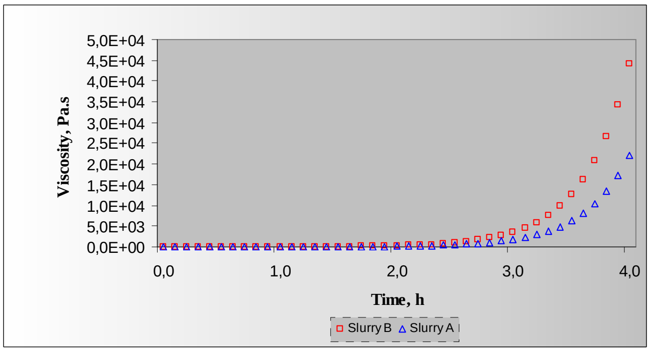

Fig. 6 - Viscosity changing over time.

The behavior is characteristic of cement slurry where they remain fluid for some time and then quickly gels. To determine the moment that the gas migration starts is necessary to evaluate the critical time, i.e. the time to reach critical static gel strength by gel strength experiment.

Gel Strength

Figure 7 shows the gel strength development versus time for cement slurries A and B.

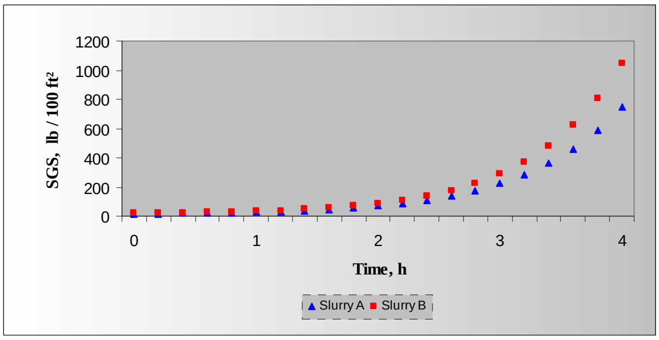

Fig. 7 - Static gel strength changing over time.

The behavior is similar to that obtained for viscosity because they have similar characteristics. For the proposed cement project it was calculated the $SGS_{crit.}$= 70 lb/100 ft^2 and determined the $t_{crit.}$ for each cement slurry. In this work we considered the values $t_{crit.}$ = 0,4 h and 0,5 h for the cement slurries A and B.

Model

Figure 8 shows the model application for representing experimental result after discarded the data prior to $t_{crit.}$ and reset the scale to start from time 0.

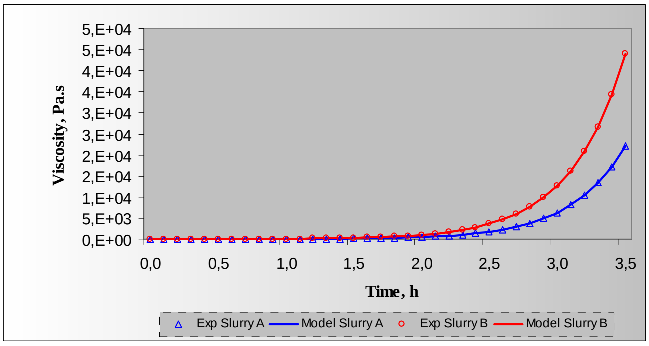

Fig. 8 - Comparison between experimental and model.

The model can represent the experimental data using Eq. 26.

$$\eta_f = \eta_0 + Ae^{\frac{t}{k}} \quad \text{...(26)}$$

Where:

η_0 = initial viscosity obtained from the rheological test for $t_{crit.}$;

A e k = parameters that modify the viscosity growth intensity.

t = elapsed time during the analysis;

Case Study

It was considered in this study the depth of the gas zone 1,590 m and there are two oil-producing zones at (1,501 – 1,503)m and (1,510 – 1,513)m. Figure 9 shows the bubble displacement when using the 2 cement slurries.

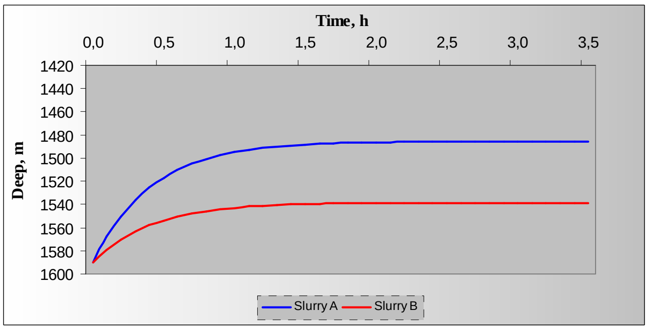

Fig. 9 - Bubble displacement for cement slurries A and B.

Figures 10 and 11 show gas migration inside the oilwell.

