

Liner Hanger Annular Pressure Drop: Theoretical vs. Actual Results and the Implications to Narrow Margin Pressure Regions

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Abstract

Environments where the margin between pore pressure and fracture gradient is depleted are found in openhole intervals in mature fields, as well as deepwater basins and HPHT regimes. Operators have employed many methods to mitigate narrow margins, including Expandable Liners, Managed Pressure Drilling, and Low ECD Drilling Fluids. As a consequence, drilling these hydraulically challenging intervals is possible and quite routine. Operators encounter additional challenges when production quality cement jobs are required for effective zonal isolation. Examining the annular friction pressure components highlights the significance of pressure drop across the liner hanger during the pre-cement job circulation and during the primary cement job. Shell conducted flow tests using conventional liner hangers and a low ECD liner hanger to better understand this pressure drop, and will here compare actual with expected results, present data on observed pressure anomalies, and suggest future work.

Introduction

Modern drilling techniques and high energy prices allow operators to drill wells from existing structures in mature fields well beyond what was once considered possible. Many of these wells are drilled through complex geology, including intervals depleted from prior production. In many cases, the ability to drill narrow margin wells and get casing to bottom has outstripped our ability to successfully cement these wells. Narrow fracture gradient pore pressure margins are further reduced when highly deviated wells require increased mud weight for bore stability.

Openhole annular clearance during the cement job is usually narrower than annular clearance while drilling. At similar circulating rates, equivalent circulating density (ECD) is inherently higher after the casing or liner has been run, and complex well geometry and tight annular clearance can prevent adequate casing centralization. To achieve effective mud displacement, cementing fluids are generally higher density and higher apparent viscosity than the drilling fluid. To maintain ECD below fracture gradient, annular velocity during cement placement is held well below acceptable design limits to prevent losses during cement placement.

Zonal isolation in a narrow margin environment requires cement job design optimization. Operations teams

must consider every aspect of the cement job. When one design goal cannot be met, they must examine other possible improvements. Pressure drop across the liner hanger assembly is significant, but not well understood. Friction pressure from tight annular clearance increases ECD, and radial clearance around a production liner hanger assembly is often less than 5/32-in. (4mm). Accurate prediction of pressure drop across the liner hanger assembly would improve cement job design optimization and increase the probability of zonal isolation success.

Recent attempts to accurately model pressure drop using computational fluid dynamics were unsuccessful. Modern cement job simulation software cannot accurately model pressure drop across the liner hanger assembly's complex geometry and fluid flow paths. We have conducted a series of flow tests using conventional liner hangers and a low-ECD liner hanger to 1) better understand actual liner hanger pressure drop, 2) benchmark potential ECD reduction, 3) define a working definition for low ECD liner systems, and 4) better understand the accuracy of cement job simulation software.

Modeling Summary

A Deepwater Development Well

The motivation for this work is best illustrated by the case of a new deepwater development well in a mature subsea field. In this context the final hole section is considered, where a 7-5/8-in. production liner hanger will be set in a 9-5/8-in production liner with a 8-1/2-in open hole that is opened to 9-7/8-in. In practice this hole section would be drilled with a Synthetic Oil Based Mud (SOBM), but for the purposes of this work, all simulations were conducted with Water Based Mud (WBM). The WBM rheological profile closely matched the rheological profile of the SOBM to improve correlation between simulation results and experimental results. The authors simulated ECD in the annulus of this well using Shell's hydraulics software, Integrated Drilling Model (IDM), for two different liner hangers at flow rates consistent with this openhole diameter and liner size. These results are illustrated in Figures 1 & 2.

Figure 1 shows the ECD of this well exceeding the fracture gradient of the depleted sand at rates necessary for

adequate displacement efficiency. Figure 2 shows the ECD very close to the fracture gradient in the depleted sand. While the modeling software, lacks the ability to account for actual liner hanger geometry, this simulation does illustrate the influence a liner hanger geometry can have on the ECD profile.

