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An analytical study on early kick detection and well control considerations for casing while drilling technology

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Graphical abstract

Casing while drilling technique and drilling problem solutions.

Public summary

- The goal of the casing while drilling (CwD) technology is to drive the casing deeper as possible to close the problematic zone.
- Drilling with casing provides a significantly different fluid flow path geometry than the conventional drilling method.
- When using the CwD technology, kick tolerances should be carefully analyzed during the well-planning phase.

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Abstract: Casing while drilling (CwD) technology is designed to reduce drilling time and expenses by improving the wellbore stability, fracture gradient, and formation damage while reducing the exposure time. However, for the purpose well control, the wellbore geometry and volumes differ from those obtained via a conventional drilling technique, thereby requiring a different approach. This study discusses well control principles for CwD operations. It presents a simplified method for evaluating the maximum kick tolerance and allowable well shut-in time for both conventional and CwD techniques using a mathematical model. Preliminary results revealed that the use of CwD leads to an annulus pressure loss three times higher than that observed in the conventional drilling. In addition, the kick tolerance is reduced by 50% and the maximum allowable well shut-in time is reduced by 65%, making an early kick detection system necessary.

Keywords: casing while drilling; conventional drilling; kick tolerance; early kick detection; well control

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Nomenclature

APL(psi)	Annular pressure loss	FP (psi)	Formation pressure
BBL	Barrel	FPG (psi/ft)	Formation pressure gradient
BHA	Bottom hole assembly	FG	Fracture gradient
BOP	Blowout preventer	G (psi/ft)	Gas kick pressure gradient
CwD	Casing while drilling	$\mathrm{H_{kick}}$(ft)	Kick height
DLA	Drill lock assembly	HP (psi)	Hydrostatic pressure
EKD	Early kick detection	HSE	Health, safety, and environmental
KDV(bbl)	Kick detection volume	K (md)	Permeability
KPI	Key performance indicators	L (ft)	length of the drilled section in overbalanced formation
KT (bbl)	Kick tolerance	LWD	Logging while drilling
KRT (min)	Kick response time	MAASP (psi)	Maximum allowable annular surface pressure
NPT	Non-productive time	$P1$ (psi)	Fracture pressure at the shoe
PDC	Polycrystalline diamond compact	$P2$ (psi)	Formation pressure at the kick zone
TD (ft)	Total depth	Q_{influx}(bbl/min)	Influx flow rate
WBM	Water-based mud	Re (ft)	The radius of drainage
AV (ft/min)	Annular velocity	Rw (ft)	The radius of wellbore
BHP (psi)	Bottomhole pressure	$T1$ (F$^{\circ}$)	The temperature at shoe
BTC	Buttress thread connection	$T2$ (F$^{\circ}$)	The temperature at kick zone
Ca (bbl/ft)	Annular capacity	$\mathrm{TVD_{kick}}$(ft)	Kick true vertical depth
D (ft)	True vertical depth of weakest point in open hole section	$\mathrm{TVD_{shoe}}$(ft)	True vertical depth of casing shoe
D_{h}(inch)	Hole diameter	Z	Gas compressibility factor
D_{p}(inch)	Drillpipe diameter	ρ_{mud} (ppg)	Mud weight
V	Poisson ratio	$\rho_{\mathrm{overburden}}$ (psi/ft)	Overburden stress gradient
D_{casing} (inch)	Casing outside diameter	Δ_{P} (psi)	Differential pressure
		μ (cp)	Gas viscosity

1 Introduction

As deeper, more complex, and more expensive reservoirs are being developed, an increasing demand emerges for technical solutions that can achieve effective drilling and completion while minimizing risks and costs. Casing while drilling (CwD) technology relieves drilling problems by providing beyond conventional capabilities, enabling the casing to effectively reach the total depth (TD) and succesfully optimize the well structure (Fig. 1)[1]. In addition, CwD may be the most suitable solution for drilling through soft formations, for which various borehole problems are encountered in the top section of the well[2].

In CwD operations, the casing is used as a drill string, and the required energy (hydraulic and mechanical) is provided by the top drive system from the surface to the casing string and its drill bit. As shown in Fig. 2, the pilot bit, reamer, stabilizer, and drill lock assembly (DLA) are usually contained in the CwD's bottom hole assembly (BHA). The DLA is the hydraulic sealing connection between the drilling assembly and the casing string (Fig. 3). For surface and intermediate wellbore sections, an underreamer above the pilot bit is used to open the borehole to the final required borehole diameter[3].

On the mud circulation side, the drilling fluid is pumped into the drill string and circulates upward through the annulus, as in conventional drilling. This improvement in pipe handling enhances wellsite safety, while allowing drillers to use conventional rig size or smaller rigs, which are specifically designed for casing drilling[4].

The main objective and scope of this study are limited to the maximum allowable well shut-in time as a measure of kick tolerance and inflow rate. Well control in a simulated

