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The Novel Method to Estimate Effect of Cement Slurry Consistency toward Friction Pressure in Oil/Gas Well Cementing

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Abstract: The aim of this study is to investigate effect of cement slurry consistency toward friction pressure during oil/gas cementing operation. Completion of an oil/gas well has become more important because the reserve has become harder to find. The oil/gas company cannot afford to lose million dollars they spent when locating, drilling and recovering the oil from the Earth if they failed it. The safety, health and environment also have become more important issue, because any completion problem can lead to prolong operation and creating more hazard and risk. Cementing operation plays a very important role during completion because it creates a secure conduit to bring the precious oil/gas to the surface and a place to install completion jewelry. During cementing operation lost circulation can be one of the serious problems that arise. Circulation is said to be lost when the cement slurry pumped flows into one or more geological formations instead of returning up casing annulus. This is due to sum of hydrostatic pressure and friction pressure is exceeding fracture gradient. Method that commonly used to calculate friction from American Petroleum Institute (API) assumed the cement slurry will exhibit time independent nature. Cement slurry consistency was found to have significant effect to friction pressure.

Keywords: API, cementing, completion, friction pressure, lost circulation, thickening time, viscometer

INTRODUCTION

Oil/gas well cementing occurs throughout the world and has become increasingly more complex. The basic functions of primary cementing, however, have remained the same (Suman and Ellis, 1977):

- To support the axial load of the casing string and strings to be run later
- To seal intended production or injection intervals from overlying or underlying permeable sections (zonal isolation)
- To protect the casing from damage or failure
- To support the borehole through the productive interval

The primary cementing process proceeds as follows; a new section of the well is drilled. The drill pipe is removed from the wellbore, leaving drilling mud inside the wellbore. A steel tube (casing or liner) is inserted into the wellbore, typically leaving a gap of ≈2 cm between the outside of the tube and the inside of the wellbore, i.e., the annulus. The tubing is inserted in sections of length ≈10 m each. At certain points, centralizers are fitted to the outside of the tube, to prevent the heavy steel tubing from slumping to the lower side of the wellbore. Once the tube is in place, with drilling mud on the inside and outside, a sequence of fluids are circulated down the inside of the tubing reaching bottom-hole and returning up the outside of the annulus. Typically, a wash or spacer fluid is pumped first, followed by one or more cement slurries. The rheologies and densities of the spacer and cement slurries can be designed so as to aid in displacement of the annulus drilling mud, within the constraints of maintaining well security. The fluid volumes are designed so that the cement slurries fill the annular space to be cemented. Drilling mud follows the final cement slurry to be pumped and the circulation is stopped with a few meters of cement at the bottom of the inside of the casing and the cement is allowed to set. The final part of cement inside the tubing is drilled out as the well proceeds (Bittleston *et al*., 2004).

From the completion viewpoint, proper primary cementing should be the operator's main concern. Poor displacement efficiency which leaves a substantial volume of mud at the cement-formation interface can lead to just about every completion and production problem in the book. Oil and gas can be lost from the pay zone, stimulation fluids and enhanced recovery chemicals can bypass the formation, extraneous fluids may be produced and the borehole may not be properly supported. It is important to plan for the primary cement job long before casing is run into the hole, to avoid common problems such as improperly conditioned mud and stuck pipe. And

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the casing string itself should be carefully inspected and handled to avoid damage that can cause failure in otherwise properly designed strings (Suman and Ellis, 1977).

The main objective of a cement job is to displace wellbore fluid and obtain a good bond to casing and formation. Displacement efficiency increases with an increase in the rate at which the slurry is pumped; however there is a risk of fracturing the formations at higher flow rates. Hence the slurry must always be pumped at flow rates that will attain an equivalent circulating density that will not fracture the formations (Ravi and Sutton, 1990).

As the slurry is pumped down the casing and up the annulus a pressure loss from friction is experienced. This pressure drop must be overcome by the pumping unit on the surface. If rheological properties are overestimated, frictional pressures and hence circulating pressures calculated will be overestimated at a specified flow rate. Based on these calculations, the design flow rate will be underestimated. Whereas if plastic viscosity and yield point were known as a function of temperature, then the cement slurry could have been pumped at a higher flow rate and the displacement efficiency could have been improved without causing any formation breakdown (Ravi and Sutton, 1990).

Simulators used a constant rheology (normally measured at surface, BHCT, or some midpoint value) throughout the wellbore. In deep wells with a substantial bottom hole temperature, temperature thinning fluids will exert considerably different frictional pressures at different depths. If a single rheology profile is used across the entire wellbore length, a significant error may be induced (Kulakofsky *et al*., 1993).

Estimating the Reynolds number, flow regime and friction pressure of different fluids involved in a primary cement job-mud, spacer, cement-can be important for the success of the operation. Temperature prediction of the pressure and profiles in the wellbore, the control of the return flow rate and the optimization of mud removal all depend, among other things, on these three parameters (Guillot and Denis, 1988).

