A NEW MODEL FOR THE EVALUATION OF THE MAXIMUM SURFACE PUMP PRESSURE DURING A CASING CEMENTING JOB

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INTRODUCTION

While drilling oil & gas wells it is necessary to insulate different parts and sections of the crossed formations. In this way, a well is drilled with smaller and smaller sizes of the bit to be used and each time a column of casing, having smaller and smaller sizes, is set in order to insulate the thickness of the drilled formations.

After that, when the casing string has been run to the bottom of the section inside the hole, formed by the previous cemented casing column and the open hole, the cementing job starts in order to fix the casing at the bore hole wall.

In this scenario, performing a careful analysis on several cementing jobs carried out with casing of different sizes and weights, emerges the fact that rarely the people working on the rig exploits the maximum available fracture margin during the displacement of the drilling mud by means of the cement slurry. In this way, fearing to fracture the formation for high annular frictional pressure losses, very low pump rates are used that, very often, can compromise both the efficiency of the displacement and the quality of the cementing jobs, besides a loss of rig time.

So, in order to provide the operational people, working on the rig, with an helpful tool for optimising the maximum displacement pump rate of the mud on respect to the available fracture margin, a practical end easy to use method of evaluation of the rheology properties of the mud, the percentage of the distribution of the frictional pressure losses inside the casing and the annulus and the maximum displacement pump rate and the maximum available surface pump pressure have been developed.

In this paper a field case will be analysed comparing the field (measured) data to the data calculated using this practical procedure and making a crossing check of the validity of the proposed method against the CBL data of the well.

The technical contribution that we can have using this new procedure can be resume as follows:

- Determination of the true rheological parameters (according to the Herschel and Bulkley model by means of an original numerical calculation procedure developed in house) of the circulating drilling fluids by performing two circulation test while running into the hole the casing string.
- Determination of the exact distribution of the pressure drop along the well profile in the annular section in order to define the maximum available dynamic pressure drop at the weakest point in the annulus (e.g., previous cemented casing shoe).
- Determination of the maximum displacement pump rate of the drilling mud and the maximum available surface pump pressure to be used while performing the cementing job in order to better exploit the restrictions imposed by the cementing hydraulic circuit.

FIELD CASE STUDY

The field case considered for this study is concerning an onshore well (Well A) located in the Po Valley (North Italy). This inclined well was used to test, analyse and compare all the data obtained from the field job and those using the new operational procedure. It was 1854 m deep, measured depth (MD), with a 7" 29 lb/ft casing to be cemented inside a 8 1/2" bore hole of 539 m (MD) of open hole. The maximum inclination of the well was about 45° at 1854 m MD. Figure 1 shows the scheme of the considered well.

The lithostratigrafic profile of the crossed formations is the following: clay, sand and gravel from 0 to 200 m; silty shale from 200 to 550 m; silty shale with sand level in place from 550 to 1330 m; sand and gravel with clay level in place from 1330 to 1580 m. The casing centralisation program used while running in hole the 7" casing string was the following: 2C from 1854 to 1750 m, C1 from 1750 to 1300 m, C2 PO from 1300 to 400 m. The circulating mud in the well while performing the cementing job and also used to drill the 8 1/2" section was an OBM-LT having a density of about 1630 kg/m^3.