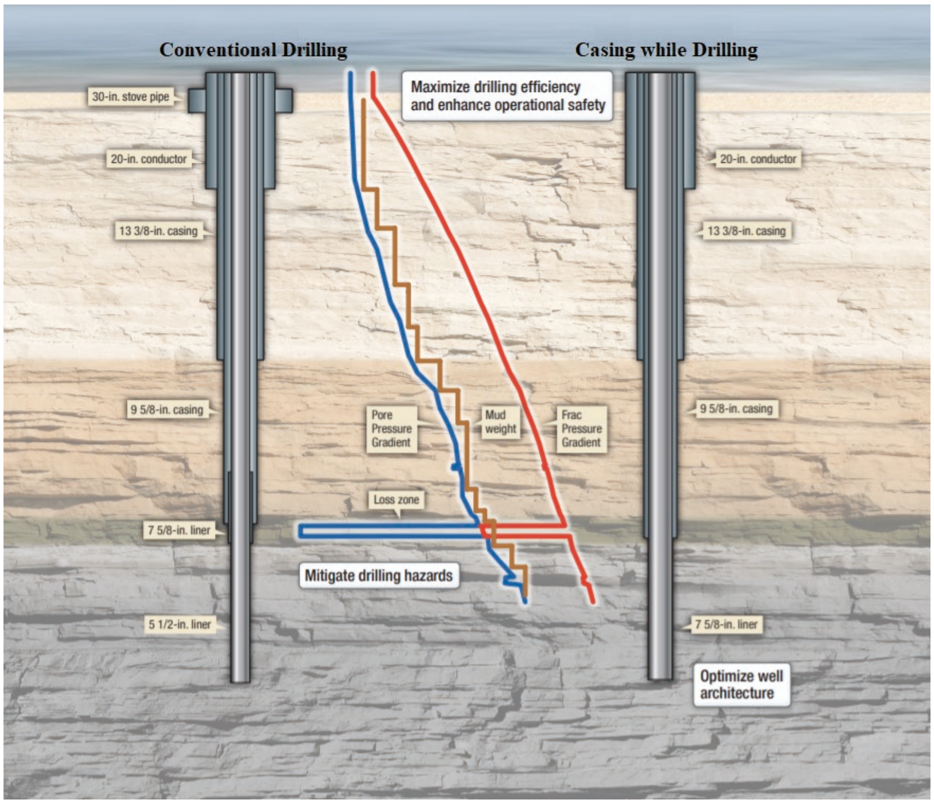


Fig. 1. Conventional drilling vs. casing while drilling technology.

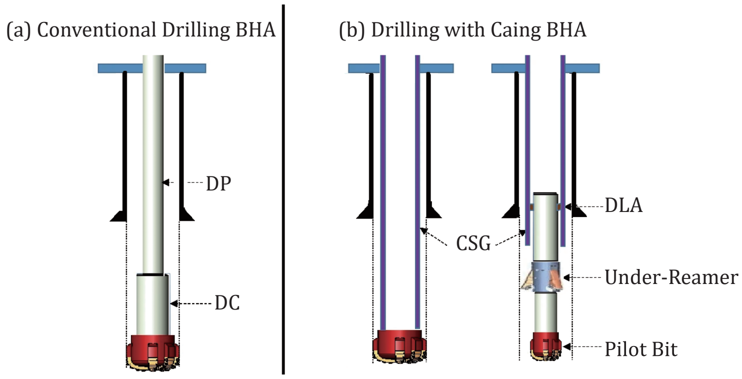


Fig. 2. Conventional drilling BHA vs. casing while drilling BHA.

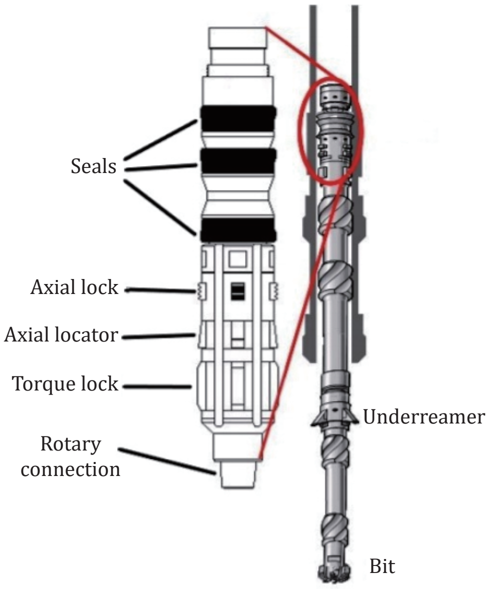


Fig. 3. Drill lock assembly.

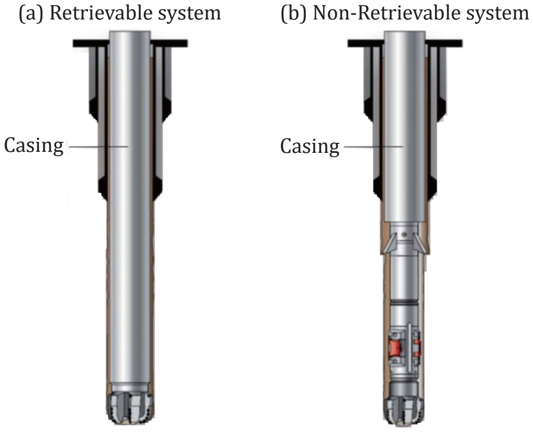


Fig. 4. Retrievable and non-retrievable CwD BHA (modified from Ref. [3]).

vertical well drilled conventionally and using casing while drilling technology is considered. Using a single-phase kick tolerance model, a water-based mud (WBM) with a gas kick is considered to eliminate the difficulties caused by gas solubility.

2 Background

Since the first field test in 1990[5], CwD technology has been developed to solve various drilling problems and obstacles to drill from one casing shoe to the next in a curved directional hole[6]. Drilling engineers developed a new strategy based on rotary drilling, using a casing to drill a well and then retrieve the hydraulic expansion bit[7]. In 1926, another patent was filed, which added a recoverable and repeatable casing bit[8].

In 2001, British Petroleum (BP) and Tesco used CwD technology to record the drilling surface and production casing interval of 15 gas wells in the Wamsutter area of Wyoming, USA. The depths of these wells ranged from 8200 feet to 9500 feet[9]. Shell Exploration and Production not only improved drilling efficiency considerably in southern Texas, but also reduced the cost by about 30% through casing underbalanced drilling[3].

By 2005, different operators had used a casing to drill more than 2000 wellbore sections. More than 1020 sections were drilled vertically using casing and non-retrievable systems, about 620 sections were drilled using partial liners, more than 400 sections used vertical drilling systems with retrievable systems, and approximately 12 intervals were drilled using directional retrievable systems[10]. All of these early uses of auxiliary CwD evolved from new technology with questionable reliability to a viable solution that can save costs, increase drilling productivity, and reduce rig downtime[3].

