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What are the Well Control Complications While Drilling with Casing or Liner?

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Abstract

Drilling with casing (DwC) and drilling with liner (DwL) technologies have been used recently to minimize drilling time and total costs. These innovative drilling techniques were successful in improving wellbore stability, fracture gradient and minimizing formation damage and exposure time. Differences in wellbore configurations and related volumes when compared to standard drilling practices require a different strategy when a well control situation is encountered.

In this study, we present the critical well control parameters while drilling with complex tubular/wellbore configurations. This investigation utilizes an interactive well control simulator to re-evaluate the kick control procedures in vertical, directional and horizontal wells drilled with casing and/or liner. In contrast to drilling with conventional drill string, the small annular clearance would affect the kick detection and handling procedures. Besides, the high difference between the Equivalent Circulating Density (ECD) and mud density should be thoroughly considered to prevent lost circulation/kick cycles. Therefore, the impact of kick size, circulation rate, wellbore configuration and well design on kick behavior was studied.

Preliminary results show that in DwC/DwL pressure loss profile is inverted and annulus pressure loss (APL) is higher than friction inside casing/liner. Besides, gas influx occupied longer lengths and reaches surface much quicker than similar wells drilled with drill pipe. Consequently, choke and casing shoe experience higher pressures.

Introduction

Recently, as the oil prices dropped, the oil and gas industry implemented unconventional drilling techniques. DwC/DwL are innovative techniques that eliminated the need for a conventional drill string and instead it utilizes casing/liner string with special bottomhole assemblies. Application of DwC/DwL has accelerated in the recent decades due to its benefits. However, the complex pipe geometry raises more questions about the applicability of conventional well control procedures as a result of high APL and ECD.

Mud hydraulics studies the impact of mud flow rate, mud density, and rheological properties on wellbore pressure losses. This is critical for a successful well control operation where it is essential to keep constant bottomhole pressure at all times. However, complications arise in deviated wells and also with complex tubular/wellbore configurations.

In this study, an interactive full scale well control simulator is used to re-evaluate the kick control procedures in wells drilled with casing/liner. The real-time simulation provides comprehensive understanding of parameters impacting well control. Furthermore, hydraulics study and sensitivity analysis were accomplished utilizing a commercial software.

Problem Statement

In relatively narrow annulus between the borehole and casing/liner string, the friction loss excessively increases at normal flow rates. Usually, annular pressure loss (APL) is small compared to pressure loss inside the string but in DwC/DwL it is an inverted profile. Investigating factors that affect mud hydraulics is critical since well control process can be considered as a pressurized hydraulic system.

In conventional well control where slow pump rates are used, APL is considered negligible and a straight line step down from ICP to FCP is approximated. This assumption is questionable in tight annulus as in DwC/DwL that have an inverted pressure loss profile. Additionally, well control complications due to hole deviation should be carefully studied, as friction is a function of measured depth and heavy mud back pressure is a function of vertical depth. Finally, a sensitivity analysis is needed to investigate the impact of kick size, kick intensity and pump circulation rate.

Drilling with casing/liner Background

Researchers reported that DwC showed a 10% reduction in cost and 30% saving in time [(Lopez and Bonilla. 2010) and (Sánchez et al. 2012)]. Other investigators showed that lost circulation was significantly reduced [(Fontenot et al. 2003) and (Karimi et al. 2011)] and claimed fracture gradient has improved (Salehi et al. 2013). Also, examples of successful field application of DwC technology was published [(Aadnoy et al. 2009) and (Radwan and Karimi. 2011)]. Different approaches to simulate the smear and plastering effect associated with the success of DwC/DwL technologies presented by several researchers [(Arlanoglu. 2011), (Mokhtari et al. 2013), (Satkan. 2013) and (Kiran et al. 2014)]. A new research investigated well control procedures in horizontal wells drilled with casing and proposed a neural network model for real time application (Elshehabi. 2015).