The rheology of cement slurries is an indication of the interaction between the cement particles and water molecules. The properties of hardened cement depend to a large extent on the chemical reactions and physical processes that occur during the early stages of hydration. Calorimetric and electron microscopy studies of cement hydration indicate an initial stage of rapid formation of a gelatinous hydrate coating around the cement grains within the first few minutes of mixing cement with water. An intermediate stage with a very low reaction rate then follows for several hours the induction or dormant period. At the end of the induction period, the reaction rate accelerates again as the surface coatings break and hydration products grow away from the surfaces into the space between grains. The cement slurry develops physical strength rapidly at this stage and cement set (Chow *et al*., 1988).

In order to safely place cement (cement slurry) to its desired location, it must remain pumpable throughout pumping process. In the oilfield the length of time a slurry remain pumpable under simulated well condition is called thickening time. This parameter is used to characterize the behavior of cement slurry under downhole conditions. It is measured with a consistometer in which torque is applied to a spring-loaded paddle to cement slurry in a rotating 150 rev/min slurry cup. The torque is interpreted in terms of cement-slurry consistency, which increases as cement sets. Specifically, the API thickening time is the time that elapse until a specified value of consistency (100 Bearden units, BC) is reached (Van Kleef and Van Vliet, 1993). Cement slurry may also be considered "unpumpable" at BC's ranging from 40 to 100, depending on operator preference (Purvis *et al*., 1993). Slurry that has reached that value of consistency will fracture the formation due to increase in viscosity that leads to excessive frictional pressure. This value is commonly used to determine the safe pumping time for the cement slurry.

Drilling muds and cement slurries are non-Newtonian. Extensive study has developed mathematical models that can be used to predict flow properties and pressure-velocity relationships of such muds and cements. The Bingham Plastic Model and the Power Law Model are most commonly used. The former has been utilized for drilling fluid analysis since the mid-1940s (Suman and Ellis, 1977).

Equivalent Circulating Density (ECD) is a term to represent the additional friction pressure to hydrostatic pressure due to flow properties. Additional friction pressure will only exist during pumping. In cementing operation ECD is used to estimate the safe pumping rate, optimum effective diameter and good viscosity of fluid to pump cement in place and to avoid the possibility of the overall pressure of the job at the specific depth to exceed fracture gradient during cementing operation. Exceeding fracture gradient will result lost circulation. Lost circulation is happening when the whole fluid breaking into the formation. And when this happened there will be inadequate zonal isolation or the possibility of blow out. This is due to less height of fluid and less hydrostatic pressure above formation zone.

To understand and to prevent aforementioned problem it is important to know the effect of cement slurry consistency toward viscosity and friction pressure. The assumption that fluid exhibits essentially time independent behavior in the API Recommended Practice 10A will disregard this effect (American Petroleum Institute, 1997).

Complete pressure drop and flow analysis calculations, even with electronic calculators, are tedious but acceptable results can be obtained. Computer facilities in most service companies and many operating companies, have made more detailed flow analyses practical. For example, variations of flow area due to borehole irregularities and presence of more than one type of fluid can be easily considered. However, with computerized analyses, the analytical procedure, the type of mathematical model used and input data should be completely understood, to avoid misleading results (Suman and Ellis, 1977). For this research Microsoft Visual Basic and MathWorks MATLAB has been used to do computerized analysis.

In the oil field, following equation from API RP 10B can be used for calculating pressure drop and flow regime for cement slurries in casing and concentric annuli. The equations outline a procedure to estimate pressure drop and flow regime in a concentric annulus by using the rheological data from a rotational viscometer (American Petroleum Institute, 1997).

In order to achieve the result of this research, several assumptions were used:

- The fluid is assumed to be homogeneous
- The fluid temperature is assumed to be homogeneous
- The flow is fully developed
- For annular flow, it is assumed that the geometry is concentric
- Slip at the wall is negligible
- It is assumed there is no free fall effect

Rheological models describe the relationship between shear-stress and shear-rate of a fluid. The most commonly used models to describe the rheological properties of cement slurries are the Bingham plastic and Power Law models (American Petroleum Institute, 1997). Recently Herschel Bulkley model also being used.

When plotting shear-stress versus shear-rate on Cartesian (rectangular) coordinates, cement slurry behaving as a Bingham plastic will result in a straight line with a positive shear-stress at zero shear-rate. For this model, the shear-stress is related to the shear-rate by the relationship:

$$\tau = \tau_0 + \mu_p \times \gamma \tag{1}$$

In this equation, τ_0 is the positive shear-stress at zero shear rate and is referred to as yield stress or yield point (often denoted as YP). Above the yield point, the shear-stress of the fluid is proportional to the shear-rate and the proportionality constant μ_p is referred to as the plastic viscosity (often denoted as PV). If in Eq. (1) the yield point is equal to zero, the equation then becomes the relationship for the simplest of all rheological models, the Newtonian fluid model. The units are 1/s for the shear-rate, Pa for the shear-stress and for the yield point and Pa.s for the plastic viscosity (American Petroleum Institute, 1997).