2.1 Types of CwD systems

The casing usually rotates and cements the well to the required total depth (TD). There are many types of CwD models that have been developed. These models can be classified into two types as illustrated in Fig. 4 [8].

2.1.1 Retrievable system

If the required target depth is reached, a wireline unit (wireline retrievable system) or drill pipe can be used to retrieve the BHA connected to the first joint of the casing string with the DLA.

2.1.2 Non-retrievable system

This system does not recover BHA; if it does, it will cement the well immediately after reaching the required depth, and if it is necessary to continue the drilling procedure, the drill bit will be drilled out. Drillable polycrystalline diamond composite (PDC) drill bits are commonly used in this technology.

2.2 Features and benefits of CwD technology

Although this technology does not seem to be significantly different from conventional drilling methods with drill pipes as the backbone, drilling operations using casing has become one of the most important technological revolutions in our industry[11].

CwD technology can save rig equipment capital and operating costs by eliminating expenditures related to acquiring, handling, inspecting, transporting and tripping drill strings[12]. According to researchers, CwD reduces costs by 10% and saves 30% of the time[13, 14]. Other studies[3] found that the loss of circulation is greatly reduced. In addition, Radwan and Karimi[15] have recorded the characteristics of successful implementation of CwD technology in the field. Suggestions for improving the fracture gradient have been made[16].

Addressing the reduction of well costs has been accomplished by the following factors.

2.2.1 Reducing drilling time & increasing efficiency

Each foot of the borehole will be casing running, making it a two-in-one procedure so that the section can be completed faster (Fig. 5). If the casing gets stuck before reaching the planned setting depth, it can be there setting and cementing[17].

Washing and reaming, which are necessary for every connection, take up to 60% of the total drilling time; washing and reaming thus elongates the exposure time to aqueous conditions which is saved by using CwD technology[18].

2.2.2 Controlling casing strings cost

It is worth noting that the casing used in this method has the same grade and weight as the casing used in the entire conventional drilling method. Therefore, in the case of the CwD method, the use of casing strings will not incur more or additional costs[19].

2.2.3 Reducing cementing costs

Using CwD, the smaller annulus requires less cement than conventional drilling, and there is less cement excess [20]. As reported, the return volume during cementing has increased from 20% of the conventional drilling method to 92%–98% of the excess pumping by using CwD technology[18].

2.2.4 Improving borehole cleaning efficiency

CwD technology features a small annular gap between the casing and the borehole wall (Fig. 6), which improves the annulus velocity and wellbore cleaning efficiency[20].

2.2.5 Improving wellbore stability

When the BHA needs to be replaced or reaches the TD, CwD can eliminate borehole problems related to tripping, because most of the borehole instability and sticking difficulties occur during tripping of the drill string and non-productive time (NPT)[21].

2.2.6 Reducing loss of circulation

Casing while drilling helps minimize mud loss into the formation. Therefore, the problems and hazards related to swabs, pit volume monitoring, hole volume, and filling related to steel removed from the wellbore under loss of circulation conditions, such as hole collapse and stuck pipe, are no longer a problem[22].

2.2.7 Plastering/smearing effect

When the casing string rotates with a limited annulus clearance, the casing contact strengthens and improves the integrity of the wellbore, while the plaster filter cake (Fig. 7) reduces the permeability of the wellbore zone, improves the fracture gradient, and allows wider mud weight window which eliminates any possible loss of circulation (Fig. 8) and well control events, referred to “plastering/smearing effect”[23] .

2.2.8 Rig operating costs

As the circulation pressure is reduced and the periodic tripping of the draw works is eliminated, the rig requires less horsepower, thereby reducing maintenance and fuel costs[23]. This new technology can also optimize existing rigs, reduce the cost and size of rig printing, and minimize HSE risks when dealing with large outer diameter casings and extremely heavy drill collars[18].

2.3 Limitation of CwD

CwD is becoming more widely regarded as a feasible means of lowering drilling expenses and resolving drilling challenges but still there are some practical limitations in CwD as follows[1].

2.3.1 Formation evaluation

Casing while drilling necessitates casing the well as soon as drilling begins. Once the hole section is complete, traditional wireline logging tools cannot be used to log the open hole un-

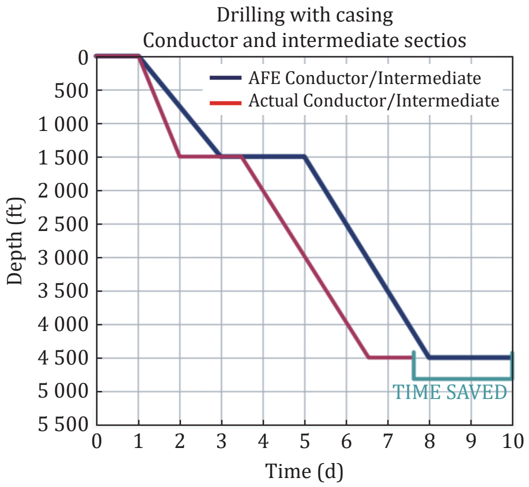


Fig. 5. Tesco’s CwD practice.