Casing/liner dynamic loads (like torque and drag) are high due to string weight and large pipe diameter. Lateral vibration of whirl is the most damaging vibration which cause fatigue failure at coupling. Furthermore, torsional oscillation is relatively common in harder rocks which damages the connections, and as a worst case it initiates stick/slip scenario (Aadnoy et al. 2009). Centralization of casing during cementing is a major operational concern (Galloway. 2004). As the pump starts and flow rate increases the hookload start decreasing due to the hydraulic lift force acting on the bottom of the casing string which reduces weight on bit. Also, pipe movement during connections might cause severe surge and swab if flow rate is not reduced.

Approach

The objective of this study was to investigate well control complications in vertical, directional and horizontal wells drilled with casing/liner. A commonly used wellbore trajectories are selected. A water based mud with a gas kick is considered to eliminate complications due to gas solubility. Different circulation rates, kick sizes and circulation methods were investigated. A full-sized drilling rig simulator (CS Inc. 2011) designed to provide real time hands on training and research was employed for this purpose. Also, a commercial software (Drillbench) was used for hydraulics study and sensitivity analysis.

Wellbore Configuration

The wellbore configurations used in this study are shown in Table 1.

Table 1: Wellbore configuration for vertical, directional and horizontal wells

Property	Value	Units
Drillpipe (OD x ID)	5.0 x 4.276	in.
Drill collars (OD x ID)	6.75 x 2.875	in.
Casing/liner (OD x ID)	7.00 x 6.094	in.
Previous casing (OD x ID)	9.625 x 8.921	in.
Casing shoe depth	4000	ft.
Bit diameter	8.75	in.
Inclination angles	0 ° -50 ° -90 °	
True vertical depth (TVD)	7000	ft.
Total measured depth (TMD)	7000-8,390-15,000	ft.
Mud density	12.0	ppg
Mud plastic viscosity	18.0	cp
Mud yield point	12.0	lbs./100 ft^2
Bit nozzle size	3 x 12	1/32 in.
Pump displacement	0.09967	bbls./stroke

Hydraulics Study

Different rheological models (Bingham Plastic, Power law and Herschel-Bulkley) have been developed to model non-Newtonian fluid flow. Majority of drilling fluids behavior is not well approximated by Bingham Plastic or Power law models as no single model fits over the entire shear rate range. However, many drilling fluids are well represented by the Herschel-Bulkley "Yield power law model (YPL)" (Aadnoy et al. 2009).

Hydraulics in this research inspects the impact of flow rate on pump pressures and the resulting equivalent circulating density (ECD) for different wellbores profiles. ECD is increasing as mud flow rate increases at casing shoe. Plots of ECD versus pump rate are given for vertical, directional and horizontal wells for DwP (green line) DwL (red line) and (DwC) (blue line). (Figure 1, Figure 2 and Figure 3) show dramatic change in ECD at pump rates higher than 500 gpm in vertical, directional and horizontal wells, respectively. Each ECD curve on the 3 figures shows 3 slopes that can attributed to different flow regimes (laminar, transition and turbulent flow). In tight annulus as in drilling with casing/liner ECD increase exponentially at higher flow rates compared to DwP. It is essential to operate the mud pump at slower rates when drilling with casing/liner to prevent loss circulation in depleted zones. In DwC annular velocity can be achieved with only at 50% of conventional flow rate in DwP. In deviated wells the difference between vertical and measured depth increases, and ECD shows higher deviation between DwC/DwL from DwP.

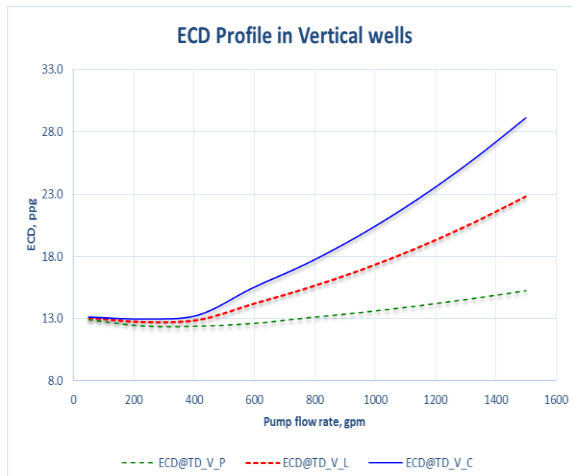

Figure 1: ECD profile at total depth for vertical well drilled with pipe/casing/liner