When plotting shear-stress versus shear-rate on Cartesian (rectangular) coordinates, Power Law model will produce a curve with zero shear-stress at zero shear-rate. When plotting shear-stress versus shear-rate on log-log paper cement slurry behaving as a Power Law fluid will result in a straight line. For this model, the shear-stress is related to the shear-rate by the relationship:

$$\tau = k \times \gamma^n \tag{2}$$

In this Equation *n* is referred to as the Power Law exponent or flow behavior index and *k* is a constant, referred to as the consistency index. For shear thinning fluids (pseudo-plastic) *n* is a positive number between zero and 1. Cement slurries normally exhibit pseudo-plastic behavior. For shear thickening fluids (dilatants) *n* is a positive number greater than one. Cement slurries normally do not exhibit dilating behavior. If an *n* is equal to 1, the equation then conforms to the Newtonian fluid model. The units in above equation are S1 units i.e., 1/s for the shear-rate, Pa for the shear-stress and Pa. s^n for the consistency index (American Petroleum Institute, 1997).

The parameters are obtained using regression analysis on the logarithmic form of Power Law Equation:

$$log\,(\tau) = log\,(k) + n \times log\,(\gamma) \tag{3}$$

Regardless of the unit system, the flow behavior index can be derived directly from the slope C:

$$n = C \tag{4}$$

If shear-stresses τ are expressed in lbf/ft^2 and shear rates γ are expressed in l/s, the consistency index in Ibf.s^n/ft^2 can be derived from the intercept D using:

$$k(\text{lbf. sn / ft}^2) = (0.01) \times 10^D \tag{5}$$

If shear-stresses τ are expressed in Pa and shear-rates γ are expressed in l/s, the consistency index in Pa.s^n can be derived from the intercept D using:

$$k\,(\text{Pa. s}^n) = 10^D \tag{6}$$

The rheological model conceived by Herschel and Bulkley at the beginning of this century has been considered to simulate the flow behavior of a drilling fluid. The model is a modified power law, concerning the flow of a yield pseudoplastic fluid as follow:

$$\tau = \tau_0 + k \times \gamma^n \tag{7}$$

where, the three rheological parameters are the yield point τ_0, the consistency index *k* and the flow behaviour index *n* Maglione *et al*., (2000).

To determine whether the fluid is Bingham Plastic Model or Power Law Model the statistic calculation was performed. The statistic calculation has been done using R-square method. R-Square equation:

$$R^2 = 1 - SSE / SST \tag{8}$$

where, SSE is the sum of the squared error and SST is the sum of the squared total. SST is the same as the SSE if the model was fitting the average. Between Bingham Plastic and Power Law, cement slurry researched has shown to follow Power Law Model. The Herschel Bulkley model was used for comparison.

Bolivar and Young in their study on the drilling fluid conclude that low rheology drilling fluid has demonstrated considerable ECD reduction as well as other technical benefits that have contributed toward reduced drilling risk (Bolivar *et al*., 2007). Cement-slurry rheology must be optimized for mud displacement and this cannot be done if the slurry thickens during displacement. Furthermore, a slurry that has thickened to >30 to 40 B, is unlikely to be pumped without generating frictional pressure drops that lead to formation fracturing (Van Kleef and Van Vliet, 1993).

The engineering and economics considerations of a primary cementing job cannot be overemphasized. A poor cementing job can result in a failure to isolate zones and can be very costly in the productive life of any well. Failure to isolate between producing zones can lead to ineffective stimulation treatments, improper reservoir evaluation, annular communication with unwanted well fluids and accumulation gas in the annulus (Smith, 1976).

This research has discovered a new method to determine the effect of cement slurry consistency change because of thickening time to friction pressure. This method is applicable for oil/gas well cementing job that has negligible free fall effect and pump at below turbulence rate inside a concentric annulus.

MATERIALS AND METHODS

This study was carried out in 2010 at PT Halliburton Indonesia in Riau, Indonesia and at Universiti Teknologi PETRONAS in Perak, Malaysia.

Cement and distilled water: For this research the cement used was Class G Cement and distilled water. Although it is very unlikely pure cement and distilled water is used in the oilfield, but it is necessary to make sure there is no external factor can affect the research (American Petroleum Institute, 2002).

HPHT consistometer: The measuring of thickening time, as determined in a high temperature, high-pressure consistometer, is related to the torque being placed on a stationary paddle within the rotating slurry cup. As the cement thickens, the torque increases on the spring-loaded potentiometer connected to the paddle shaft. This torque is recorded as a Direct Current (DC) voltage across a resistor on top of the potentiometer. The actual viscosity of the cement can then be derived from a linear plot of DC volts versus viscosity in Bearden Units of Consistency (BC). Thickening time test was performed following API 10A Schedule 5 and API RP 10B document was used as guidelines to do the thickening time test (American Petroleum Institute, 1997)

Viscometer: API RP 10A document was used as guidelines to do the viscosity test (American Petroleum Institute, 2002). The rotational viscometer used for the research was Fann Viscometer. Based on the manual viscosity can be determined by using this formula (Kiker *et al*., 1996):

$$\mu = \tau / \gamma \tag{9}$$

where,

τ = $k_1 . k_2 . q$
γ = $k_3 N$
k_1 = Torsion constant (dyne-cm/degree deflection)
k_2 = Shear stress constant for the effective bob surface (cm^3)
k_3 = Shear rate constant (sec^{-1}/rpm)
q = Reading from Fann Viscometer
N = Rate of evolution of the outer cylinder

All of these constants can be retrieved from the viscometer manuals and the equipment (Kiker *et al*., 1996).