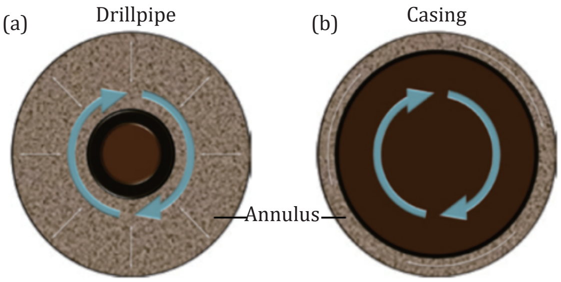
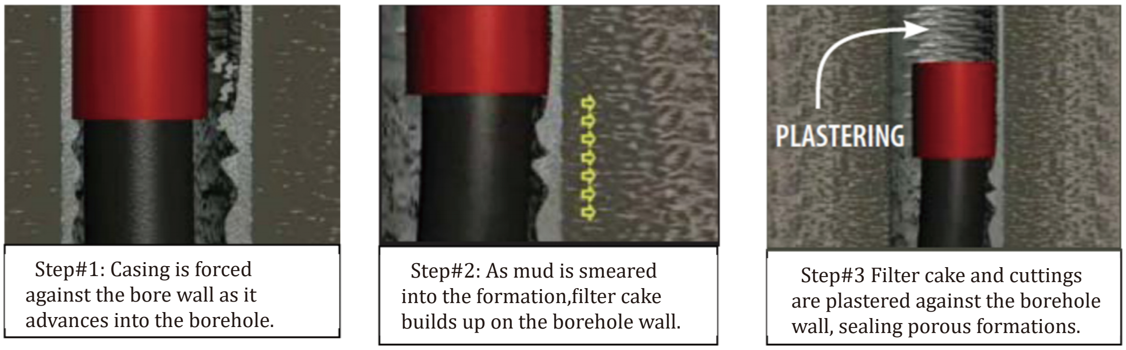


Fig. 6. Annular space of the conventional drilling (a) versus CwD (b).



Step#1: Casing is forced against the bore wall as it advances into the borehole.

Step#2: As mud is smeared into the formation,filter cake builds up on the borehole wall.

Step#3 Filter cake and cuttings are plastered against the borehole wall, sealing porous formations.

Fig. 7. Plastering effect in the casing while drilling operation[22].

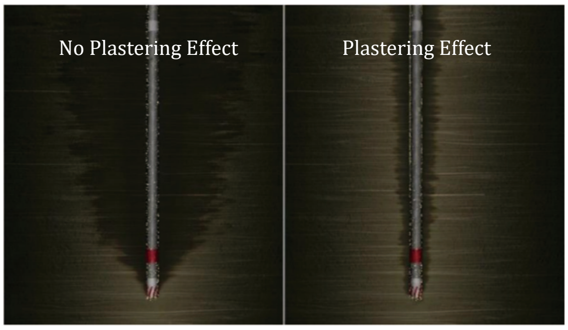


Fig. 8. Illustration of plastering effect.

less the casing is raised above the zone and logged below the bottom. Logging while drilling (LWD) is one answer to this problem. Cased hole logs can be run through the casing or open hole logs can be sent out the bottom of the casing to log interest intervals, depending on the type of wireline logs or specific intervals that need to be logged. Other formation evaluation instruments, like core barrels, can be attached to the wireline retrieval tools and then used as usual once the casing is latched.

2.3.2 Casing connections

Casing connections are commonly guaranteed to operate stationary in the hole as in conventional drilling and may not be able to withstand high torque and compressive loads in a buckling environment, so the Casing while drilling operation is restricted to drill with low torque, low weight on bit, and maintain buckling to a lower limit with smaller hole sizes.

2.3.3 Cementing

The BHA is wireline recovered in the casing while drilling once the casing has been drilled to the planned casing setting depth. The cement plug will be landed without the need for a float collar, The displacement plug should drop and latch onto the casing, acting as a float, to solve this problem. To drill out the plug and cement in the shoe joint, an underreamer and pilot bit assembly linked to the next smaller size of casing must then be used.

3 Well control for CwD and problem statement

Well control is an important aspect of any drilling project. It is expressed as a series of technologies used to reduce the "kick potential" of hydrocarbon wellbore in case of accidental flow of reservoir fluid into the wellbore during drilling, completion, and workover or maintenance activities to keep it under control. It requires the use of procedures, technologies, and equipment to ensure the safety of on-site operations and the environment[24].

More than 70% of well control incidents occur during drill string tripping in and out of the borehole, according to reports. In CwD, the bottom of the string is always at the bottom of the hole. Therefore, when using CwD, the chance of kicking events is reduced, but the study of the allowable response time of kicking is still an important part of this research[3].

When the CwD technique is used instead of the conventional drilling method, the entire borehole geometry changes (see Fig. 9). This condition is critical to well control methods and procedures. Therefore, it is important to understand the differences between conventional drilling and CwD in terms of well control and its monitoring system, because blowout will occur if the well control system does not detect the kick early and terminates it quickly and effectively[25].

There are many definitions to describe kick tolerance (KT); however, for practical purposes, kick tolerance can be defined as the largest kick volume that can be tolerated without fracturing the previous casing shoe[26]. Regardless of the definition of kick tolerance that an engineer uses when designing a well, a common philosophy is that every design has an imaginary engineering limit and that changes made outside of that design limit pose risks to well integrity and operational safety during well design[27].

There is also a risk of misrepresenting the significance of the unique combination of historical events and impacts. This is because if a 50-barrel (bbl) kick did not result in a blowout under certain conditions it does not mean that 5 bbl improperly handled under identical conditions would not result in a catastrophic blowout and vice versa. In general, the occurrence of one series of events and their consequences may or may not have an impact on subsequent series of events. These different combinations are often caused by the definition of KT[28].

Recently, KT has been used to determine casing depths during well planning, which makes the drilling process safer because the amount of kick volume entering the well can be determined by: ① the underbalance between mud weight and formation pressure, reservoir properties (porosity and permeability), ② the type of inflow (gas, oil, or water), ③ the sensitivity and reliability of kick detection equipment, and ④ the response time of well control's crew[28].

(a) (b)

Fig. 9. (a) Conventional drilling, and (b) CwD wellbore geometry[22].

Effective early kick detection (EKD) and blowout prevention are among the most important activities in the oilfield. Failure to do so can result in costly human, material, and financial losses, as well as potential environmental contamination[29].

The most important key performance indicators (KPIs) for kick safety that require special attention and regular monitoring are[16]:

① Kick detection volume (KDV): How much influx volume happens before a kick is positively detected?

② Kick response time (KRT): How long does it take after a kick has been positively detected before the influx is stopped by well-controlled procedures?