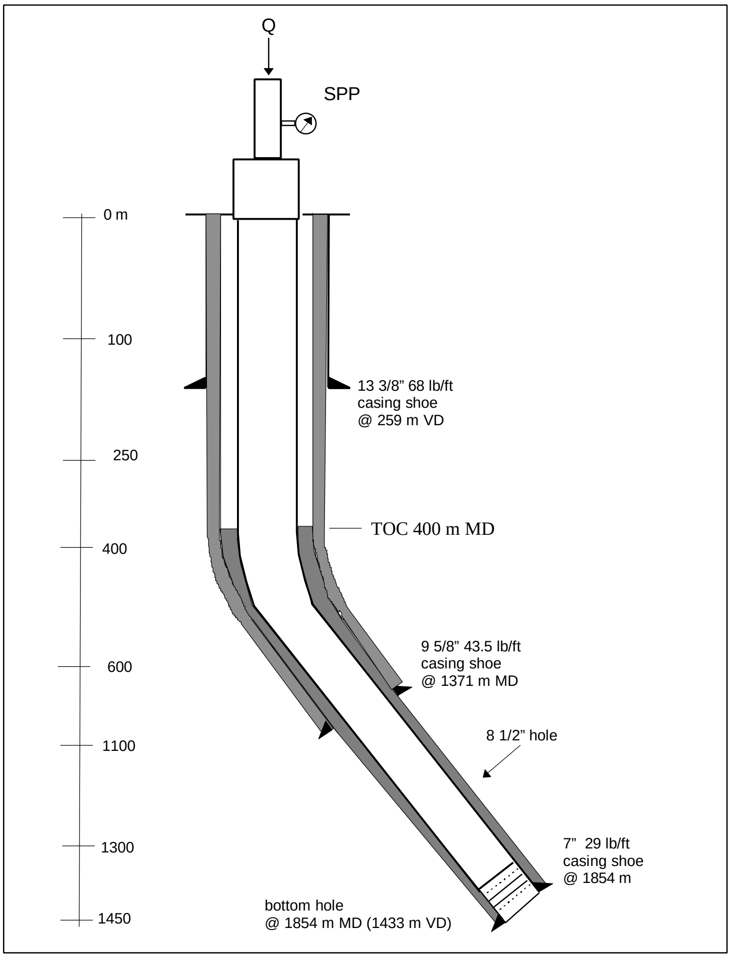

Figure 1

The rheological parameters of the circulating mud obtained from measurements on the Fann VG 35 viscometer, at the temperature of about 36 °C (309 K) upon the Herschel & Bulkley rheological model, are the following:

- yield point, τ_0 = 4.643 Pa
- consistency index , k = 0.155 Pa·s^n
- flow behaviour index, n = 0.813

Table 1 reports the data obtained from the measurements carried out on a circulating mud sample (taken at the shale shaker) at the Fann VG 35 viscometer on the rig site.

N rpm	reading degree
600	94
300	57
200	43
100	30
6	11
3	10

Table 1

The developed procedure can be split in three different step: in the first step the determination of the true rheological behaviour of the circulating mud is done; the second one consists of calculating the distribution of the pressure loss inside the casing string and in the annular gap against the pump rate and the third step regards the evaluation of the maximum value of the most important operational parameters needed to perform the cementing job without compromising the integrity of the cementing hydraulic circuit.

As mentioned the **first step** of the procedure consists of performing pump rate/pump pressure test (Q/P test) while running into the casing string at two different depth and at least three different pump rates. In this way for the Well A, the Q/P test was performed after running in hole 8 joints (104 m MD) of the 7" 29 lb/ft casing string and at the bottom hole (1804 m MD) with the same surface hydraulic circuit used for the cementing job. Table 2 reports all the recorded data of pump rate and surface pump pressure.

circulation test at 8 joints @ 104 m				
pump rate, l/min	400	800	1212	1612
pump pressure, bar	2	8	16	29
circulation test at bottom hole @ 1854 m				
pump rate, l/min	400	800	1212	1612
pump pressure, bar	27	42	64	88

Table 2

Starting from the values of surface pump pressure and pump rate and knowing both the fluid density and the geometries of the cementing hydraulic circuit, using a software developed in house (Maglione-Robotti, MR, model), the true rheological parameters of the circulating mud that are the best fit of the field data have been calculated. This tern, called WAV (well as viscometer) tern, is which one that gives the best results when the pressure drops in the well, using the classical equations from literature in according to the Herschel & Bulkley rheological model, are calculated. In this case the rheological parameters determined with the MR model (WAV tern from Q/P test) are the following:

- yield point, $\tau_0 = 2.877$ Pa
- consistency index, $k = 0.161$ $Pa \cdot s^n$
- flow behaviour index, $n = 0.8$.

