# DYNAMIC CHARACTERISTICS OF NITRIFIED CEMENTS

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The dynamic properties of nitrified cements are dependent on the temperature and pressure state of the downhole system as well as the physical properties of the base fluid. The density, viscosity, volume, and rate of a nitrified fluid change as the downhole temperature and pressure circumstances change. Mathematical formulas based on gas density, molecular weight, specific gravity, and Ideal Gas Law provide the means of calculating the fluid properties at any point in its pumping history.

## INTRODUCTION

The placement of a cement slurry over a specific interval in a wellbore is the primary objective of a cementing operation. Once set, the cement will protect and support the casing while prohibiting fluid movement by hydraulically isolating fluid bearing strata.

Of critical importance in the successful placement of a cement slurry is the maintenance of a hydrostatic pressure that does not exceed formation fracture pressure. Formation breakdown during the cementing process may result in a variety of undesirable conditions including; (1) inadequate zonal coverage, (2) abnormal pressures due to annular restrictions, and (3) premature cessation of pumping operations. Accordingly, hydrostatic pressure considerations will often warrant the use of lightweight cement systems.

Most commonly used extenders--bentonite, metasilicate, gilsonite, diatomeceous earth, and others,[1] achieve density reduction by allowing the addition of water necessary to hydrate or wet the extending agent. An alternate means of density reduction is the addition of an inert gas as the density reducing medium. One method entrains the gas in a pozzolan or glass sphere while another technique calls for the direct injection of nitrogen into the cement slurry.[2-3] A stable dispersion is created when a cement slurry containing a foaming agent is commingled, in a high shear environment, with nitrogen. The nitrogen is held in discrete cells of similar size within the volume of the slurry. Once hardened, the dispersion maintains the cementitious properties of the base fluid while having a low density cellular structure.

## DETERMINING FRACTION

The downhole properties of nitrified cements are directly dependent on nitrogen quality or fraction. Quality is defined as the percent volume occupied by the gaseous (nitrogen) phase. Fraction is the expression of quality in decimal form. When the amount of nitrogen gas injected into a given volume of base cement is known, then:

$$f = \frac{1}{\frac{(199.3)\ (P)}{TzB} + 1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where:

- B = nitrogen injection rate in scf/bbl base cement
- f = fraction due to nitrogen, decimal
- P = pressure in psi
- T = Rankine temperature, (°F + 459.7)
- z = gas deviation factor

When a specific in situ density is desired, the fraction appropriate for that density is found by:

$$f = \frac{D_{nc} - D_{bc}}{\frac{(0.34902)\ (P)}{Tz} - D_{bc}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where:

- $D_{bc}$ = density in lbm/gal of base cement
- $D_{nc}$ = density in lbm/gal of nitrified cement

The amount of nitrogen needed to produce a given density in situ is found by solving for B in equation 3 with the same temperature, pressure, and z used to find f in equation 2.

$$B = 199.3\ \frac{P}{Tz}\ \frac{f}{1-f} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

In summary, equation 1 is used to determine the in situ properties of nitrified cements, while equations 2 and 3 are most commonly used when a specific in situ property is desired.

## DENSITY CALCULATION

The density of a nitrified cement for a specific wellbore condition is given by:

$$D_{nc} = D_{bc}\ (1-f) + \frac{(0.34902)\ (P)\ (f)}{Tz} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

## VOLUME CALCULATION

The ratio of base cement to nitrogen for a chosen annular volume can be determined once the fraction has been found. The amount of base cement contained in an annular volume is found by:

$$V_{bc} = (V_{ann})\ (1-f) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where:

$V_{bc}$ = volume of base cement contained in the annulus
$V_{ann}$ = total volume of the annulus

The amount of nitrogen contained in a given annular volume is therefore:

$$V_{n2} = (V_{ann})\ (f)$$

Where:

$V_{n2}$ = volume occupied by nitrogen gas

When a given volume of base cement containing nitrogen is in a dynamic state in the casing or annulus, the actual downhole volume is found by solving for fraction for the downhole temperature and pressure. Once fraction is determined, downhole volume is found by:

$$V_{dh} = V_{bc}\ \left(\frac{1}{1-f}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

The term $\left(\frac{1}{1-f}\right)$ is known as the Nitrified Volume Factor or NVF.

