Casing Integrity Evaluation in Deep Well with Extreme Heavy Mud in Tarim Basin
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Abstract

The high dip angle in formations is one of the reasons makes it difficult to drill in Tarim Basin, resulting in much longer drilling time. To counteract the high pressure from the salt layer above the targeted gas zone, 16-mm heavy casing and drilling mud as heavy as 1.9 g/cc must be used. As drill bit and pipes continue repeatedly tripping in and out the well the heavy casing may get wore thinner. Therefore it’s important to know the degree of the casing wear, and to recalculate the remaining strength. Furthermore, if channel in cement behind the casing exists across the high pressure layer, it will pose another threat to corrode the casing from outside and reduce the overall strength of the casing. Hence the cement quality behind the heavy casing must be measured and assessed by reliable means. The tradition technology for well integrity evaluation has limitations in providing answers to the casing corrosion and zonal isolation in such challenge downhole condition.

A new generation of the ultrasonic imaging tool was introduced to increase the certainty of casing mechanical property measurement and cement evaluation. The technique combines the pulse-echo ultrasonic measurement with a new flexural wave measurement. The analysis from this combination allows not only a better discrimination between solid, liquid and gas for cement evaluation behind casing, but also more accurate casing information including internal diameter and casing thickness at high resolution in one trip in a well. A logging example was illustrated in this paper with high quality logging data acquired in difficult down hole conditions. As can be seen in this example, many casing grooves were found, and metal loss were up to maximum 4mm at some spots. This paper also shows a new way to look at cement quality behind the heavy casing.

Introduction

Tarim Basin in west China is a primary natural gas source for the well-known West-To-East gas pipeline that provides gas from Xinjiang to Shanghai. One of gas fields located in front of the Tianshan Mountain has been facing a very challenging drilling environment. The high dip angle in formations is one of the reasons makes it difficult to drill, resulting in much longer drilling time for the deep (up to 7200m) wells. Another challenge is that there is a high pressure salt layer above the targeted gas zone. To counteract the high pressure from the salt layer, the 16-mm heavy and high strength casing and drilling mud as heavy as 1.9 to 2.25 g/cm³ have to be used. As drill bit and pipes continue repeatedly tripping in and out the well, the heavy casing may get wore thinner. Therefore it’s important to know the degree of the casing wear, and to calculate the remaining strength, hence to ensure the well safety during its life. Furthermore, if channel in cement behind the casing exists across the high pressure layer, it will pose another threat to corrode the casing from outside and reduce the overall strength of the casing. Therefore, the cement quality behind the heavy casing must be measured and assessed by reliable means.

Apart from that the old generations of CBL-VDL tools do not have the capacity to evaluate the casing integrity; also they are greatly affected by the heavy mud and thick casing which in combination significantly attenuate the acoustic signals used for the cement quality measurement. For the same reason, some later generations of the ultrasonic tools, though may be able to provide casing measurement, work poorly in providing reliable answers for the cement quality behind the thick casing. To overcome the
difficulties induced from the heavy mud and thick casing on the traditional technologies, a new generation ultrasonic tool was successfully introduced.

**Measuring and interpreting principle**

The new-generation ultrasonic imaging tool utilizes classic pulse-echo technology and latest flexural wave imaging technology to accurately evaluate any type of cement\(^1\). The tool’s combination of the two independent measurements differentiates low-density solids from liquids, to distinguish lightweight, foam, and contaminated cements from liquids. Its azimuthal coverage provides an answer around the entire circumference of the casing with 3-in depth of investigation, pinpointing any channels in the cement and confirming the effectiveness of a cement job for zonal isolation. Through measurements the third interface echoes from cement-borehole or cement-second casing, casing centralization information can be obtained, these can assist for cement quality evaluation and possible afterward operations. The new imaging tool can identify casing (internal or external) corrosion or drilling-induced wear through measurements of the internal diameter and thickness of the casing by the pulse-echo transducer.