Correlation test: Correlation test was performed by combining methods from API RP 10A and API RP 10B: Repeat the thickening time test:

- Stop at 10 min interval to collect the cement slurry sample from the thickening time cup
- Perform rheology test to find the rheological property
- Record the Bearden Consistency from the consistometer
- Record the related dial reading from viscometer
- Repeat the test until limit of dial reading viscometer is exceeded

Friction pressure calculation: Equations presented below taken from API RP 10B: Recommended Practice for Testing Well Cements is detailed procedure on how to

calculate Power Law Fluid pressure/friction loss.
For Pipe Flows:

$$V = 4QK_v / \pi D^2_I \tag{10}$$

For Annular Flow:

$$V = 4QK_v / \pi (D^2_h - D^2_O) \tag{11}$$

Friction pressure gradients, $\Delta P/L$ will be calculated from the relationship between at least two dimensionless groups: the Reynolds number *Re* and the friction factor *f*. The Reynolds number represents the ratio of the inertia forces to the viscous forces. The friction factor represents the ratio of the wall shear stresses to kinetic energy per unit volume (American Petroleum Institute, 1997).

Once the friction factor is known, the friction pressure gradient can be determined from:
For Pipe Flow:

$$\frac{\Delta P}{L} = \frac{2\rho V^2 f K_{\Delta P/L}}{D_I} \tag{12}$$

For Annular Flow:

$$\frac{\Delta P}{L} = \frac{2\rho V^2 f K_{\Delta P/L}}{(D_h - D_o)} \tag{13}$$

For a Power Law fluid with a Power Law index *n*, a consistency index *k* and a density ρ, the Reynolds number for Power Law fluid, Re_{PL}, is defined as:

For Pipe Flow:

$$Re_{PL} = \frac{K_{\mathrm{Re}\,PL} \rho V^{2-n} D_I^n}{8^{n-1}\left[(3n+1)/(4n)\right]^n k} \tag{14}$$

For Annular Flow (D_h/D_o<0.3):

$$Re_{PL} = \frac{K_{\mathrm{Re}\,PL} \rho V^{2-n} (D_h - D_o)^n}{8^{n-1}\left[(3n+1)/(4n)\right]^n k} \tag{15}$$

For Annular Flow (D_h/D_o>0.3):

$$Re_{PL} = \frac{K_{RL\rho L} \rho V^{2-n} (D_h - D_o)^n}{12^{n-1}\left[(2n+1)/(3n)\right]^n k} \tag{16}$$

In laminar flow the friction factor, *f*, can be calculated from the following equations:

For Pipe Flow:

$$f = 16 / Re_{PL} \tag{17}$$

For Annular Flow (D_h/D_o<0.3):

$$f = 16 / Re_{PL} \tag{18}$$

For Annular Flow (D_h/D_o>0.3):

$$f = 24 / Re_{PL} \tag{19}$$

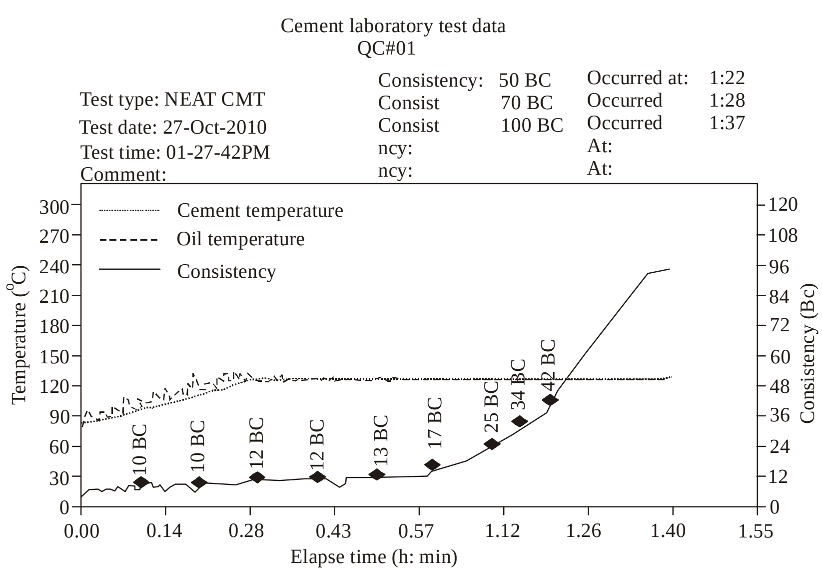

Fig. 1: Thickening time test result

RESULTS AND DISCUSSION

Thickening time/consistency test: First test was a thickening time test performed to provide base line for cement slurry consistency as shown in Fig. 1. Each mark in the figure represent the time when samples for rheology tests were taken. The base line was used to confirm if the reading during the research is valid.