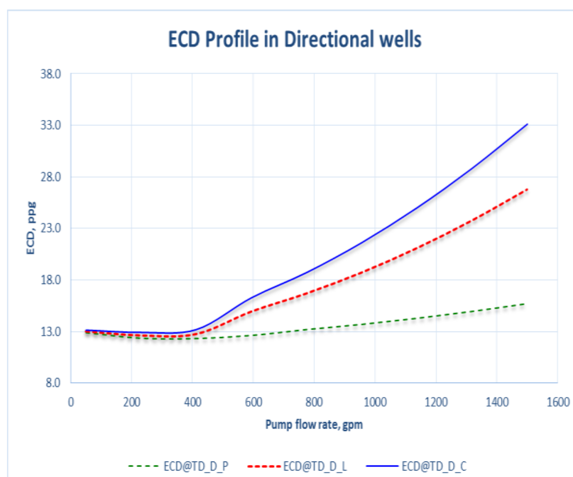

Figure 2: ECD profile at total depth for directional well drilled with pipe/casing/liner

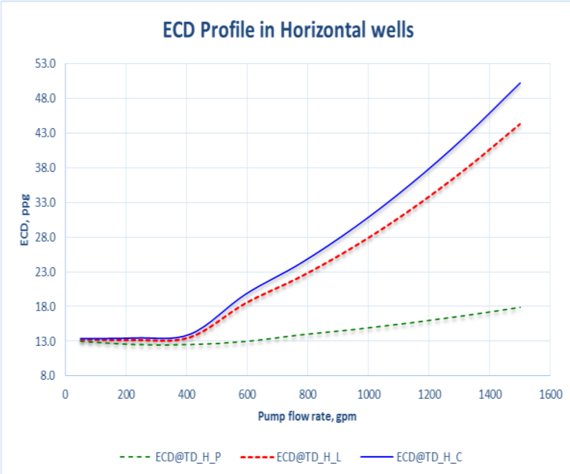

Figure 3: ECD profile at total depth for horizontal well drilled with pipe/casing/liner

Figure 4, Figure 5 and Figure 6 presents values of APL and ECD were studied at slow (kill) pump rates (up to 250 gpm) to investigate their impact on well control operations. The ratio (R) between the pressure losses in annulus (APL) and pressure losses inside drill string without bit losses is calculated. In conventional drilling the R is less than or equal to one, but in DwC/DwL it is increasing up to 12. Higher the well deviation with smaller annulus, higher the ECD and R values. As an example, in vertical well drilled with pipe, ECD is 12.2 ppg and R is 0.3. In a horizontal well drilled with casing at the same slow pump rate, ECD is 13.8 ppg and R is 12. Even the pump rates are slow, DwC/DwL are subjected to an inverse friction loss profile. With high ECD and APL values, it is difficult to detect kicks.

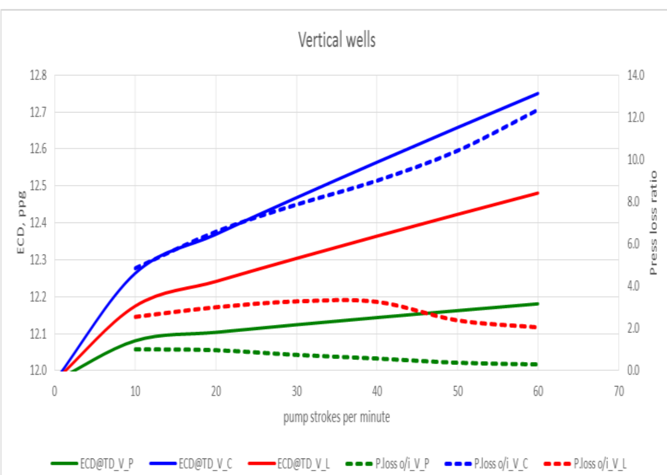

Figure 4: ECD profile and pressure loss ratio (R) at slow pump rates in vertical wells