Analytically Determined Pressure Drop

As work progressed on this project, the variance in calculated results from flagship industry hydraulics software became so large that our ability to successfully plan cement jobs came into question. A study by a Shell J.V. company on a different but closely aligned tight annular clearance hydraulics application revealed discrepancies between calculated and measured values ranging from 40% to 70%. [1] Figure 3 summarizes the calculated pressure drop of two conventional liner hangers and one low ECD system. For reference, the most appropriate results of Jackson, Watson and Moran [2] are also presented. When comparing the Shell – IDM results with those calculated by [2], different mud rheologies are assumed and the results should not be identical. These models also discount several important features of liner hangers systems, such as turbulence caused by step changes in geometry, multi-path tortuous flow by channels around setting slips, and hanger slips set into the casing.

Impact of OD Change

The envelope or characteristics required to obtain the ‘Low ECD’ designation are not defined by industry. Low ECD design first requires an understanding of the actual pressure drop and the ability to analytically or with actual test values determine the performance of proposed changes in liner hanger outside diameter and lengths. As an illustration, Figure 4 shows the change in calculated differential pressure as the minimum flow area is increased at a constant flow rate. The rate of pressure drop decreases once the flow area reaches 2.0 to 2.5 times the original value. A recommended starting point for Low ECD classification would be a differential pressure around 10% of that achieved with the original conventional liner hanger, and an increase in flow area by a factor of 2 to 2.5. The geometry can further be reduced to a point approaching the diameter of the liner, as shown with the dotted line, but this does not significantly reduce the circulating pressure. The impact on burst, collapse and system complexity offsets any benefit of further decreasing the OD.

Test Results

Flow Loop Configuration

The flow loop configuration used in this test is provided in Figure 5. The parent casing has two pressure ports tapped 85 inches above and below the target interval, allowing differential pressures to be measured by sensors rated to 5,000 psi and accurate within 1% at full scale. Spacing these ports at 10 times the nominal test casing diameter minimizes the impact of end effects. These two pressures, standpipe manifold pressure, and pump rate are recorded

during each test. The circulation path is conventional, down the work string, and then returns up the cased hole / work string annulus. The sampling rate on-board the Cement Unit Digital Acquisition System was 10 Hz. A 10-sample moving average was calculated for data captured on the DAQ and stored, resulting in recorded data of 1 Hz.

Test Configurations

Each liner hanger design was placed into the target test area in two configurations. The first configuration was designed for 100% stand-off, placing the liner hanger in a concentric transverse position. The second configuration was designed for 0% stand-off, placing the liner hanger on the low side of the casing and producing an eccentric configuration. Special centralizers and eccentric stabilizers were used to achieve these configurations.

Flow Test Results

Figure 6 compares test results for two conventional liner hangers in the concentric position and the low ECD hanger in the eccentric position. This configuration represents the conditions while performing the primary cement job. To simplify retrieval/re-running for subsequent tests, the conventional liner hanger slips were not set. While the absolute test values did not align with calculated values across the entire range of flow rates, the overall trend and circulating performance closely matched the analytic results. At 5 bbl/min, the pressure drop across the low ECD liner hanger is 32 psi, approximately 1/3 to 1/5 of the pressure drop across the conventional liner hangers.

Setting the liner hanger slips after the cement job is performed is one strategy for reducing the ECD across a conventional liner hanger. This places the liner hanger on the low side of the hole during the cement job, lowers the annular velocities, and provides a lower ECD for a given casing/liner hanger geometry. Figure 7 shows the flow test results of conventional liner hanger A in the concentric and eccentric positions. At 5 bbl/min, the concentric configuration yields differential pressure of 150 psi, and the eccentric configuration 125 psi.

Figure 8 shows a comparison of calculation results and experimental results for the liner hangers tested, along with published service company data. Note that the measured results shown in Figure 8 are the average of the pressure differentials recorded during for a given rate. The calculated results tend to track the experimental results with a high degree of accuracy for conventional liner hanger B and the low ECD liner hanger. The simulated pressure differential shows the characteristics of flow regime change from laminar to transitional, then turbulent, but this behavior is noticeably absent from the experimental results. Calculated and experimental results for liner hanger A correlate most strongly at lower flow rates, while liner hanger B shows a stronger correlation at higher flow rates. The low ECD system shows strong agreement across the entire range of flow rates.