The validity of result can be confirmed by comparing the time and BC reading between base test and the test for rheology test. This class G cement reach 100 BC after 1 h 37 min. From each thickening time chart increasing in the cement slurry consistency is not really apparent, except at 70 min and above. After 80 min slurry was no longer measurable by viscometer. Cement slurry that undergo 80 min thickening time test has shown that the 300 rpm reading is beyond dial reading of viscometer. That's why the 80 min reading is not used for Shear Rate-Shear Stress calculation. The detail cement temperature, chamber temperature and the consistency value at specified time can be found in Table 1.

Rheology test: By converting rpm and dial reading in Table 2 to shear rate and shear stress in Table 3, the fluid model can be determined. Using slope and intercept from a logarithmic plot of shear rate as the abscissa and shear stress as the ordinate, calculated shear stress can be determined by finding the *n* and *k* factor of Power Law fluid, as show in Table 4. The resulted calculated shear stress subsequently compared to actual shear stress using R-square method. By definition, R-Squared is "The percent of the variance that can be explained by all of the independent variables taken together." In the case of measuring viscosity, which is a natural process, it is expected near perfect fits to fit the right model to the data and the measurement error is small enough. The Power Law Model was chosen because for all the calculated shear stress the minimum R square is 0.9824 as shown in Table 5.

Table 1: Time, cement temperature, chamber temperature and BC of consistency test at x minutes

	Cement temp. (°F)		Chamber temp (°F)		Consistency (BC)	
Time (min)	Base test	Rheology test	Base test	Rheology test	Base test	Rheology test
0	83	83	80	80	5	5
10	96	95	98	10	21	07
20	111	110	114	116	10	10
30	125	124	126	123	12	9
40	125	124	125	125	12	12
50	125	124	124	124	13	12
60	125	125	124	125	17	18
70	125	123	124	112	26	29
75	126	126	124	122	34	24
80	127	125	122	123	47	44

Table 2: Average dial reading from viscometer at x minutes

	Dial reading at specific shear rate (rpm)				
Time (min)	3	6	100	200	300
0	18	21.5	50.5	62.0	73.0
10	21	27.5	66.5	81.5	92.5
20	28	36.0	70.5	83.5	94.0
30	19	32.0	67.0	80.5	91.5
40	21	34.5	82.5	90.5	105.5
50	22	37.0	89.0	100.5	111.5
60	35	42.0	92.59	8.0	121.0
70	33	40.5	136.0	155.0	174.5
75	58	63.5	161.0	186.5	212.0
80	78	83.5	239.0	272	N/A

Table 3: Shear-stress based on actual reading of viscometer at x minutes

	Shear stress (lb/100ft^2) (sec^{-1})				
Time (min)	5.12	10.23	170.5	341	511.5
0	19.17	22.90	53.78	66.03	77.75
10	22.37	29.29	70.82	86.80	98.51
20	29.82	38.34	75.08	88.93	100.11
30	20.24	34.08	71.36	85.73	97.45
40	22.37	36.74	87.86	96.38	112.36
50	23.43	39.41	94.79	107.03	118.75
60	37.28	44.73	98.51	104.37	128.87
70	35.15	43.13	144.84	165.08	185.84
75	61.77	67.63	171.47	198.62	225.78

Table 4: Power law's flow behaviour index and consistency index at x minutes

Time (min)	n	k (lbf S^n/ft^2)
0	0.30	0.12
10	0.32	0.14
20	0.25	0.20
30	0.31	0.14
40	0.33	0.15
50	0.33	0.16
60	0.26	0.24
70	0.38	0.19
75	0.29	0.37

Table 5: Calculated shear-stress and R-squared value using power law

	Shear stress (lb/100ft^2) (sec^{-1})					
Time (min)	5.12	10.23	170.5	341	511.5	R^2
0	18.85	23.24	54.40	67.07	75.81	0.9981
10	22.90	28.56	69.98	87.27	99.30	0.9996
20	30.84	36.79	75.30	89.83	99.60	0.9988
30	23.28	28.96	70.25	87.39	99.30	0.9915
40	25.50	32.04	80.95	101.71	116.24	0.9824
50	26.99	34.04	87.27	110.05	126.04	0.9812
60	37.39	44.84	93.74	112.42	125.02	0.9839
70	34.69	45.04	129.96	168.73	196.56	0.9836
75	58.92	72.19	164.68	201.78	227.25	0.9962

To discuss Fig. 2 "minimum shear-stress" and "maximum shear-stress" will be used. Minimum shear-stress in this context means shear-stress at minimum shear-rate tested (5.12/sec). Maximum shear-stress in this context means shear-stress at maximum shear rate tested (511.50/sec).