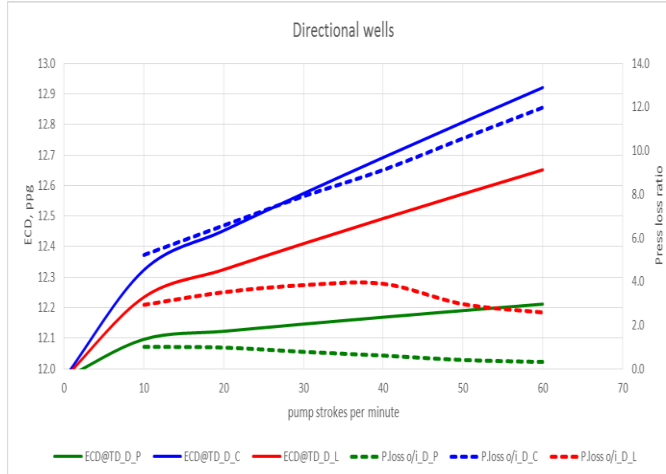

Figure 5: ECD profile and pressure loss ratio (R) at slow pump rates in directional wells

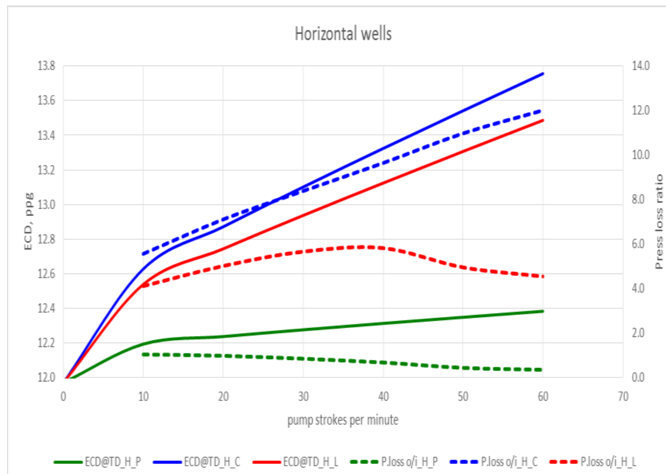

Figure 6: ECD profile and pressure loss ratio (R) at slow pump rates in horizontal wells

Well Control Philosophy

Several conditions can result in a kick and some examples are insufficient mud weight, abnormal pressure zones, improper swabbing, severe loss of circulation and improper fill-up during tripping out (Watson et al. 2003). An increase in mud flow rate in return line can be a direct indication of well receiving a kick and a flow when pumps are stopped is a positive indication. Early kick detection is critical in minimizing the influx volume and subsequently reducing surface and casing shoe pressure during the kill operation.

The mud displacement in a wellbore can be visualized as a U-tube model. Starting with mud pump, the drill pipe and drilling assembly is on one side and the annular sections ending with the variable choke is on the other side of the U-tube. Bit is at mid-point located at the lowermost section of U-tube representing the bottom-hole at total depth (TD). The main objective in well control is to keep the bottom-hole pressure constant during kick circulation in order to prevent entering of new kick fluids into the wellbore.

The two commonly used and industrially accepted methods are Driller's (also known as two circulations) method, and Wait-and-Weight (also known as one circulation or Engineer's) method. Advantages of Driller's method are the simple calculations and no waiting time due to mud preparations. Additionally, it can control swabbed gases without the need to increase mud weight. The drawbacks are longer circulation time, and higher pressures in annulus and at casing shoe with the risk of fracturing the formation. The benefits for using Wait-and-Weight method are lower annulus pressure when heavy mud reaches annulus before kick reaches casing shoe. Disadvantages are waiting time for mud preparation which may result in gas migrations. Further, a step-down chart calculation is difficult in deviated wells (Grace. 2003).