Unexpected Results

Unexpected pressure anomalies were observed for all liner hangers while in the flow loop. Figure 9 represents all of the pressure differentials across liner hanger A as a function of flow rate. Figure 10 is time based representation of the pressure differential for conventional liner hanger A, but is representative for all liner hanger tests. At similar rates and in very narrow rate intervals, the pressure differential across the liner hangers begins to oscillate. Pressures differentials across the liner hanger systems increased dramatically, and at the same time, a sinusoidal wave form appeared in the recorded data. The dramatic shift in pressure differential magnitude was also observed at times when the wave form was not present, as shown in Figure 10. The data presented in Figure 10 is more closely examined in Figure 11. This portion of data is from conventional liner hanger A, during the concentric flow test at 6 bbl/min. The average pressure differential across the liner at 6 BPM can be obtained from Figure 6, and is approximately 200 psi. Figure 11 suggests a sinusoidal wave form with an amplitude of 87 psi and frequency of 1/26 radians/sec. The pressure differentials reach maximum/minimum values of approximately 287 psi and 113 psi respectively. It is important to note that all of the liner hanger systems tested exhibited some form of this sine wave during the flow test at similar rates, and these pressure fluctuations were not observed on the stand-pipe manifold, only in the differential pressure sensor data from the test specimens.

Figures

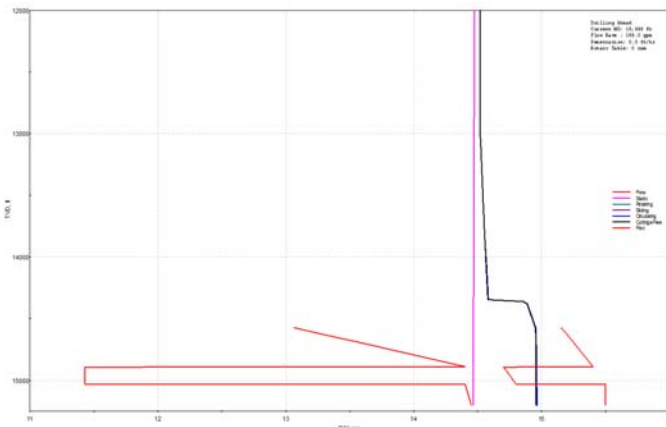


Figure 1 - Circulating bottoms-up with a conventional liner hanger in a deepwater development well.

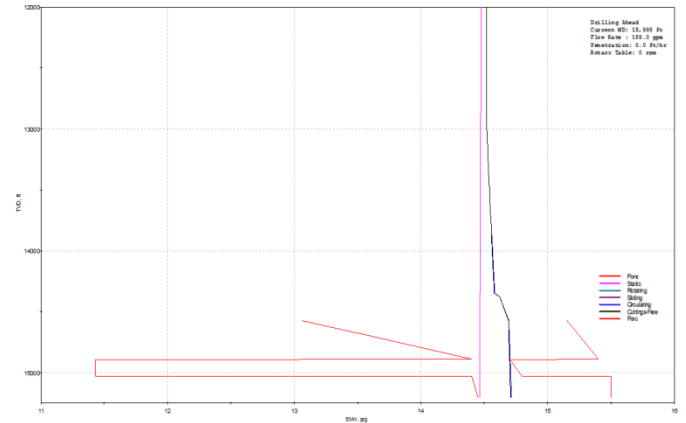


Figure 2 – Circulating bottoms-up with a low ECD liner hanger in a deepwater development well.