## NITRIFIED YIELD

The $ft^3/sk$ value for a nitrified cement is a function of the fraction for the specific conditions. Nitrified yield is defined as:

$$\frac{\text{base cement yield } (ft^3/sk)}{(1-f)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

## DETERMINING DOWNHOLE RATE

Downhole rate of a nitrified cement is influenced by the surface pumping rate (at the moment of observation) and the rate due to the addition of nitrogen. In addition, the method for resolving downhole rate depends on the nature of the fluid that follows the nitrified cement. When the path traced from the point of observation back to the origin at surface contains only nitrified fluids of a single $N_2$ content (in scf/bbl), downhole rate is defined by:

$$q_{dh} = (q_s)\ (NVF) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Where:

$q_{dh}$ = Downhole rate for nitrified cement

$q_s$ = Surface pumping rate

NVF = Nitrified volume factor $\left(\frac{1}{1-f}\right)$

The incompressible fluid (tail cement, mud, etc.) that follows the nitrified cement translates its current surface pumping rate through the system. The non-nitrified fluid will be moving the interface with the nitrified fluid at the same volumetric rate. Past the interface, into the nitrified stage, the rate due to the addition of nitrogen must also be considered. When the nitrified cement contains a single nitrogen content in scf/bbl (i.e., the constant rate technique), downhole rate is approximated by:

$$q_{dh} = \frac{q_s}{NVF_i}\ (NVF_o) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

$NVF_i$ = Nitrified volume factor (1/1-f) at interface of nitrified-nonnitrified fluid.

$NVF_o$ = Nitrified volume factor (1/1-f) at point of observation

$q_{dh}$ = Downhole rate of nitrified system

$q_s$ = Surface pumping rate at moment of observation

The constant density and three-step rate designs call for nitrified stages with different nitrogen contents (in scf/bbl) to exist in the annulus. Downhole rates for the stages will be influenced by underlying stages containing more nitrogen (in scf/bbl). To sum the downhole rates through the various stages, begin at the nitrified fluid-nonnitrified fluid interface and determine $q_{dh}$ at the top of the particular stage using equation (9). The $q_{dh}$ obtained at the top of the bottommost stage will translate into the $q_{dh}$ at the bottom of the next stage. Dividing the $q_{dh}$ found at the bottom of the stage by the NVF at the bottom of that stage will yield the factor ($q_{dh}$/NVF) that is multiplied by the NVF at the top of the stage to yield a new $q_{dh}$. This process is continued through the nitrified stages until the $q_{dh}$ at the uppermost nitrified stage has been determined.

## THE RHEOLOGY OF NITRIFIED CEMENT

Foams are classified as non-Newtonian fluids as they possess a non-linear relationship between shear stress and shear rate.[7] Rheological models of foams have included the Bingham plastic model, yield-pseudoplastic (Herschel-Bulkley) model, and the pseudoplastic (power-law) model[4-6]. It has also been suggested that foams follow a different rheological model in different shear ranges, behaving as a pseudoplastic fluid at low shear rates (less than 420 $sec^{-1}$) and Bingham plastics at higher shear rates.[8] The apparent viscosity found at a given shear rate also appears to be dependent on such factors as foam fraction, base fluid viscosity, and temperature.[7,9] Accordingly, a rheological model chosen to describe nitrified cements should take into account the following:

1. The fact that the base cement is a non-Newtonian fluid.

2. The effect on fluid parameters due to temperature.

3. The effect on fluid parameters ($n'$, $K'$, $\tau_{yp}$) due to fraction.

4. Consideration that foam fluids do not thin as rapidly as the base fluids under similar conditions.[9]

Accurate rheological modeling is necessary to predict nitrified cement viscosity, a prerequisite for the calculation of pressure loss due to friction.

Harris and Reidenbach,[9] in their study of high temperature foam rheologies, found by curve fitting the experimental data and incorporating a yield pseudoplastic (Herschel-Bulkley) solution, that:

1. "As quality increases, viscosity increases.

2. The temperature thinning effect (drop in viscosity) from 75 to 300°F, is greater at low quality than at high quality.

3. The increase in flow behavior index, $n'_t$, with increasing temperature is greater at low quality than at high quality.

4. The decrease in fluid consistency index, $K'_t$, with increasing temperature is greater at low quality than at high quality."