The shear-stress at initial condition (0 min) was relatively small. This is because at this condition the cement was still in liquid form and not yet developing consistency. The minimum shear-stress at this point was

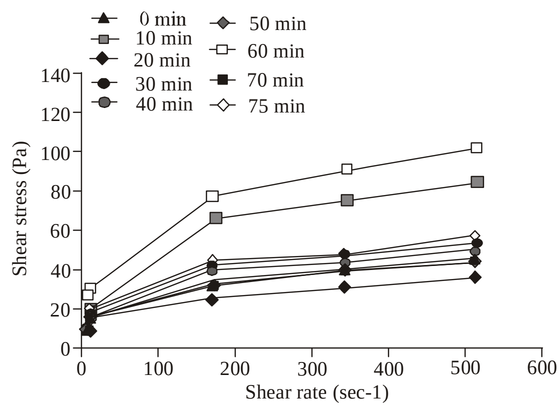

Fig. 2: Shear-stress and shear-rate chart

9.18 Pa (19.17 lb/100ft^2) and the maximum shear-stress was 37.22 Pa (77.75 lb/100ft^2).

There was increase in the shear-stress showing that at 10 min there had been change in the viscosity of the cement slurry. The minimum shear-stress at this pointwas 10.71 Pa (22.37 lb/100ft^2) and the maximum shear-stress was 47.17 Pa (98.51 lb/100ft^2).

After 20 min there was continuing increasing in the shear-stress. The minimum shear-stress at this point was 14.28 Pa (29.82 lb/100ft^2) and the maximum shear-stress was 47.93 Pa (100.11 lb/100ft^2)

The data collected after 30 min reflect the consistency reading when there was decrease in consistency. The minimum shear-stress at this point was 9.69 Pa (20.24 lb/100ft^2) and the maximum shear-stress was 46.66 Pa (97.45 lb/100ft^2).

Table 6: Herschel bulkley three parameters from MATLAB

Time	τ_o (lb/100ft^2)	k (lbf S^n/ft^2)	n
0	7.154	0.08	0.3817
10	7.18E-0	80.11	0.314
20	3.002E-0	70.13	0.2534
30	1.798E-0	70.12	0.2988
40	1.853E-0	70.12	0.3027
50	1.853E-0	70.13	0.3027
60	0.00004094	0.14	0.2679
70	3.039E-07	0.13	0.3463
75	2.758E-08	0.16	0.2899

After 40 min minimum shear-stress was 10.71Pa (22.37 lb/100ft^2) and the maximum shear-stress was 53.80 Pa (112.36 lb/100ft^2). Although consistency was not visibly high at this point the increase in the shear rate was quite significant.

The minimum shear-stress at 50 min was 11.22 Pa (23.43 lb/100ft^2) and the maximum shear-stress was 56.86 Pa (118.75 lb/100ft^2). There was continuing increase of shear-stress at every shear-rate at this chart.

After 60 min there was significant increase in the shear-stress because the increase in consistency also significant. At this point the cement slurry consistency was 18 BC. The minimum shear-stress at this point was 17.85 Pa (37.28 lb/100ft^2) and the maximum shear-stress was 61.7 Pa (128.87 lb/100ft^2).

At 70 min the maximum shear-stress was greatly increased to 88.98 Pa (185.84 lb/100ft^2) and minimum shear-stress at this point was 16.83 Pa (35.15 lb/100ft^2). This is due to the high consistency of the cement slurry.

And at 75 min maximum shear-stress was 108.10 Pa (225.78 lb/100ft^2) and minimum shear-stress at this point was 29.58 Pa (61.77 lb/100ft^2). At this point the cement slurry was very thick due to the cement was gelling up.

Further analysis using MATLAB software had resulted 3 Herschel Bulkley parameters. Table 6 showing

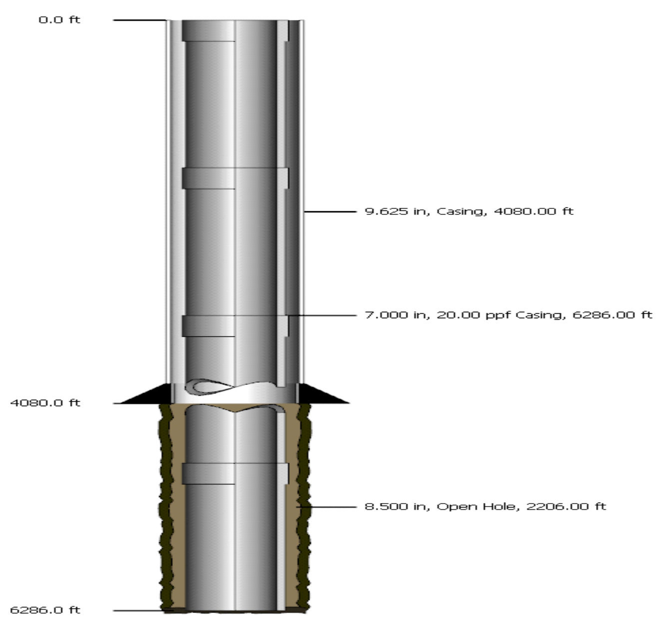

Fig. 3: Well schematic

the result of using General model Power2 f(x) = a*x^b+c in MATLAB using *cftool* function. Non-linear fit to various data with numerical package (i.e., MATLAB) sometimes has given the best fit (highest correlation coefficient R^2) with negative values for the $\tau_0$which is meaningless. The condition $\tau_0>0$ was imposed to get meaningful results affecting thus the optimum determination of all three parameters (Kelessidis *et al*., 2006). At 10 to 75 min MATLAB had shown the intercept τ_0 is very close to zero. This can be interpreted that the actual τ_0 is 0 which means it follow Power Law model.