Table 3 shows a comparison between the rheological parameters determinated using the Fann VG 35 viscometer and the Q/P test (WAV mud).

rheological parameters	
Fann VG 35 mud	WAV mud
$n = 0.813$	$n = 0.8$
$k = 0.155$ $Pa \cdot s^n$	$k = 0.161$ $Pa \cdot s^n$
$\tau_0 = 4.643$ Pa	$\tau_0 = 2.877$ Pa

Table 3

Figure 2 shows the behaviour of the circulating mud in according to the different methods used to determine the rheological tern. The circulating mud, in the range of shear rate achieved in the well bore (1 - 800 1/s), has a yield pseudoplastic behaviour in both the case (Fann VG 35 mud and WAV mud).

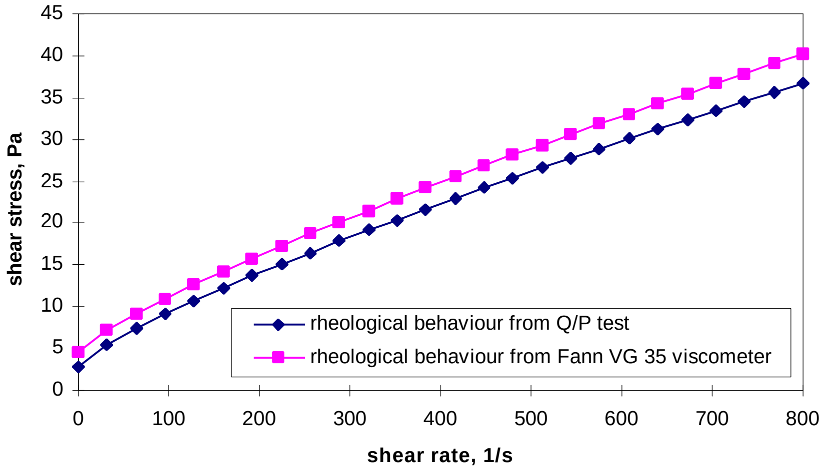

Figure 2

Based on the above results, the pressure losses, considered as the sum of the pressure loss inside the casing string and in the annular section, have been calculated with both rheological parameters from Fann VG 35 viscometer and Q/P test. Table 4 shows all the calculated data using the two rheological tern. The measured Δp value reported in the table has been determined simply making the difference between the surface pump pressure readings recorded at the two different depth of the test at the same pump rate.

pump rate l/min	measured Δp bar	calculated Δp using Fann VG 35 tern bar	error %	calculated Δp using WAV tern bar	error %
400	25	30.0	19.9	24.2	-3.3
800	34	41.9	23.2	35.6	4.7
1212	48	53.0	10.5	46.8	-2.5
1612	59	65.1	10.3	59.3	0.5
standard deviation, bar			6.1		1.1

Table 4

From the above table it can be seen that the values of the pressure losses calculated with the WAV tern match much better the Q/P field data than those calculate whit the Fann VG 35 tern. Infact, the standard deviation is 1.1 bar for the WAV tern and 6.1 bar for the Fann VG 35 tern denoting the best fit of the field data given by the WAV tern with a very low error.

The second step of the procedure consists of redoing the pressure drop calculations separately for the circular section (inside the casing string) and the annular section, considering the WAV mud only. In this way, we can obtain the percentage distribution of the annular frictional pressure losses in the cementing hydraulic circuit. Table 5 shows the data concerning the pressure losses both inside the casing string and in the annulus and the relative percentage distribution, ξ, against the pump rate.

pump rate l/min	measured Δp bar	calculated Δp inside casing string bar	calculated Δp in the annulus bar	ξ -
400	25	2.5	22.5	0.90
800	34	2.7	31.3	0.92
1212	48	3.8	44.2	0.92
1612	59	5.9	53.1	0.90

Table 5

This calculation has been repeated and done for several other cementing job case carried out in different drilling scenario and particularly for the most common used weights (23, 29, 32, 35 and 38 lb/ft) of the 7" casing inside a 8 1/2" hole. For all the considered cases the percentage distribution of the annular pressure losses against the pump rate has been plotted. Figure 3 reports the ratio between annular and total frictional pressure losses against the pump rate for the most common used weights of 7" casing inside a 8 1/2" section.