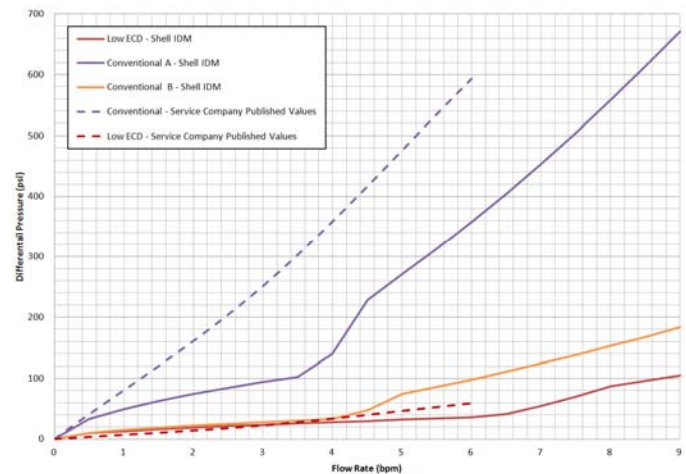


Figure 3 – Summary of calculated differential pressure

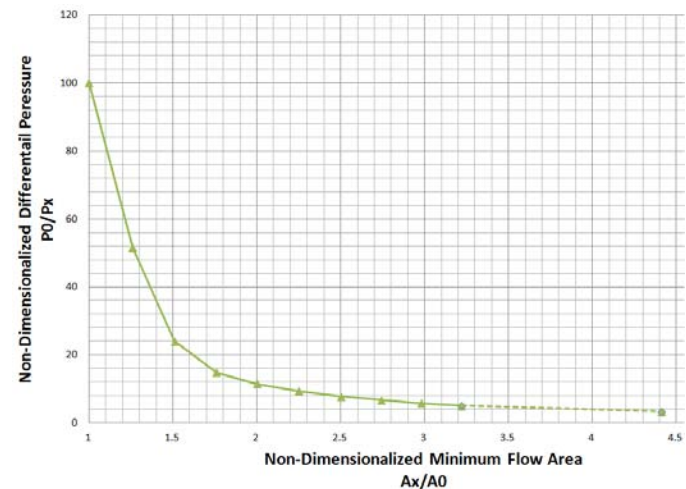


Figure 4 – Non-Dimensional differential as a function of non-dimensional area increase