Pressure Step-down Calculations

Basically, pump pressure is adjusted with the variable choke from initial circulating pressure (ICP) to final circulating pressure (FCP) corresponding to strokes-to-bit (STB) value. However, pump pressure can be considered with two components: static-head pressure and dynamic-frictional pressure. The static-head pressure represents the extra hydrostatic "back" pressure exerted by the kill mud weight to balances the formation pressure. This static-head component changes linearly as a function of vertical depth. The dynamic-frictional pressure is linearly increasing with the measured depth as the high density of kill mud creates higher friction. In vertical wells at slow pump rate APL is assumed to be neglected and friction loss (including bit losses) is linearly distributed inside drill string as shown as line 1 in Figure 7.

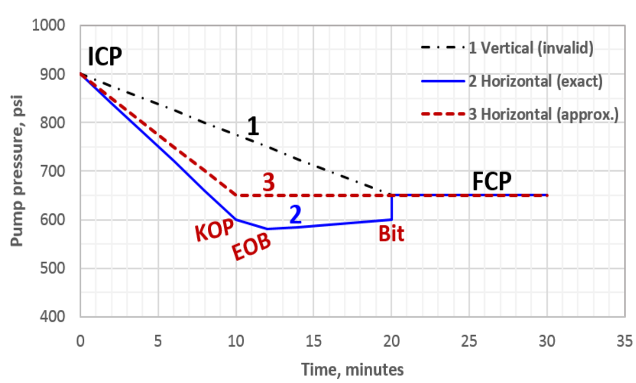

Figure 7: Pump pressure step-down approaches for vertical and horizontal wells

Vertical step-down assumption proven to be invalid in horizontal wells as bottom-hole pressure increases and reaches maximum when the heavy mud is at the KOP (Santos. 1991). This assumption needs to be re-evaluated in DwC/DwL as APL is the greatest component of friction loss (Elshehabi. 2015). In deviated wells step-down pressure schedule depends on the wellbore geometry as shown as (line 2 in Figure 7). Also, Figure 7 (line 3) shows a modified step-down proposed by assuming that the FCP should be reached when the heavy mud reaches the TVD.

The approximated step-down maintained bottom-hole pressure slightly constant while the heavy mud is displacing the initial mud in the entire drill string (Elshehabi and Bilgesu. 2015). The following formula was used to determine the step-down values in psi/100 strokes;

$$psi/100\ stroke = \frac{ICP-FCP}{Strokes\ to\ KOP} x100 \quad \ldots\ldots\ldots\ldots (1)$$

Well Control Results

In this study a gas influx size was kept constant, at a volume of to 20 bbls measured at the surface. The kill rate was selected as 40 spm (167.6 gallon per minute). The average shut-in drill pipe pressure (SIDPP) was recorded as 350 psi. Shut-in casing pressure (SICP) is usually higher and depends on gas column height. In vertical wells, ICP in DwP is 810 psi and FCP is 500 psi. In DwC/DwL ICP is 780 psi and FCP is 460 psi. In all cases total number of strokes from surface-to-surface is around 4600 or 120 minutes.

Figure 8 and Figure 9 show results of tight annulus where gas kick is twice in height with DwC and reaches surface earlier with higher surface choke and casing shoe pressures. The pump pressure is higher in DwP but bottomhole pressure is higher in DwC. In DwL the step-down is not a straight line and can be considered as an inverted tapered string where friction loss is not linearly distributed. Also, as gas moves from tight liner annulus to wider annular pipe section, a sharp decrease in choke pressure is experienced as gas height decreased.