The new tool includes a rotating subassembly supporting four transducers (figure 1). A normally aligned transducer for generating and detecting the pulse echo is positioned on one side of the tool. The other three transducers are on the opposite side of the tool and are aligned obliquely for flexural wave attenuation measurement. When performing the logging operation, the transducers rotate at 7.5 revolutions per second to render an azimuthal resolution of 5 or 10 degrees. The ultrasonic transducer sends a slightly divergent beam toward the casing to excite the casing into its thickness resonance mode. This yields 36 or 72 separate waveforms at each depth. These are processed to yield the casing thickness, internal radius and inner wall smoothness from the initial echo, thus to evaluate casing corrosion or wear by drilling pipes (figure2). The azimuthal image of cement acoustic impedance can be derived from the resonance decay.

One of the flexural transducers transmits a high-frequency pulsed beam of about 250 kHz to excite a flexural mode in the casing. As it propagates, this mode radiates acoustic energy into the annulus; this energy reflects at interfaces that present an acoustic contrast, such as the cement/formation interface, and propagates back through the casing predominantly as a flexural wave to reradiate energy into the casing fluid. The two receiving transducers are placed to allow optimal acquisition of these signals. Processing of the resulting signals provides information about the nature and acoustic velocity of the material filling the annulus, the position of the casing in the hole and the geometrical shape of the hole as well.

Apart from the density, a solid material is acoustically defined by 2 velocities, the compressional and shear velocities. Typical cement properties\(^2\), together with mud, are listed in table 1. Light weight cement has similar acoustic impedance as drilling mud or contaminated cement; it’s difficult to distinguish between them with their acoustic impedance alone. The additional flexural attenuation measurement provides a density-independent means to identify solid in extreme low density (low acoustic impedance) environment such as light weight cement, foam cement or contaminated cement.
Table 1: Annulus material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Acoustic impedance (Mrayl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>1.3 - 130</td>
<td>0.0004 - 0.04</td>
</tr>
<tr>
<td>Water</td>
<td>1000</td>
<td>1.5</td>
</tr>
<tr>
<td>Drilling mud</td>
<td>1000 - 2000</td>
<td>1.5 - 3.0</td>
</tr>
<tr>
<td>Slurry</td>
<td>1000 - 2000</td>
<td>1.8 - 3.0</td>
</tr>
<tr>
<td>Light weight cement</td>
<td>1000 - 1400</td>
<td>2 – 5</td>
</tr>
<tr>
<td>Class G cement</td>
<td>1900</td>
<td>5.0 – 7.0</td>
</tr>
</tbody>
</table>

When the annulus is filled with a liquid (figure3), the only possible leakage is compressional, and the attenuation has a value of A. Once the annulus is filled with solid material (light, with slow compressional velocity), the flexural mode starts to leak in both compressional and shear, increasing the leakage and consequently increasing the attenuation to a value of A + B. Because of Snell’s law, no leakage occurs faster than 2,700 m/s (the flexural velocity in casing). High density cements have a higher compressional velocity, which causes the compressional leakage to disappear, decreasing the attenuation to the lower value of B, corresponding to only the shear mode of propagation. The disappearance of the compressional leakage occurs sharply and is known as “evanescence” or the “critical value”. While acoustic impedance increased linearly with density, flexural attenuation reaches a maximum in light-density solid material, which is the fundamental principle behind the new technique. On the other hand, liquid, gas, and fast cements have low attenuation and cannot be differentiated solely by flexural attenuation; acoustic impedance is needed as well.

![Figure 3: Radiation of the Flexural Wave](image)

The final output is a solid-liquid-gas (SLG) map (Figure 4) displaying the most likely material state behind the casing. The state is obtained for each azimuth by locating the two measurements, corrected for the effects due to the inside fluid, on a crossplot of attenuation and acoustic impedance, giving the area encompassed by each state. The white-colored areas in the SLG map for a composite log correspond to locations with non-solvable inconsistencies between measurements, such as might appear at the casing collars. The SLG map can be generated in real time when performing the logging operation, it becomes much quick and very easy to evaluate the cement quality on wellsite, and it simplifies the interpretation with high reliable results.

Comparing to CBL-VDL, cement evaluation through SLG does not affect by wet micro-annulus, contaminated cement, fast formation and dual casings. It is applicable to run in thicker casing up to 20mm and heavy mud (based on toolplanner), without any density requirement for cement to be evaluated.