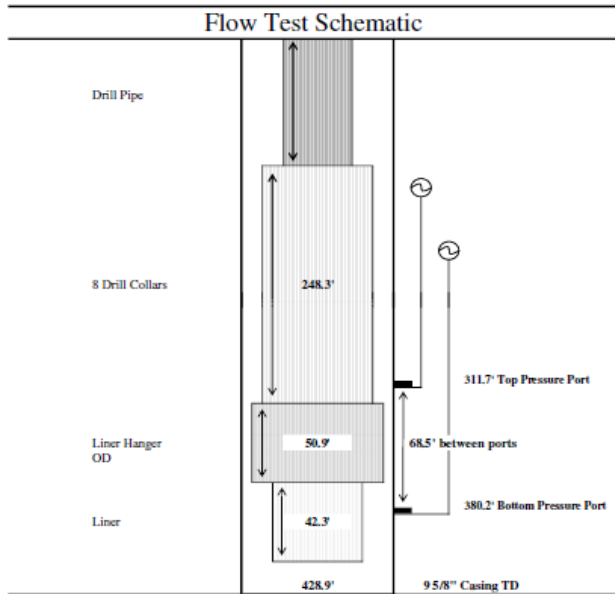


Figure 5 – Flow Loop Configuration

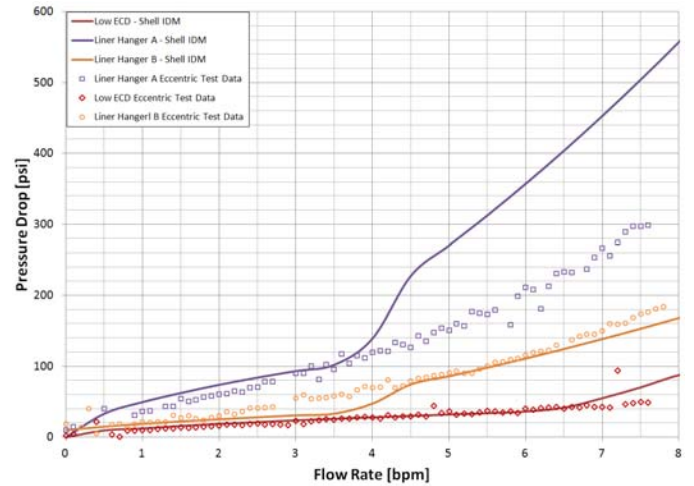


Figure 8 – Expected and actual pressure differential drop summary

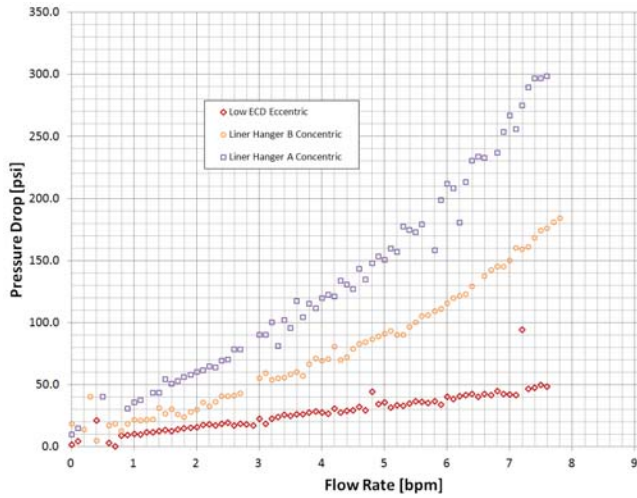


Figure 6 – Actual liner hanger differential pressure

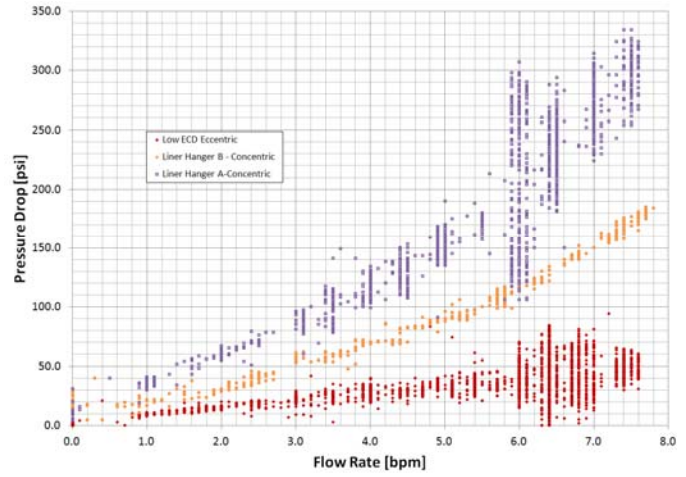


Figure 9 – Rate based representation of flow test data.

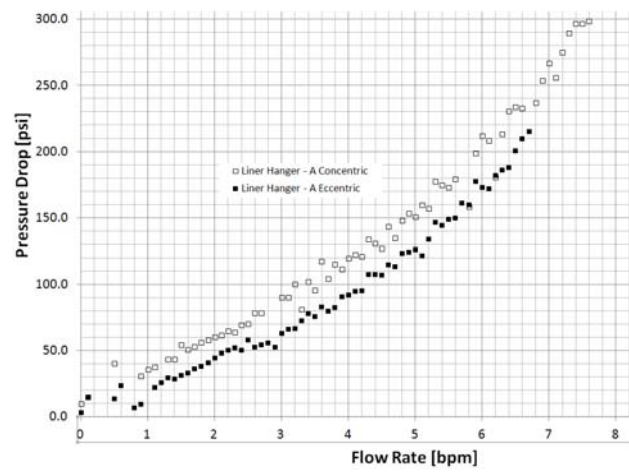


Figure 7 – Differential pressure concentric and eccentric liner configuration

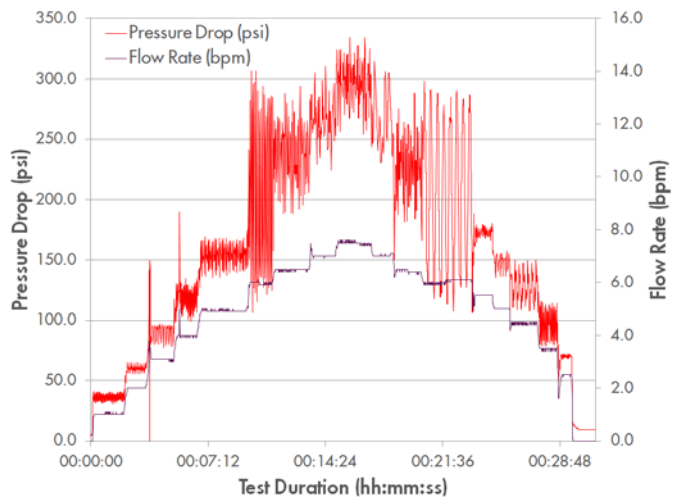


Figure 10 – Time based representation of flow test data.