The foam viscosity using the Harris-Reidenbach model[9] is found by first determining the yield point of the fluid. If fraction is less than or equal to 0.6, then:

$$\tau_{YP} = 0.07\,\Gamma \qquad (10)$$

Where: $\Gamma$ = gas fraction, decimal

If fraction is greater than 0.6, yield point is determined by:

$$\tau_{YP} = 0.0002\,e^{9\Gamma} \qquad (11)$$

The $n'_t$ produced at a specific temperature and fraction is found by:

$$n'_t = n'_{75}\,e^{(0.0028 - 0.0019\Gamma)(T_f-75)} \qquad (12)$$

Where:

$n'_t$ = flow behavior index of liquid phase at temperature at point of observation

$n'_{75}$ = flow behavior index of liquid phase at 75°F

$T_f$ = temperature at point of observation in °F

Knowing $n'_{75}$ will allow the calculation of the foam consistency index exponents, $C_1$ and $C_2$, as given by:

$$C_1 = 4n'_{75}{}^{1.8} \quad (13)$$

$$C_2 = e^{-(3.1 + 3n'_{75})} \quad (14)$$

The value of $K'_f$ at temperature is found by first solving for $K_t'$ as follows:

$$K'_t = K'_{75}\, e^{(C_2\Gamma - 0.018)(T_f - 75)} \quad (15)$$

Using $K'_t$, the fluid consistency index for the nitrified cement is then found by:

$$(K'_f) = K'_t\, e^{(C_1\Gamma + 0.75\Gamma^2)} \quad (16)$$

Apparent viscosity can now be determined using the appropriate $\tau_{yp}$ from equation (8) or (9), the $n'_t$ found in equation (12), and the $K'_f$ from equation (16). The equation is:[4]

$$\mu app = (47880)\left[\left(\frac{4}{3}\right)^{n'}(\tau yp)/(sec^{-1}) + \left(\frac{3n'+1}{4n'}\right)^{n'} (K'_f)\ (sec^{-1})^{n'-1}\right] \quad (17)$$

The frictional pressure for a given annular length can now be found using the viscosity found in equation (17) as an apparent Newtonian viscosity and solving the standard pressure drop formula.[7] Frictional pressure may also be found using the $n'_t$ in equation (12) and the $K'_f$ found in equation (16) as components in the pseudoplastic (Power Law) model friction loss equation.

## PLACEMENT DYNAMICS AND ITERATIVE ANALYSIS

The determination of fraction, and all of the properties dependent on fraction, demands a knowledge of wellbore pressure. Because of the interdependence of frictional and hydrostatic pressure in a compressible system,[4] values predicted for fraction in the dynamic state (inclusive of frictional pressure drop) will vary slightly from the values found when solving for fraction using only hydrostatic pressure plus back pressure. As a consequence, an iterative solution based on the length of the nitrified cement stages provides the best means of resolving the differences inherent to static versus dynamic calculations. The properties determined from the static calculation (not including friction) will provide a basis for dynamic simulations.

Using the annular interface of the spacer and the nitrified cement as a starting point, a range of possible slurry rates can be estimated from equations (8) or (9). A corresponding frictional pressure drop for each rate can then be added to static pressure to approximate an initial dynamic pressure. The accuracy of the rate and pressure assumption at the spacer-nitrified cement interface can then be verified. The dynamic pressure found at the interface then serves as a reference point for subsequent calculations further downhole.

When a nitrified cement travels up the annulus after exiting the guide (float) shoe, the cement will be exposed to decreasing pressure and temperature. This, in turn, will directly affect fraction and all the properties dependent on fraction. To simulate the evolution of the nitrified cement as it travels up the annulus, a static (not inclusive of friction) simulation was performed. Thirty cement stages were entered into an annulus and were moved uphole by the addition of subsequent stages. The analysis showed an orderly, subtle increase in fraction for most of the pumping history. Only when a stage approached its final residence point did its fraction change more quickly than seen further downhole. The movement of a compressible fluid up an annulus containing an incompressible fluid is not accompanied by uncontrolled rate and volumetric increases. Rather, the subtle evolution of the nitrified cement properties is largely governed by the small pressure changes within the system.

A dynamic simulation was also performed to investigate the effects of frictional pressure loss on downhole properties. Using the Harris-Reidenbach model for foam viscosity, it was found that frictional pressure imparted an additional 0.3 lbm/gal [36 $Kg/m^3$] density at total depth. The additional pressure due to friction is on the same order as would be expected when comparing static densities and equivalent circulating densities for a normal (non-nitrified) cement operation. In field operations, the net effect of additional pressure due to friction loss translates to a decrease in the volume of nitrified cement produced as compared to that originally designed.

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