**Mud density and casing thickness effect on cement evaluation**

The pulse-echo ultrasonic measurement has two main limitations. The first one is mud attenuation, which decreases the overall signal level. The second one is large casing thicknesses, for which the fundamental resonance frequency falls outside of the frequency band of the transducer. Instead of a fixed attenuation value, a limit is applied on the attenuation at the casing resonance frequency of 30 dB. The ultrasonic pulse-echo transducer specification on thickness has increased to 20-mm from 15-mm with new design of the transducer. Beyond this value, the fundamental resonance frequency falls below the transducer band, and the frequency based processing cannot handle such cases.
For the flexural attenuation measurement, a limit of 30 dB for the mud loss is applied too, leaving head room for extra losses due to flexural attenuation in the casing or for amplitude drop due to tool eccentering. There is no real limitation on casing thickness, apart from a gradual decrease in sensitivity with casing thickness.

The flexural group velocity exhibits a peculiar feature: all the frequency components of a broadband wave packet within this frequency range (100 to 300 kHz) will propagate at the same velocity, and the wave packet will remain compact. This is the flexural wave attenuation measurement fundamental. The effect of casing thickness is to change both the frequency axis and the attenuation axis, both being inversely proportional to thickness: for an 8 mm thick plate, this curve goes through a broad minimum of 0.31 dB/cm over the frequency range of flat group velocity (100-300 kHz). The fact that the attenuation is approximately constant with frequency means that it is possible to measure this attenuation by measuring the decay rate of the envelop of a broadband pulse. For a 16 mm casing, the frequency of minimum attenuation is 100 kHz, and the minimum attenuation is 0.15 dB/cm, half the value of the 8 mm thickness (Figure 5). A value of 0.15 dB/cm means that the amplitude of the flexural pulse is decreased by 1.5 dB over a distance of 10 cm. Such an amplitude change can easily and accurately be measured.

![Figure 5: Flexural and Extensional Modes Attenuations versus Frequency for 8-mm and 16-mm Thick Plates with Water on One Side](image)

Log example

Well information:
Open hole size: 9.5 in
Casing outer diameter and grade: 8.125in, TP140
Casing inner diameter: 6.865in
Casing thickness: 0.63in (16mm)
Mud type and density: WBM, 1.9g/cm³
Cement density: 2.53g/cm³
Total depth: 7065m
Downhole temperature: 155 DegC
Bottomhole pressure: 17200psi @6350m
Logging interval: 5360m to 6350m

In order to contain the high pressure when drilling through the salt layer and as well to protect the casing from excessive wear caused by drill pipes, both heavy mud and thick casing have to be selected. In this example, a complex casing program was picked to ensure the casing integrity, i.e. 10.6in casing from surface to 5528m, 8.125in casing from 5360m to 6900m, 5in casing from 6350m-7065m. And the mud weight of 2.25g/cm³ was used when drilling through the salt layer in the 9.5in hole, it was then reduced to 1.9g/cm³ in drilling the 6in hole after the salt layer was drilled through and cased with the 8.125in casing. The pre-job planning was carefully carried out on the job to ensure the tool works in the window without exceeding its limitation. The figure (Figure 6) below on the left is a snapshot of the simulation software that serves for that purpose. Figure 7 below on the right shows the tool string configuration for the operation. With the careful pre-job planning, the job was performed smoothly and successfully, high quality logging data were acquired.
Casing wear detection

From pulse-echo ultrasonic transducer, casing information such as inner radii and casing thickness can be obtained simultaneously. The accurate measurements enable the drillers to understand the casing deformation and/or wear caused by drilling activity, or casing corrosion if any.