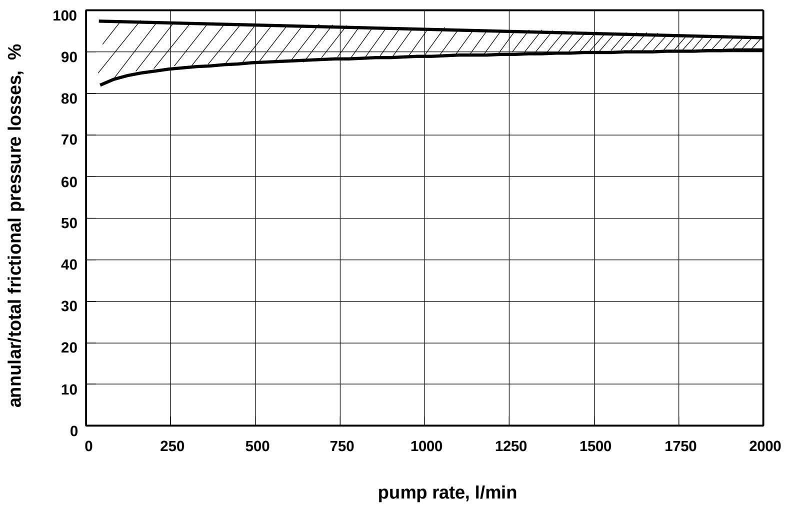

Figure 3

From the graphs it can be seen that the distribution of the percentage of the frictional pressure losses in the annulus is very high in all the examined cases and always lies in the dotted area. For the usual pump rates used to perform the cementing job is about 88-97% (for pump rate of about 800-1000 l/min). These results are of very practical utility because while performing the cementing job it is possible to evaluate, directly on the rig, the maximum frictional pressure drop in the annular section in order to establish the maximum pump rate to be used without fracturing the crossed formations to be cemented, optimising in very short time the displacement pump rate of the mud and the efficiency of the cementing job. In the case a more accurate evaluation is needed the percentage of the annular pressure drop can be calculated using the MR model directly on the rig but in this case the use of a personal computer and just more time to get the results is needed.

The third step of the procedure consists of calculating the maximum value of the most important operational parameters to be used in order to exploit at the best the performances of the cementing hydraulic circuit such as the maximum final displacement pump rate and the maximum available displacement surface pump pressure. In order to assure the integrity of the formations, in this procedure the weakest fracture gradient of the formations to be cemented is considered: it can be located at the bottom hole, the most frequent case, or in an other different depth called in this case weak point depth.

The input data for the calculation of the maximum surface pump pressure and the displacement pump rate can be split in three different groups as follows: general data, hydrostatic pressure data and circulation test (Q/P test) data. The first group of data (general data) includes parameter characteristic of the crossed formations such as vertical depth of the bottom hole or the weak point (if any) and fracture gradient of the formation at the bottom hole or at the weak point (if any). However in practice, in most of the case the weakest point of the formation to be cemented corresponds to the bottom hole, so generally all the calculations are referred to the bottom hole conditions. Output data from this calculation module is the evaluation of the fracture pressure at the bottom hole (or at the weak point).

The second group of data (hydrostatic pressure data) includes input data such as circulating mud, spacer and slurries weights and the corresponding depths in the annulus sections at the end of the displacement, namely when the bump plug is reached. Output data of this calculation module are the hydrostatic pressures corresponding to the displaced mud, spacers and slurries at the end of the slurry displacement, the final hydrostatic pressure (at the bump plug) and the corresponding hydrostatic pressure balance, given by the difference between the final and the mud hydrostatic pressure.