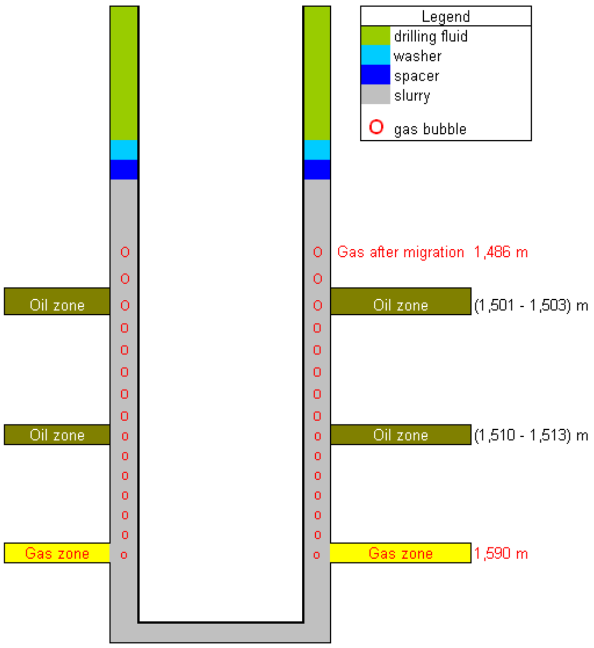

Fig. 10 – Gas migration using cement slurry A.

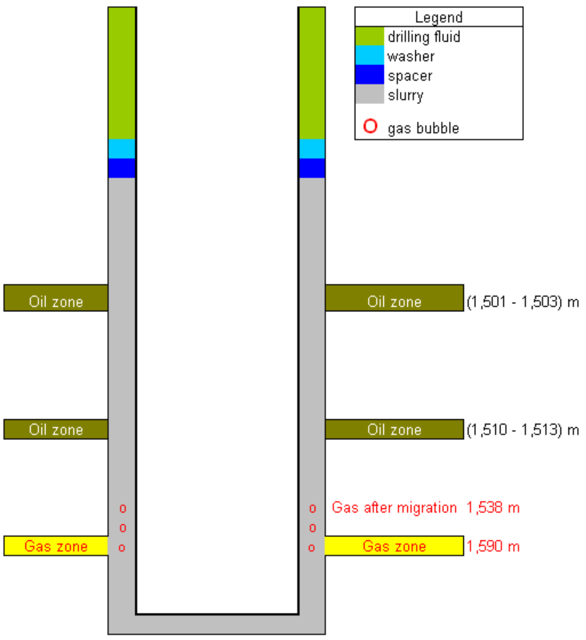

Fig. 11 – Gas migration using slurry B.

For the proposed project using slurry A gas migration was significant to damage the hydraulic isolation coming out at 1,590 m and reaching 1,486 m communicating the two interest zones so the slurry B must be selected.

Conclusions

The oil well construction is a complex activity that requires the previous simulation of the operations to be performed to ensure the technical and economic project feasibility. The gas migration is potentially dangerous because it can intercommunicate interest zones or migrate to the surface resulting in a blowout with catastrophic results and loss of the well. It is necessary that the slurries transmit the hydrostatic pressure in order to keep it above the gas zone pressure. This is achieved by keeping the gel strength below the critical value and after reaching this value the viscosity must increase quickly. With the methodology developed it was possible to evaluate the gas migration criticality and make changes in the slurry design getting the more appropriate one to the scenario, in this case the slurry B, which despite allowing the gas migration, the bubble displacement wasn't enough to affect the interest zones isolation.

Nomenclature

A = parameter that modify the viscosity growth intensity
A_{an} = annular space area, m²
A_H = hydrostatic area, m²
Cr = friction coefficient or flow resistance.
D_c = casing diameter, m
D_{well} = open hole diameter, m
g = gravity acceleration, m/s²
h_f = vertical depth, m
$h_{vert.\ slurry}$ = cement column height, m
k = parameter that modify the viscosity growth intensity
m = particle mass, kg
n = index behavior, dimensionless
p_h = hydrostatic pressure, psi
P = pressure at initial time, psi
p_c = capillary pressure, psi
P_0 = pressure at initial time, psi
r_b = bubble radius, m
Re= Reynolds number, dimensionless
SGS = static gel strength, lbf/100ft²
$SGS_{crit.}$ = critical static gel strength, lbf/100ft²
t = elapsed time during the analysis, s
V_0 = volume at initial time, m³
V_f = volume lost by filtration, m³
V_h = volume reduction by hydration, m³
T = temperature at final time, ºC
T_0 = temperature at initial time, ºC
X= factor deviation of friction coefficient, dimensionless
Δp_{an} = pressure drop in the annulus, psi
Δp_{ob} = overbalance pressure, psi
η_0 = initial viscosity, Pa.s
ρ_f = fluid density, kg/m³
σ = surface tension, N/m

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