In this log example, it is evident that casing has got severe wore caused by drill pipes and bit. More than 15 grooves were found across the 900m logging interval, among which the maximum metal loss at one spot even reached 4.6mm. An s-shape groove wore by drilling is shown on the composite log (figure 8, next page). On the log, a groove is represented with two dark and parallel lines in the echo amplitude channel (track 3); and/or one red line on casing inner diameter channel (track 6) that indicates that the inner diameter has become bigger than the normalized casing ID, the color darkness represents the degree of the wear; and/or a red line appears on the casing thickness channel (track 8) meaning that thickness reduction has occurred compared with the normalized casing thickness. The casing thickness curves in track 7 also reads the the minimal casing thickness or remaining casing thickness. Since drill pipes by gravity trend to lay on the low side the casing in the deviated or horizontal wells, as such the casing wear often are found on the low side of the casing in those wells. A 3D imaging also can be produced which helps visualize the casing condition through different angles (figure 9). At this interval, the SLG map (1st track from right, figure 8) is also displayed and shows good cement quality.
Cement quality evaluation

The new generation ultrasonic imaging tool provides high confident cement quality evaluation through the two measurements-acoustic impedance and flexural wave attenuation. And third interface echoes (TIE)\textsuperscript{1,5} give another new way to interpret the cement quality, it provides casing eccentriculation and annulus thickness measurements that this feature is the only one in industry currently. It gives answer why the channels are easily formed.

Even high density cement (2.53-g/cm\textsuperscript{3}) was used aiming to seal the high pressure salt layer, however the cement quality is not as good as expected. With Solid-Liquid-Gas map (figure 10, 4\textsuperscript{th} track from left), it becomes very easy to make the cement quality interpretation. Good cement (brown color) exists below 6238m and above 6134m. A long and narrow channel with fluid (blue color) exists between 6134m to 6180m. From 6180m to 6238m, a wide channel almost covers the whole annulus. In flexural wave attenuation track (3\textsuperscript{rd} track from left), fluid with low attenuation is displayed in blue color, the solid is displayed as yellow or red color that indicates higher flexural attenuation, an indication that the high density cement in this well has been somehow contaminated. The annulus thickness (right 1\textsuperscript{st} and 2\textsuperscript{nd} track) shows that the casing is not well centralized inside the wellbore; this may have resulted in failure to fully clean up the drilling mud in the annulus. The 3D display software assists to analyze the annulus geometry measurements from TIE. The narrow and long channel is located at the azimuth from 240 deg to 330 deg (figure 11), around 25\% of the casing circumference. The wide channel occupies around 80\% to 90\% of the annulus (figure 12), the casing is very much eccentrolized here and little cement is seen in the wide side of the annulus.

Although thick (16-mm) casing and the heavy mud were used in this well, the new-generation ultrasonic tool did not get affected. It did not only worked well to provide the high quality cement evaluation, including to pinpoint clearly where the channels occurred and their azimuth around the wellbore, but also provide a comprehensive way to evaluate the well and the casing integrity.
Conclusions

In this paper, one field example of new generation ultrasonic imaging logging has been presented. The following are the main conclusions of this work in the Tarim basin:

- New ultrasonic imaging logging can meet the requirements for casing wear detection in heavy mud (1.9g/cm³), thicker casing (16-mm) and deep wells in the Tarim oilfield.
- Together with flexural wave attenuation and ultrasonic measurements, high confident cements quality evaluation can be provided even behind the heavy casing.
- Casing eccentricization and annulus thickness from third interface echoes do not affect the measurements in the thick casing and heavy mud. It provides a new way to evaluate cement quality by visually analyzing the channels in annulus.

Figure 10: Solid-Liquid-Gas map shown channels that associated with casing eccentricization.

Figure 11: The narrow channel shown on azimuth 240 to 330 degree. Casing slightly eccentric.

Figure 12: The wide channel shown on 3D display. Casing is badly eccentricing in borehole.
Acknowledgments

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Nomenclature

SLG map = Solid (brown) Liquid (blue) Gas (red) map image
Zmud = Acoustic impedance of mud, Mrayl
Zcem = Acoustic impedance of cement, Mrayl
ECCE = Tool eccentering, in
AWBK = Amplitude of echo minus maximum
THAV = Thickness average of casing, in
THMN = Thickness minimum of casing, in
THMX = Thickness maximum of casing, in
THBK = Thickness minus average, in. Red color represents thickness smaller than average and blue color is on the contrary.
IRAV = Internal radius average of casing, in.
IRMN = Internal radius minimum of casing, in
IRMX = Internal radius maximum of casing, in
IRBK = Internal radii minus average, in. Red color represents casing internal radii bigger than average and blue color is on the contrary.

References