The third group of data (circulation test data) includes the stand pipe pressure data collected from circulation test (Q/P test) at two or sometimes three different depths (generally after running six joints, at the casing shoe of the previous cemented casing and at the bottom hole, carried out while the casing string is running into the hole) at three or more pump rate. The maximum circulating pump rate, Q_{max}, should not exceed the safety pump rate of the floating valve and the casing shoe. Generally this flow rate is determined in lab test by the manufactures and noticed to the people on the rig before performing the cementing job.

During the cement slurries displacement the people working on the rig floor should have to use the maximum available final displacement pump rate determined by the Q/P test and also must give a look to the surface pressure dial as the maximum available stand pipe pressure while displacing the cement slurries must not be exceeded: *this is a guide rule to follow all the displacement time. In the case, going with the maximum displacement pump rate, this pressure is overcome the pump rate must be lowered until to a value corresponding to the maximum stand pipe pressure (SPP_{max})*. This is due to the fact the determination of the maximum displacement pump rate is done making some assumptions in order to ease the procedure. Assumption such as the pressure losses of the cement slurries in the annular sections are considered equal to the pressure losses of the circulating mud, could change slightly the value of the parameters involved (Q_{max} and SPP_{max}).

Table 6 reports the input data needed to make the evaluation of the maximum available final pump rate without fracturing the crossed formations for the Well A. In this case the weakest point is not located at the bottom hole but at the shoe of the 9 5/8" 43.5 lb/ft casing located at 1063 m (vertical depth). At this depth the fracture pressure margin is about 25.2 bar and on this value all the following calculations are based. From the table 6, after doing all the calculations, one can see that the maximum available pump rate that could be used lies between 800 and 1212 l/min. Infact, by means interpolation methods, the pump rate that satisfies the condition the maximum annular pressure drop must be lower than the fracture pressure margin at the weakest point (25.2 bar) has been found. The maximum value is about 945 l/min. The corresponding maximum available surface pump pressure, SPP_{max}, is about 74 bar. *This value must be considered as guide data to follow for all the displacement time. In the case this value is overcome, while the displacement is going on at the maximum pump rate (945 l/min), the pump rate must be reduced until to reach the SPP_{max} value (74 bar)*. In other words the maximum available surface pump pressure must be kept constant all the displacement time at (if possible) the maximum available pump rate or other smaller pump rate if the value of the surface pump pressure is overcome.

general Data	**Well A**			
bottom hole vertical depth, m	1433	1433	1433	1433
bottom hole measured depth, m	1856	1856	1856	1856
weak point vertical depth, m	1063	1063	1063	1063
weak point measured depth, m	1315	1315	1315	1315
bottom hole fracture gradient, atm/10m	2.16	2.16	2.16	2.16
weak point fracture gradient, atm/10m	2.02	2.02	2.02	2.02
bottom hole fracture pressure, atm	312.39	312.39	312.39	312.39
weak point fracture pressure, atm	214.73	214.73	214.73	214.73

hydrostatic pressure data

mud weight, kg/l	1.63	1.63	1.63	1.63
bottom hole hydrostatic mud pressure, atm	233.6	233.6	233.6	233.6
bottom hole hydrostatic pressure at the end of the displacement, atm	258.0	258.0	258.0	258.0
weak point hydrostatic pressure at the end of the displacement, atm	189.5	189.5	189.5	189.5
bottom hole hydrostatic pressure balance, atm **(a)**	24.4	24.4	24.4	24.4

circulation test (Q/P test) data

pump rate, l/min	400	800	1212	1612
circulation test at 6 joints, atm **(b)**	1.97	7.89	15.79	28.62
circulation test at bottom hole, atm **(c)**	26.65	41.45	63.16	86.85
ΔP = **(c-b)**, atm	24.68	33.56	47.37	58.23
bottom hole fracture pressure margin the end of displacement, atm	54.43	54.43	54.43	54.43
weak point fracture pressure margin the end of displacement, atm	25.21	25.21	25.21	25.21
pressure drop inside casing string, atm **(d)** = $\Delta P * (1-\xi)$	2.47	2.68	3.88	5.65
pressure drop inside annulus at bottom hole, atm **(e)** = $\Delta P * \xi$	22.21	30.88	43.49	52.58
pressure drop inside annulus at weak point, atm **(f)**	15.74	21.88	30.81	37.25

output data

fracturing check, $\Delta P_{an} \leq$ pressure margin, atm	f < 25.2	f < 25.2	f > 25.2	f > 25.2
maximum reading at the dial surface, atm **(a+b+d+e)**	51.05	65.85	87.56	111.25