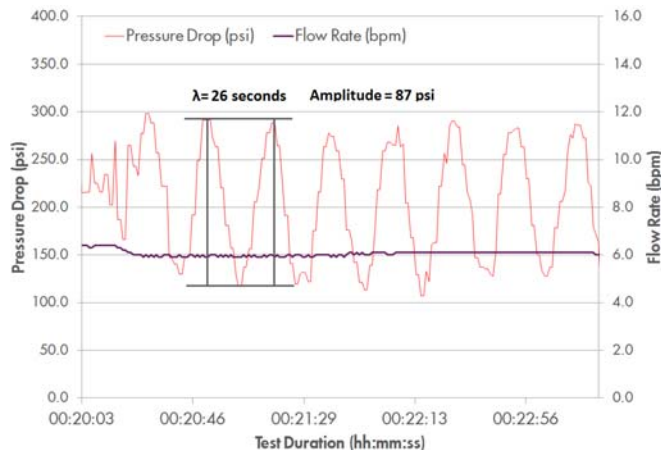


Figure 11 – Detailed view of measured sine wave.

Conclusions

Production liner cement jobs in mature deepwater basins are routinely designed to narrowly avoid critical fracture gradient while remaining just above pore pressure throughout the job. Design safety factors of 0.1 to 0.2 lb/gal are common. Continued production from mature basins will reduce fracture gradient / pore pressure margins. In some fields, water injection into stacked depleted intervals will contribute to the dilemma. Clearly, more work needs to be done to better understand and model fluid mechanics in complicated well geometry with narrow annuli.

Liner and liner hanger eccentricity have a significant effect on ECD, especially in narrow annuli. Eccentricity of tubular goods should be taken into account during cement job design and modeling. Performing a cement job with the liner hanger at 0% standoff (100% eccentricity) has two significant benefits. 1) Pressure drop through an eccentric annulus is significantly less than pressure drop through perfectly centered (100% standoff) geometry, while cross-sectional area remains constant. Pressure reduction of 100 psi equates to mud density reduction of 0.1 lb/gal in a 19,000 ft (TVD) well. Comparison of the flow loop pressure responses for three liner hangers in as cemented configurations demonstrates the additional benefits of developing low ECD liner hangers. 2) Circulation is often restricted during production liner cement jobs when drill cuttings pack off prematurely at the liner hanger assembly. Eccentric geometry provides greater clearance for residual cuttings to flow past the liner hanger assembly during pre-job mud circulation and cement slurry placement.

More work is needed to understand the differential pressure oscillations observed during flow loop testing. Are the pressure cycles an artifact of the test fixture and test procedures, or do these oscillations occur unnoticed during fluid circulation in field settings? What might the frequency and amplitude be in different annulus geometries and different well conditions? The maximum cyclic pressure for all three liner hanger designs could significantly increase ECD for a typical deepwater production liner. If the pressure oscillations are 'real', better modeling could predict oscillation-inducing

flow rates to avoid during pre-job circulation and cement placement. Rheological profiles of circulating fluids can also be modified to minimize or offset fluid oscillations.

Additional flow loop testing of various liner hanger and parent casing geometries would improve ECD prediction using existing cement job simulation software. First, the cement job simulation could be performed without the liner hanger geometry, then the liner hanger geometry could be added as a pseudo geometry of a given OD and length. ECD response with and without liner hanger geometry could be compared and the pseudo geometry adjusted as necessary to obtain a reasonable liner hanger pressure drop as predicted by flow loop testing. Even if the simulation software cannot accurately model pressure drop in narrow annuli, a look-up table of flow loop data could be incorporated into the software.

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