Effect to friction pressure: Oil well configuration need to be chosen to see the effect of cement slurry consistency toward friction pressure. One of the factors to be considered is the temperature because consistometer used temperature schedule to simulate wellbore condition. This well has Bottom Hole Circulating Temperature 125°F. The depth is chosen using assumption at the end of the job the final hydrostatic pressure needs to be 5160 psi as per schedule of Sch. 5 specification test for Classes G and H from API Recommended Practice 10A used for cement slurry thickening time test.

Figure 3 is the well data that most resemble the temperature and pressure schedule of Sch. Five specification test for Classes G and H. The previous casing selected has an outside diameter of 9 5/8 inch with 35 lb/ft weight. This casing has an inside diameter of 8.921 inch sets at 4080 ft depth. The casing being cemented has an outside diameter of 7 inch with 20 lb/ft weight. It has and inside diameter of 6.456 inch. This

Fig. 4: Fluid legend

casing is inside the hole of 8.5 inch with 100% wash out calculated from annulus volume. The depth of this casing is 6286 ft.

Based on thickening time of 88 min (70 BC) and 97 min (100 BC) and 30 min safety factor pumping time calculated is 118 min. Safety factor is needed to include time to drop bottom and top inside-casing wiper rubber plug and flushing the pipe connecting casing to cement pump from cement slurry residue before displacement. Volume of displacement and volume of slurry are used to calculate pumping time because during pumping these two fluids cement slurry is constantly mixed and pumped. Adding displacement volume of 251.4 bbls and cement slurry volume of 223.8 bbls will result 475.2 bbls. Based on this volume rate is determined to be 475.2 bbl divide by 118 min equal to 4.02 bbl/min. Figure 4 contain with the legend of the fluid pumped.

Cement slurry is still inside the casing during first 60 min of pumping cement. Because friction pressure is critical only in the annulus, this length of time was not considered to affect the well. Figure 5 and 6 are the visualizations when cement slurry already enter the annulus and Figure 7 is the end of job.