Table 6

A volume of 6 m^3 of a chemical spacer having density of 1700 kg/m^3 was pumped down into the 29 lb/ft 7" casing string before the slurry. After the spacer a volume of 24.1 m^3 of a gas-block type slurry was pumped down into the casing. The slurry was made up with 28600 kg of G cement and 15.1 m^3 of mixing water and chemical additives. Table 7 reports the list of the chemical additives used in the cement slurry and relative percentage.

product	percentage, %	application
CB-01	8	gas block
PF-01	1	dispersant
HALAD-413	0.7	fluid loss HT

Table 7

In order to compare the data calculated applying the above procedure with the field data operational parameters such as displacement pump rate surface pump pressure and the time have been monitored during all the cementing job. Figure 4 shows the behaviour of the calculated and collected field data.

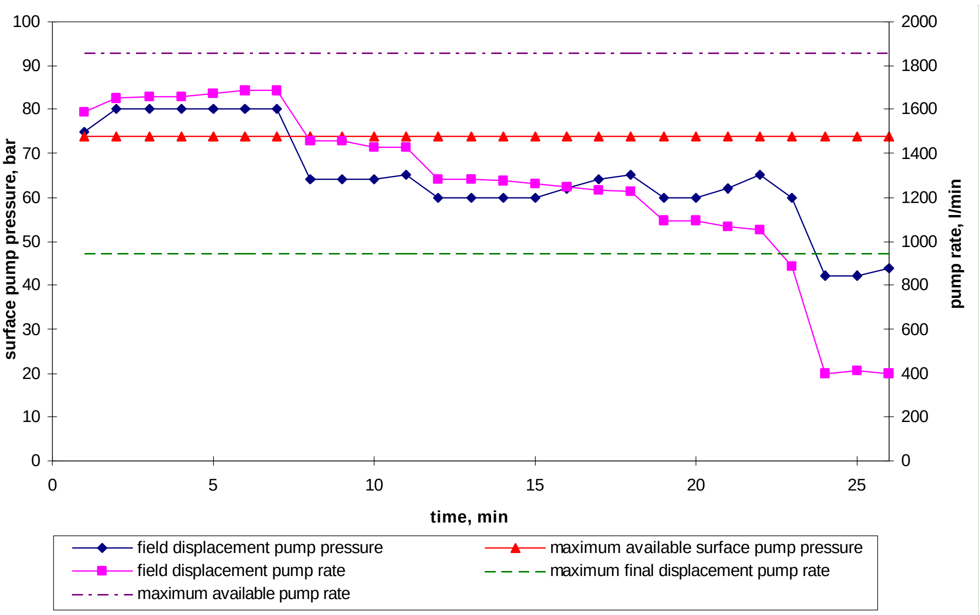

Figure 4

From figure 4 one can see that at the very beginning of the cementing job the maximum displacement pump rate used was about 1680 l/min with a corresponding surface pump pressure of 80 bar. This pressure is slightly higher than the maximum available final displacement pump pressure calculated using the procedure (74 bar) but however no problems were experienced in this interval. Starting from the eighth minute, the displacement pump rate has been decreased to about 1454 l/min with a corresponding surface pump pressure of 64 bar, 10 bar below the maximum allowed pressure, and was kept quite constant until to nearly the end of the displacement decreasing over the time the pump rate.

Approaching the end of the displacement job the pump rate has been lowered to 400 l/min with a corresponding surface pump pressure of 42 bar. Because of pump rate decrease the mud mobility went down from 2434 min/lb for 1200 l/min to 270 min/lb for 400 l/min.