No design should allow systemic abuse in any engineering discipline. When it comes to crew response time, attention, and equipment reliability, the designer must make some acceptable assumptions. Crew preparation, training, and competence must be demonstrated before a mission begins. The designer can then statistically justify variations in kick detection system performance and crew response time after establishing a framework of procedures to avoid gross errors[30].

Therefore, many working sessions must be held with the key personnel during the design phase to analyze the risks and emergency response plans for the job. This ensures that the proper response of key personnel and equipment is achieved in the event of a well control incident.

4 Research methodology

Owing to its impact on well design, drilling and well control, kick tolerance has recently gained importance in drilling operations. This article aims to increase the understanding of KT and serves as a technical basis for casing while drilling by exploring a simple method to effectively apply its proposition using field data.

The EKD is one of the most critical areas for increasing well control safety. As more casing operations are performed during drilling, the requirement for earlier, more effective, and more reliable kick detection in a wide range of wells has become increasingly important[28].

The methodology described in this article involves the use of deterministic gas flow models combined with maximum kick tolerance to investigate the likelihood of unwanted well flow during casing operations while drilling.

5 Mathematical derivation of kick tolerance and allowable well shut-in time

In the present work, the kick tolerance model is developed with the following assumptions:

A1. Gas compressibility factor “Z” = 1.

A2. Single phase kick tolerance model.

A3. Poisson ratio (V) = 0.4.

A4. Overburden stress gradient (σ) = 1 psi/ft.

A5. Drill pipe OD = 5 in.

The simplified mathematical model is based on the following algorithm:

(i) Use Eq. (1) to calculate the hydrostatic pressure (HP, psi) of the drilling fluid for the kick depth ($\mathrm{TVD_{kick}}$):

$$\mathrm{HP} = 0.052 \cdot \rho_{\mathrm{mud}} \cdot \mathrm{TVD_{kick}} \tag{1}$$

(ii) Use Eq. (2) to determine the annular pressure loss (APL, psi) at the kick depth ($\mathrm{TVD_{kick}}$) based on the annulus velocity, mud rheology, and drill string configuration:

$$\mathrm{APL} = \frac{\left(1.4327 \times 10^{-7}\right) \cdot \rho_{\mathrm{mud}} \cdot \mathrm{TVD_{kick}} \cdot \mathrm{AV}^2}{D_{\mathrm{h}} - D_{\mathrm{p}}} \tag{2}$$

(iii) According to the APL value, use Eq. (3) to calculate the bottom hole pressure (BHP, psi) for the kick depth ($\mathrm{TVD_{kick}}$):

$$\mathrm{BHP} = \mathrm{HP} + \mathrm{APL} \tag{3}$$

(iv) Use Eq. (4) to find the formation pressure (Pf, psi):

$$\mathrm{Pf} = \mathrm{FPG} \cdot \mathrm{TVD_{kick}} \tag{4}$$

(v) Use Eq. (5) of the Hubbert and Willis method to calculate the fracture gradient (FG, psi/ft) of the previous casing shoe:

$$\mathrm{FG} = \left(\frac{V}{1-V}\right) \cdot \left(\frac{\rho_{\mathrm{overburden}} - \mathrm{Pf}}{D}\right) + \frac{\mathrm{Pf}}{D} \tag{5}$$

(vi) Use Eq. (6) to determine the maximum kick height at the previous casing shoe ($\mathrm{H_{kick}}$, ft):

$$\mathrm{H_{kick}} = \frac{0.052 \cdot \rho_{\mathrm{mud}} \cdot (\mathrm{TVD_{kick}} - \mathrm{TVD_{shoe}}) + \mathrm{FG} \cdot \mathrm{TVD_{shoe}} \cdot 0.052 - \mathrm{Pf}}{0.052 \cdot \rho_{\mathrm{mud}} - G} \tag{6}$$

(vii) Use Eq. (7) to calculate the kick volume ($V1$, bbl) from the kick height ($\mathrm{H_{kick}}$, ft) at the previous casing shoe:

$$V1 = \mathrm{Ca} \cdot \mathrm{H_{kick}} \tag{7}$$

where

$$\mathrm{Ca} = \frac{D_{\mathrm{h}}{}^2 - D_{\mathrm{p}}{}^2}{1029.4} \tag{8}$$

(viii) Using Boyle's Law, under bottom hole conditions, the kick volume ($V2$, bbl) is given by Eq. (9):

$$\frac{P1 \cdot V1}{T1} = \frac{P2 \cdot V2}{T2} \tag{9}$$

Based on the results of Eqs. (7) and (9), choose a smaller kick volume as the maximum allowable kick tolerance.

(ix) Use Eq. (10) to calculate the maximum allowable annular surface pressure (MAASP, psi) at zero kick volume, and plot the relationship between MAASP and kick tolerance:

$$\mathrm{MAASP} = 0.052 \cdot (\mathrm{FG} - \rho_{\mathrm{mud}}) \cdot \mathrm{TVD_{shoe}} \tag{10}$$

(x) According to the radial flow model (Fig. 10) and according to the formation characteristics, Eq. (11) can be used to calculate the influx flow rate (Q_{influx}, bbl/min):

$$Q_{\mathrm{influx}} = \frac{0.007 \cdot K \cdot \Delta_{\mathrm{p}} \cdot L}{\mu \cdot \ln \dfrac{\mathrm{Re}}{\mathrm{Rw}} \cdot 1440} \tag{11}$$

(xi) By subtracting 5 bbl because of pit gain alarm setting and 1 bbl because of safety margin from calculated kick tolerance to get maximum allowable kick tolerance (bbl), the maximum allowable well shut-in time (min) can be calculated using Eq. (12):

$$\text{Maximum allowable well shut in time} = \frac{\text{Maximum allowable kick tolerance}}{Q_{\text{influx}}} \tag{12}$$

6 Field case study

6.1 Operation summary

The well investigated here (well X-2) was planned as a replacement for well X-1, which was 165 ft away from the surface location of the offset well X-1. Well X-1 presented a series of drilling challenges in the intermediate hole section. It had been plugged and abandoned due to borehole instability through reactive shale formation. Non-productive time (NPT) is associated with getting stuck or reaming continually to ensure a proper borehole cleaning and gauging before running casing. Whereas the refined chemistry of the water-based fluid system helps to prevent borehole instability problem, NPT has a significant impact on drilling operations in well X-1. The overall cost of drilling the intermediate hole section is considerable, and any production delays caused by these unanticipated events are costly to the company.