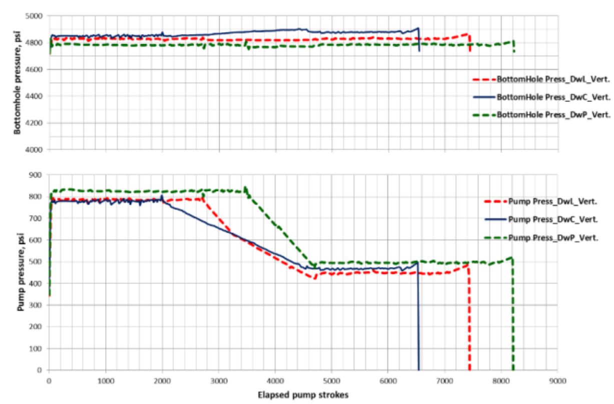

Figure 8: Pump and bottomhole pressures for vertical well controlled with Driller's method at 40 spm

DwP required 1,200 strokes to fill drill pipe with heavy mud and 3,500 strokes to displace the entire annulus. In the case of DwC 2,500 strokes were required to pump heavy mud from surface to the bit and 2,000 strokes to displace the annular volume. This results in complete displacement of gas influx from wellbore before drill string filled with heavy mud. Therefore, casing shoe pressure will not be minimized if Wait-and-Weight method is used. Driller's method should be preferred because with heavy mud displacement (step-down), casing pressure shows constant value if the proper step-down schedule is used.

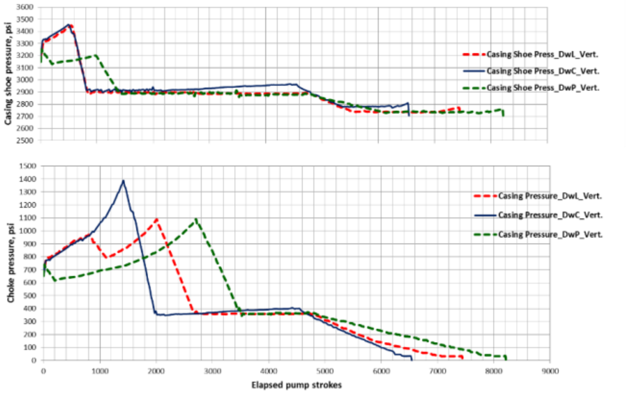

Figure 9: Choke and casing shoe pressures for vertical well controlled with Driller's method at 40 spm

Modified step-down schedule was tested in a directional well DwP as shown in Figure 10 and Figure 11. In all cases the ICP and FCP values of 810 psi and 500 psi, respectively were maintained. However, when same ICP and FCP were used, bottomhole pressure was higher for DwC. In all cases total number of strokes from surface-to-surface is around 5600 or 140 minutes. In DwP, the modified step-down was used and BHP was almost constant and it was verified by constant casing pressure. For DwL, the step-down schedule for a vertical well was applied. Results showed that bottomhole was subjected to over-pressure with increased casing shoe and choke pressures. Choke and casing shoe pressures increased at higher rate after gas kick entered KOP. It is critical that the choke operator should consider two second delay response per 1,000 ft of wellbore length when making adjustments for pressure control.

Figure 10: Pump and bottomhole pressures for directional well controlled with Driller's method at 40 spm

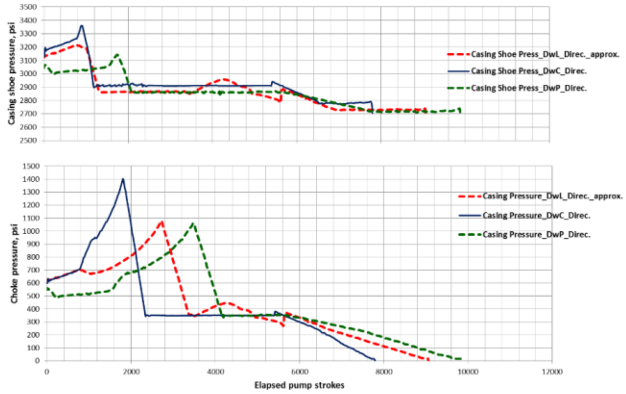

Figure 11: Choke and casing shoe pressures for directional well controlled with Driller's method at 40 spm

A commercial software was used to generate an automatic step-down that keeps BHP constant for horizontal wells as shown Figure 12 and Figure 13. ICP is higher in DwC than DwL and DwP due to small annular clearance. However, FCP is lower with DwC when an automated step-down is used. During gas kick removal the influx height is almost twice and casing and shoe pressures are higher for DwC. As heavy mud fills up the annulus the casing shoe pressure starts decreasing until choke was fully opened to alleviate back pressure. As a result of back pressure created by choke line an increase was observed in pump and shoe pressures. A new modification that uses APL can be considered for step-down in horizontal wells.