From a comparison between field and calculated (by means of the new procedure) data arises the fact that, a part the first minutes of displacement where an even higher surface pump pressure was used, the pump pressure was always lower and when approaching the end of the displacement even much lower than the calculated one. In this way the people performing the job did not exploit at the best the performances of the cementing hydraulic circuit and in particular way the maximum available fracture pressure margin. In fact in this case a surface pump pressure of about 70 bar could be kept constant for all the displacement time, without compromising the integrity of the cementing hydraulic circuit, and adjusting the displacement pump rate in according to the surface pump pressure (knowing that the final value is about 945 l/min). This choice could lead, behind the fact of a save of rig time due to the higher pump rate used, to an increase of the displacement efficiency by means of the cement slurry.

Figure 5 shows a comparison between the velocity profile of the circulating mud in the annular gap (7"-8 1/2") at 400 l/min (used in the last interval of the displacement phase) and 945 l/min (suggested in this interval by applying the procedure).

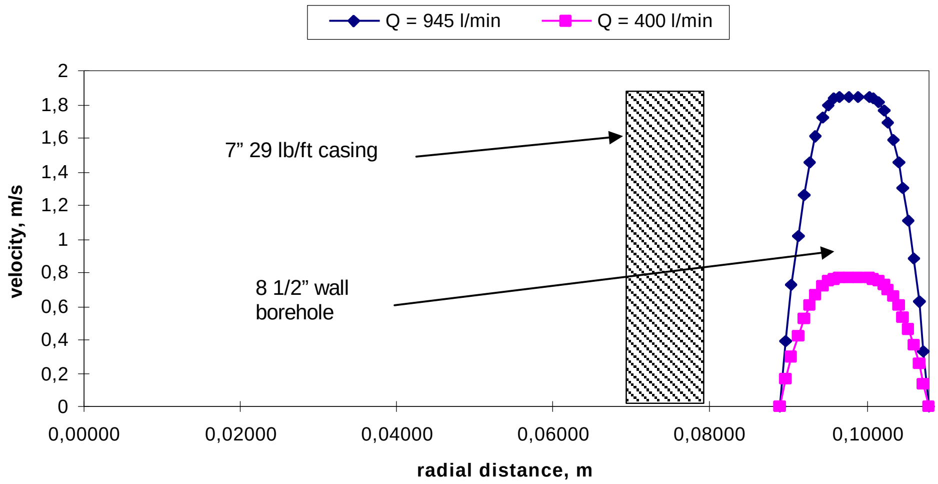

Figure 5

From the figure 5 it can be seen that the mud velocity values of the suggested pump rate (945 l/min) are much higher than the used one (400 l/min) even close to the borehole wall where generally lower velocity values are encountered permitting a better displacement of the mud by means of the cement slurry even in part of the annular section that very difficulty can be reached by the displacement. On the other hand the mud mobility increases from 270 (for 400 l/min) to 1510 (for 945 l/min).

Figure 6 reports the CBL log recorded after the cementing job. Giving a look at the CBL log one can see that the displacement efficiency is good until when the pump pressure was kept close the maximum available surface pump pressure while the results are sufficiently good in the interval where the surface pump pressure has been decreased (consequently to a decrease of the displacement pump rate).

So based on the above results, it could be stated that the higher displacement pump rate could have led to the good result in the cementing job shown in the CBL log mostly in the interval where the surface pump pressure has been kept close to the value calculated by the procedure even if the performances of the cementing hydraulic circuit are not exploited at the best. Infact, making a crossing check between field and calculated (using the procedure) data one can see that different and sometimes much higher operational parameters (a constant surface pump pressure of 70 bar) could have been used.