After several unsuccessful attempts to pull out the drill string, well engineering groups were eager to find a new solution that would allow them to lower the cost of drilling across difficult formations while improving overall drilling performance. They would also be working on a well design for future drilling campaigns, which would eliminate existing intermediate casing strings through deepening the surface casing seating point by using CwD technology in well X-2.

CwD is the proposed solution, which is well-known and well-proven around the world. In CwD, the casing is drilled through the problematic formation and cementing it once the section total depth is reached. The drilling team will therefore be able to reduce the amount of time the shale formation is exposed to aqueous drilling fluids before the clayey formation absorbs enough water to generate swelling and, as a result, wellbore collapsing, can also avoid this time-dependent effect, improve drilling performance, and limit unplanned events. Before implementing this technique, the team must first examine CwD as a leading alternative for drilling challenging formations and maximize drilling performance.

However, this method requires an accurate assessment of the control conditions as well as the borehole instability problem that CwD is designed to address.

6.2 Well planning and preparation

During the planning phase of this well, a multidisciplinary technical team analyzed two runs using conventional and CwD techniques. This was done to evaluate the comparative kick tolerance and estimate the allowable well shut-in time to reach the casing point with an appropriate well control system. A high formation pressure at 2145 ft TVD (TVD_{kick}) was predicted with a well control risk.

Both technical runs required a thorough planning phase in which the operator and major service contractors investigated and discussed hazard analyses, contingency plans, procedures, and BHA design. The first objective of the project was to demonstrate the reliability of CwD technology in terms of well control and risk mitigation. This objective is discussed in more detail in the following sections.

The drilling rig was carefully chosen depending on the availability of a top drive system with a standard drill string design; no rig modifications were necessary for this work. The top drive rotated the casing string by delivering the required energy through a casing drive mechanism, a feature that has been demonstrated in hundreds of successful works around the world.

6.2.1 Drilling program

Using a standard rotary BHA, the X-2 well was identified and drilled regularly using a standard well architecture (see Fig. 11) in four phases: 26-in, 17 ½-in, 12 ¼-in, and 8 ½-in.

After the 20-in shoe was conventionally drilled out, the 17 ½-in surface hole section was successfully drilled vertically without exceeding 1-degree inclination at section TD; controlled CwD would not shift this trend with a large diameter bit (17 ½-in. roller cone bit) and cased with 13 3/8-in, 72# L80 buttress threading (BTC) surface casing at 484 ft (Table 1).

Because the first potential high-pressure zone is located below the surface casing point, no well control is required throughout the conventional drilling operation.

According to the well design, CwD technology should be designed for the intermediate section of the candidate well (well X-2) without changing the existing drilling rig or casing design. Drillable 12 ¼-in PDC bit, fit-for-purpose stabilizer, the high-torque ring used to enhance mechanical properties of BTC connection, 9 5/8-in, 23# L80 BTC casing string, and a casing drive mechanism made-up to rig's top drive system are the main components of drill-in strings.

The intermediate hole section is to be cased with a 9 5/8-in casing at 2611 ft, as shown in Fig. 11.

It's worth noting that the non-retrievable 12 ¼" x 9 5/8" CwD with drillable bit and casing top drive mechanism do not necessitate any rig modification.

6.2.2 Formation properties

Table 2 shows the formation features.

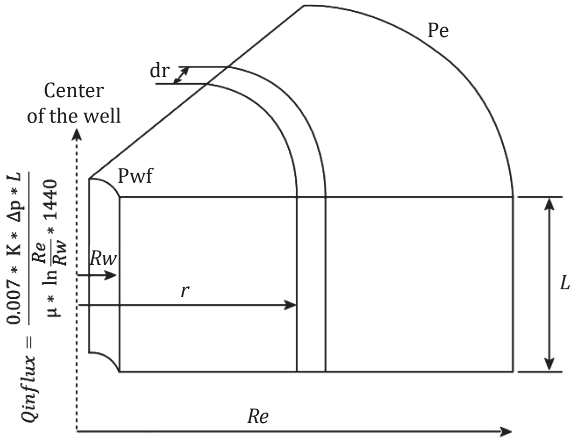


Fig. 10. Radial flow model.

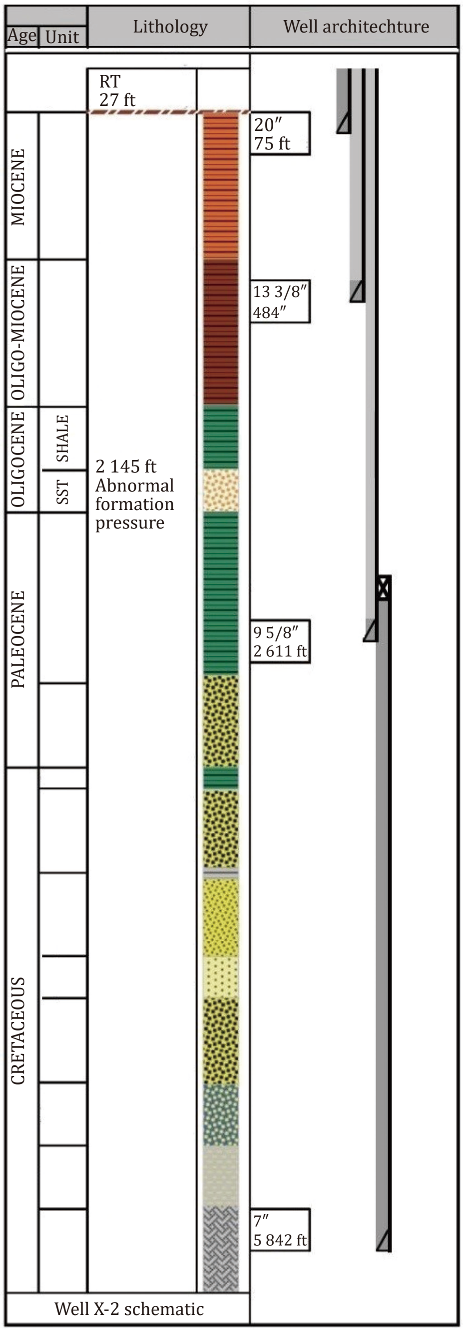


Fig. 11. Schematic diagram of wellbore.