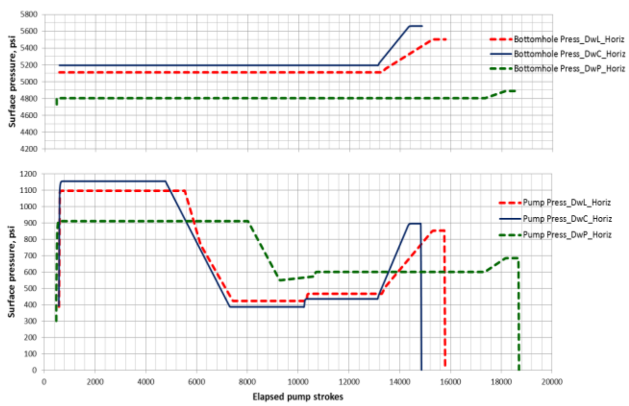

Figure 12: Pump and bottomhole pressures for horizontal well controlled with Driller's method at 40 spm

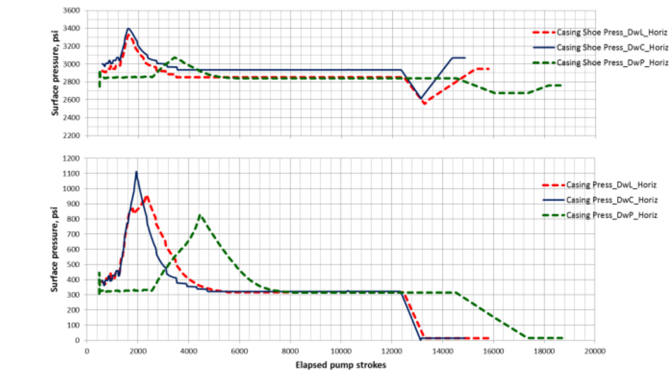

Figure 13: Choke and casing shoe pressures for horizontal well controlled with Driller's method at 40 spm

Sensitivity Analysis

In this part, the impact of circulation rate, kick intensity and kick size on choke and pump pressures were studied in a horizontal well DwC. Figure 14 shows pump and casing surface pressures for four different flow rates. Higher the pump rate, higher the frictional losses in wellbore and at surface. Casing shoe pressure increased at 40 spm up to 7% and BHP to 11% compared to 10 spm.

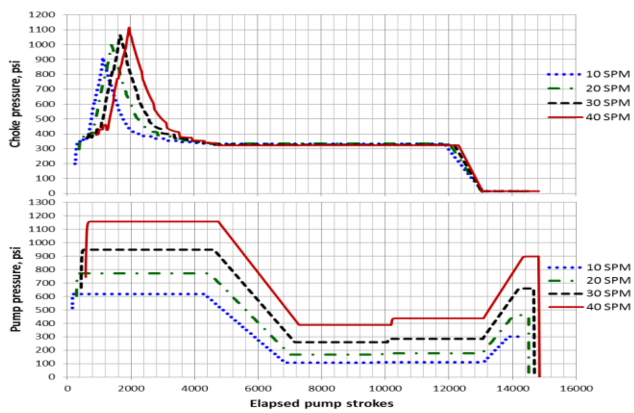

Figure 14: Impact of kick circulation rate on surface pressures

Figure 15 shows the impact of kick intensity on surface pressures. ICP, SIDPP and SICP values were higher with increased kick intensity. There was no change in FCP with kick intensity as influx was removed prior to attaining FCP. Choke pressure was greater after gas kick was circulated due to higher differential between formation and wellbore pressure. Also, BHP was higher and casing shoe pressure observed to increase by 8%.