CONCLUSIONS

- A calculation method (MR model), developed to determine the rheological behaviour of drilling fluids, according to the Herschel & Bulkley model, has been applied to the drilling muds flow in the cementing hydraulic circuit. This procedure is based on data collected from Q/P circulation test directly performed on the rig before the cementing job starts.
- Rheological behaviour of the drilling mud has been calculated and the distribution of the frictional pressure losses have been plotted for 7" casing size and also, in a more general way, for the most commonly used weights.
- These results reflects in an easier understanding of the real (field) drilling mud behaviour under flow in the cementing hydraulic circuit and in a more accurate evaluation of the frictional pressure losses in the annular section making easy the choice, directly done on the rig, of the maximum pump rate of the mud to be used for the displacement of the cement slurries without fracturing the crossed formations.
- Following these studies a practical and easy to use procedure in order to determine the maximum available displacement pump rate and the maximum surface pump pressure, exploiting the maximum available fracture margin pressure of the cementing hydraulic circuit, has been developed and explained.
- From the evaluation of the CBL logs of the cementing job performed in the considered field case arises the fact that the higher is the displacement pump rate of the cement slurry and the better is the efficiency of the displacement. But, on the other hand we have seen that it is also very important to exploit at the better the performances of the hydraulic cementing circuit. So, in this way, *it is of basic importance*, in order to assure excellent results in the cementing job, determine and use during cementing the maximum available displacement pump rate without fracturing the crossed formations.

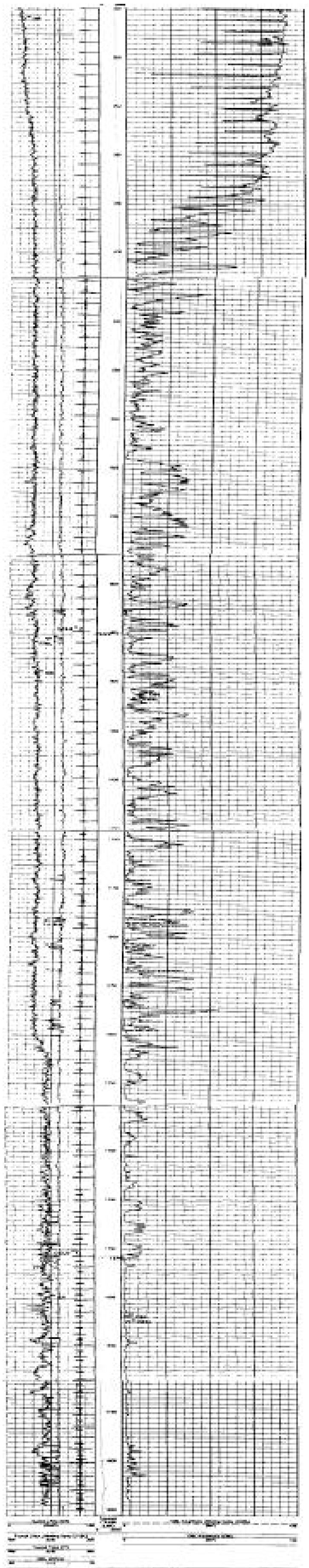

Figure 6

- The integrity of the crossed formations is an other basic factor to keep into account, so based on this statements a maximum surface pump pressure is determined. *If, during displacement, going with the maximum available pump rate this pressure is overcome, it is mandatory to reduce the pump pressure in order to restore the original value of the surface pump pressure.*

- A second important point arose in this study, determined looking thoroughly at the CBL of the cementing job, is about the role of the flow velocity profile in term that *the higher is the displacement pump rate used and the higher are the velocity values of the fluids in the annulus even close to the wall of the borehole, permitting a better displacement of the mud by means of the cement slurry even in part of the annular section that very difficulty can be reached by the displacement*. Infact it has been seen that when the maximum available displacement pump rate has been used a better efficiency of the displacement can be obtained.

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NOMENCLATURE

n	=	flow behaviour index
k	=	consistency index
τ_o	=	yield stress
MD	=	measured depth
Q,	=	pump rate
Q_{max}	=	maximum available displacement pump rate
ΔP	=	frictional pressure losses
ΔP_{an}	=	annular pressure drop
SPP	=	surface pipe pressure
SPP_{max}	=	maximum available pump pressure at the surface
ξ	=	ratio between annular and total frictional pressure losses

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