6.2.3 Drilling fluid program

When drilling shale formations, borehole instability and reactive shale problems are common. Owing to anticipated drilling problems, an inhibited polymer mud with a mud weight of 9.1 ppg with some chemical additives and considerable drilling fluid properties to alleviate these drilling problems were used to drill 12 ¼-in hole of the intermediate section to achieve a good borehole cleanout at an annular velocity (AV) = 175 ft/min (see Table 3).

A few design factors and operating methods were changed to reduce the detrimental impact of shale swelling on drilling performance. To address this drilling issue, two primary chemical solutions have been proposed in this well: ① oil-based mud or ② redefining the chemical composition of water-based muds. Although some solutions focus on wellbore stability, it is well documented that water-based mud with specific chemistry has shown to be extremely effective in clayey formations. The use of a unique drilling fluid in combination with other mitigating components such as enough mud weight and special drilling techniques could be used.

7 Results and comparison

This section outlines the study results and comparison of the results obtained from the proposed methodology of kick tolerance and allowable well shut-in time.

To evaluate the proposed methodology, data from the simulated vertical well was used. After data collection, the two sets for conventional and the CwD method were used to implement the proposed methodology as shown in Table 4.

Table 1. Casing configuration.

Casing size (in)	Casing weight (ppf)	Casing grade	Setting depth (ft)
20	94	K55	79
13 3/8	72	L80	484
9 5/8	36	J55	2611
7	23	L80	5842

Table 2. Formation properties.

Property	Value	Unit
Permeability (K)	500	md
Gas viscosity (μ)	0.3	cp
Drainage radius (Re)	400	ft
Well bore radius (Rw)	0.354	ft
Pressure drawdown (Δ_p)	200	psi
Formation pressure gradient (FPG)	0.433	psi/ft
Gas kick pressure gradient (G)	0.102	psi/ft
Temperature gradient	0.02	℉/ft

Table 3. Mud characteristics.

12 ¼-in hole (9 5/8-in casing)	
Depth (MD/TVD)	484–2611 ft
Mud Wt	8.9–9.2 lb/gal
F. V.	37–42 s
PV @ 120 ℉	9–13 cP
YP @ 120 ℉	14–20 lb/100ft^2
API filtrate	4–6 cc/ 30 min
pH	9.0–9.5
MBT	10–25 lb/bbl
Chlorides	200–1200 ppm
Hardness	80–120 ppm

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Table 4. Results of the study.

Output data	Unit	Conventional drilling method	CwD method
Hydrostatic pressure (HP)	psi	1015	1015
Annular pressure loss (APL)	psi	11.4	32.6
Bottom hole pressure (BHP)	psi	1026.4	1047.6
Formation pressure (FP)	psi	928.8	928.8
Fracture gradient (FG)	ppg	15.6	15.6
Kick height (H_{kick})	ft	673	673
Kick tolerance (KT)	bbl	36.6	16.8
Maximum allowable surface pressure (MAASP)	psi	163.6	163.6
Kick inflow rate (Q_{influx})	bbl/min	4.6	4.6
Allowable well shut-in time with 20 ft drilled into overpressured formation	min	6.6	2.3

It is critical to fully understand the impact of kick tolerance when applying the CwD technique to ensure safe drilling operations by reducing the risk of unanticipated inflow from the formation. In addition, since a hypothetical formation fracture can result in loss of circulation and a kick event, this value is critical to the reliable execution of well control procedures.

To avoid a kick event, we need to keep the bottomhole pressure higher than the formation pore pressure. For this purpose and for planning, it is necessary to prepare a kick tolerance diagram for each section, as shown in Fig. 12. The kick volume is plotted on the X-axis and the maximum allowable surface pressure (MAASP) is plotted on the Y-axis in Fig.12. The largest MAASP determined using Eq. (10) is 163.8 psi. For a maximum allowable surface pressure of zero, i.e., the maximum kick volume calculated using Eqs. (8) and (9), the kick tolerance plot is the straight line connecting points 1 and 2.

In terms of well control, the main differences between CwD and conventional drilling are kick tolerance and maximum allowable well shut-in time. Fig. 13 shows that the maximum allowable kick volume at the bottom hole for a conventionally drilled 12 ¼-in hole section at 2145 ft is 36.6 bbl compared to 16.8 bbl for a CwD drilled section. As a result, the maximum allowable kick tolerance for sections drilled with CwD is only 45.90% of what would be allowed with conventional drill pipe. Since early detection of the kick is critical for successful well control, it is suggested that the pit gain alarm be set to the lowest possible value.

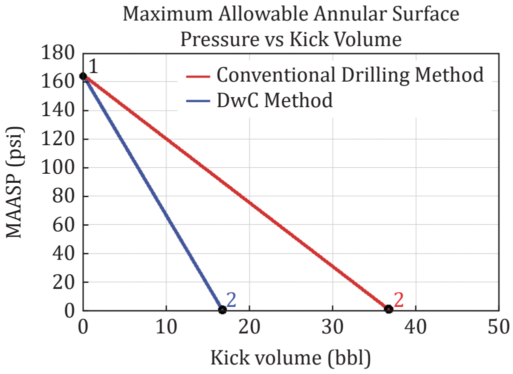

Fig. 12. Comparison between conventional and CwD methods.