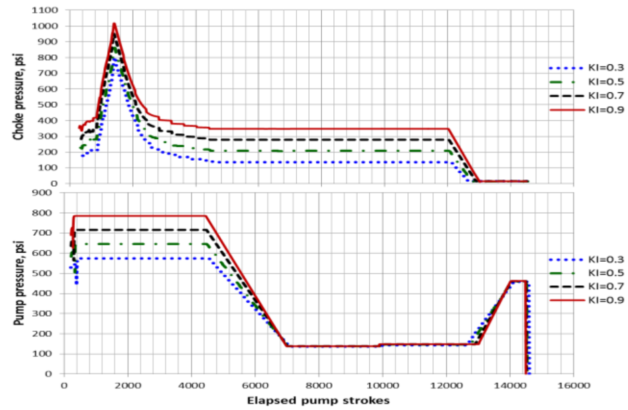

Figure 15: Impact of kick intensity on surface pressures

Four different kick sizes were selected to study the impact of early kick detection and crew awareness. Same reservoir pressure was used for all cases. The size of kick did not impact the pump schedule in keeping BHP constant. Greater kick sizes resulted in higher casing shoe and choke pressures as shown in Figure 16. This highlights the importance of selecting proper kick control procedures and practices.

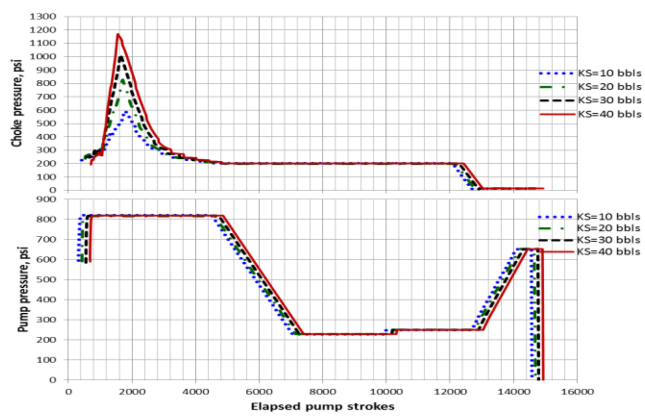

Figure 16: Impact of kick size on surface pressures

Conclusions

- In DwC/DwL lower flow rates should be used to achieve same annular velocity as in DwP and prevent high ECD.
- DwC/DwL are subjected to an inverted pressure loss profile compared to DwP, since APL is higher than pressure loss inside the string.
- Influx height can be several fold longer in In DwC/DwL with tight annulus. Further kick reaches surface earlier and creates higher choke and casing shoe pressures.
- A modified pressure step-down should be considered while displacing kill mud inside the string in deviated wells.
- Due to high APL in DwC/DwL, bottomhole pressure should be kept constant with pump adjustments.
- Use of Wait-and-Weight method for DwC/DwL is not an advantage to minimize casing shoe pressure since gas is circulated out before kill mud reaches the bit.
- High circulation rates and kick intensities in deviated wells drilled with casing/liner will result in higher wellbore and surface pressures.

Nomenclature

BHP	*Bottom-hole pressure*	*psi*
DwC	*Drilling with casing, casing drilling (CD) and casing while drilling (CwD)*	
DwL	*Drilling with liner, liner drilling (LD) and liner while drilling (LwD)*	
DwP	*Drilling with conventional drill string (drill pipe and drill collars)*	
ECD	*Equivalent circulating density*	*ppg*
FCP	*Final circulating pressure*	*psi*
ICP	*Initial circulating pressure*	*psi*
KMW	*Kill mud weight*	*ppg*
KOP	*Kick-off point depth*	*ft.*
SICP	*Shut-in casing pressure*	*psi*
SIDPP	*Shut-in drillpipe pressure*	*psi*
SPM	*Strokes per minute*	
STB	*Surface to bit strokes*	*strokes*
TMD	*Total measured depth, total depth (TD)*	*ft.*
TVD	*Total (true) vertical depth*	*ft.*

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