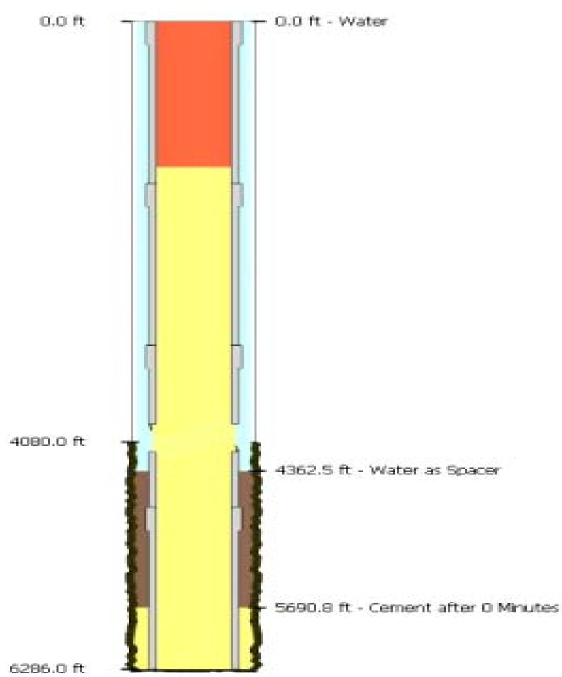

Fig. 5: After 70 min cement has entering annulus

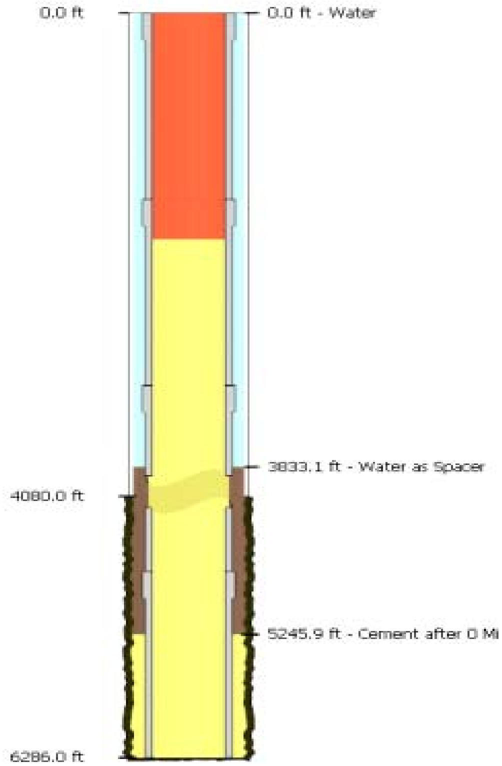

Fig. 6: After 75 min cement has entering annulus

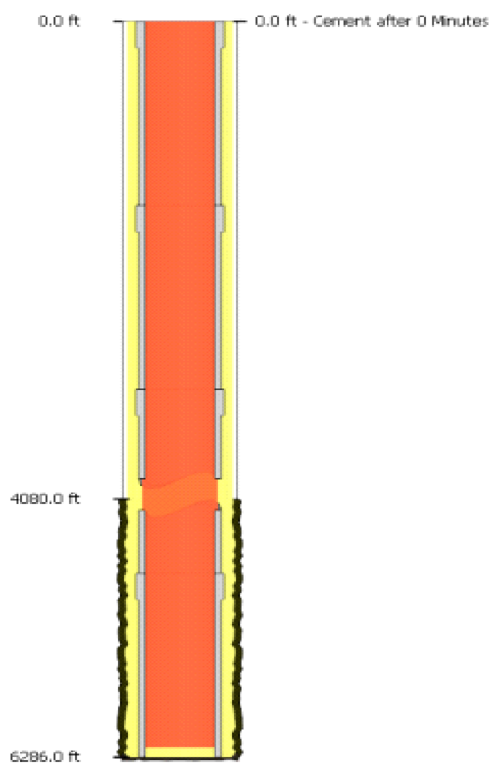

Fig. 7: End of job

Table 7: Friction pressure summary

	Without consistency		With consistency		Different	
Description	70 min	75 min	70 min	75 min	70 min (%)	75 min (%)
Cement annular open hole	37.68	65.76	83.83	194.21	122.48	195.33
Water annular open hole	17.70	12.82	17.70	12.82	0.00	0.00
Water annular casing	20.38	20.38	20.38	20.38	0.00	0.00
Total friction	75.76	98.96	121.9	2227.41	60.93	129.80

As seen in Table 7 from the research the different in friction due to consistency can go up to 129.8%. This value has never been taken into account if using API Recommended Practice 10A to calculate friction pressure due to time independent assumption. This can cause a problem if the time of the job is not carefully designed or there is a problem during pumping creating shut down time which will allow the cement slurry to develop consistency. The cement can gain viscosity and the friction can make ECD exceeding the fracture pressure which can lead to loss circulation. Too much increase in friction pressure can cause the cement slurry cannot be pumped at optimum rate where it can efficiently remove mud and push fluid in front of it.

On the opposite side the increase in consistency can help in improving oil/gas well cementing job. This is due to a thicker fluid will remove immobile mud, partially dehydrated mud and mud cake better. These mud products from drilling operation have already known are not good for cement bonding to formation and to casing due to compatibility issues with cement slurry, however disregarding this information can cause planning of using unnecessary other mean to remove them when designing the job, such us more spacer volume, faster pumping time and more centralizer.

CONCLUSION

This research has discovered a new method to utilize viscometer and consistometer to closely reproduce what is happening to cement slurry during cementing job. There was no addition or modification in the components of the laboratory devices make this new method is readily available to employ. The effect of temperature was taken into consideration by the ability of consistometer to simulate job temperature based on Schedule 5 of API Recommended Practice 10A. With given well that has previous casing outside diameter of 9 5/8 inch with 35 lb/ft weight at 4080 ft depth and cemented casing outside diameter of 7 inch with 20 lb/ft weight inside the hole of 8.5 inch with 100% wash out calculated from annulus volume and bottom hole circulating temperature at 125°F, the class G cement mixed with distilled water will have significant increase in calculated friction pressure with the value of 60.93% for 70 min pumping and 129.8% for 75 min pumping, comparing between API method and new method.

RECOMMENDATIONS

Cementing Service Company needs to include this new method in their simulation package to improve accuracy of their software output and make their software will be able to closely resemble what happen in the well during oil/gas well cementing job.

NOMENCLATURE

Parameter	Definition	U.S. oil field unit	SI unit
D_i	lnner diameter of a pipe	in	m
D_o,D_i	lnner and outer diameters of an annulus	in	m
ECD	Equivalent Circulating Density	lb/gal	kg/m^3
f	Friction factor	-	-
k	Consistency index of a Power Law fluid	lbf sec^n ft^{-2}	Pa S^n
L	Length of a pipe or of an annulus	ft	m
n	Power Law index of a Power Law fluid	-	-
Re	Reynolds number of a Newtonian fluid	-	-
Re_c	Critical values of Re	-	-
Re_{PL}	Reynolds number of a Power Law fluid	-	-
Re_{PLi}	Critical values of Re_{PL}	-	-
Q	Volumetric flow rate	bbl/min	m^3/sec
Q_c	Critical value of Q	bbl/min	m^3/sec
V	Fluid mean velocity	ft/sec	m/sec
V_c	Critical value of V	ft/sec	m/sec
ΔP	Friction pressure	psi	Pa
μ	Viscosity of a Newtonian fluid	cp	Pa S
μ_P	Plastic viscosity of a Bingham plastic fluid	cp	Pa S
ρ	Fluid density	lb/gal	kg/m^3
τ	Yield stress	lbf $(100ft^2)^{-1}$	Pa
τ_0	Yield point	lbf $(100ft^2)^{-1}$	Pa

Constant:

Constant	U.S. oil field unit	SI unit
K_v	13.4828	1
$K_{P/L}$	0.01936	1
K_{RePL}	0.2325/12	1

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