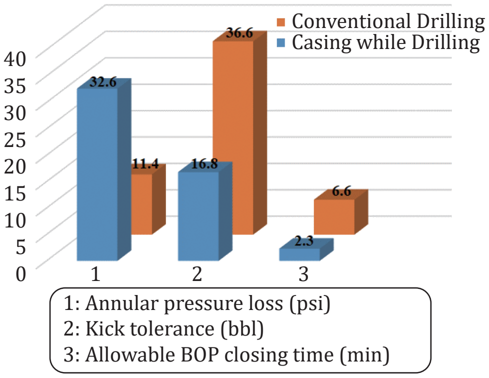

Fig. 13. Column chart of resulted APL, kick tolerance, and allowable BOP closing time of conventional and CwD technique .

Due to the high APL in CwD, pumps should be adjusted to maintain constant bottomhole pressure during well control. Another important conclusion is that the length of overpressure formation drilled before a kick is detected must be considered in careful planning (see Table 5). Because the annulus of a CwD well is so narrow compared to a conventional well, even a small change in influx volume can result in a large difference in allowable blowout preventer (BOP) closure time and well control procedure.

Table 5. Drilled length into the overpressure formation vs. allowable well shut-in time.

Length drilled (ft)	Kick inflow rate Q_{influx} (bbl/min)	Maximum allowable well shut-in time (min)	
		Conventional method	CwD method
1.00	0.23	132.8	46.9
2.00	0.46	66.4	23.4
3.00	0.69	44.3	15.6
4.00	0.92	33.2	11.7
5.00	1.15	26.6	9.4
6.00	1.38	22.1	7.8
7.00	1.61	19.0	6.7
8.00	1.84	16.6	5.9
9.00	2.07	14.8	5.2
10.00	2.30	13.3	4.7
11.00	2.54	12.1	4.3
12.00	2.77	11.1	3.9
13.00	3.00	10.2	3.6
14.00	3.23	9.5	3.3
15.00	3.46	8.9	3.1
16.00	3.69	8.3	2.9
17.00	3.92	7.8	2.8
18.00	4.15	7.4	2.6
19.00	4.38	7.0	2.5
20.00	4.61	6.6	2.3

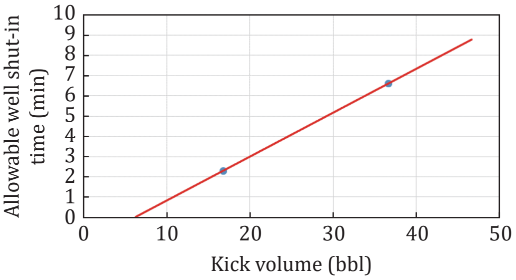

Fig. 14. Kick volume vs. allowable well shut-in time.

For example, in a CwD scenario, if 20 feet is drilled into an overpressured formation, the kick inflow rate is 4.6 bbl/min, and the pit level has been set to +/– 5 bbl, with only 2.3 min remaining after the pit level alarm to shut-in the well with a maximum kick volume of 16.8 bbl (Fig. 14), which is insufficient. Under these circumstances, it is suggested that the previous casing shoe be set deeper.

8 Discussion

To meet the oil and gas industry's need for innovative drilling and evaluate the management of well control events to improve drilling performance, well control conditions, such as undesirable formation influx, maximum kick tolerance of formations, and allowable well shut-in time, must be evaluated in each well.

CwD technology provides a significantly different fluid flow path geometry than the conventional drilling method. The frictional pressure loss and annulus velocity are increased by the smaller annulus clearance between the casing and the wellbore.

This study describes the experience and lessons learned during the technical feasibility study, planning, risk assessment, execution, and drilling of the problematic intermediate hole section. The introduced kick tolerance calculation assumes that a volume of gas that has already penetrated the wellbore has risen to the casing shoe depth. To avoid a casing shoe fracture, the volume of influx should be determined (weakest point in the wellbore). However, to use CwD technology, modifications to the previous well control systems require a full engineering analysis during the initial start-up and design phases to further improve performance and optimize well control.

This means that the capabilities of rig equipment and personnel to detect unwanted kick of formation into the wellbore as well as the competency of rig operators to manage well control events using best practices, are the main issues receiving significant attention in this approach.

The results of this study suggest that there are opportunities to improve casing while drilling by considering well control at the planning phase.

9 Conclusions

As the oil and gas industry is continuously working to improve drilling operations that are both economical and efficient, CwD was established as a drilling comparison to the conventional drilling process resulted in lower well costs, lower non-productive time (NPT), and reduced wellbore challenges. In any drilling operation, a future development promise is carefully studied to increase drilling performance, reduce cost, and improve well control.

The casing while drilling method can be utilized successfully, however it is not always cost-effective. It's generally best for softer formations and bigger casing sizes. As the CwD system becomes more widely used, expertise and equipment advancements will allow the technology to have wider application, affecting a wider range of drilling operations.

The current development of casing while drilling with an emphasis on liner systems is referred to as "retrievable liner drilling". it is a step forward in drilling liner innovation. It is like retrievable casing drilling, which uses a BHA and is retrievable through the casing. The retrievable liner is designed to provide directional control, allowing it to be used in directional wells.

As the primary application of casing while drilling technology is stated to drive the casing as deep as possible to close the problematic zone, numerous operational and technical tasks were required to ensure that this system could be deployed. In this paper, the study was conducted to perform the necessary analysis and develop a methodology presenting the importance of early kick detection during casing while drilling. The results of the study have revealed that using casing while drilling technology, the annulus pressure loss is averaged 3 times higher than via conventional drilling. In addition, the kick tolerance and maximum allowable well shut-in time are considerably reduced where kick tolerance is reduced by 50% and maximum allowable well shut-in time is reduced by 65%, making an early kick detection system necessary.

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Conflict of interest

The authors declare that they have no conflict of interest.

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