Formation Damage and Reservoir Considerations for Overbalanced and Underbalanced CT Operations
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Abstract

Horizontal drilling using coiled tubing is gaining widespread frequency throughout the world. Production results from many horizontal wells have been disappointing, and it is believed that when this has occurred in situations where viable reservoir quality has been present, near wellbore formation damage effects have been a major contributor to the marginal flow performance. Due to the fact that most horizontal wells are completed in an open hole fashion, even relatively shallow invasive near-wellbore damage (that would be penetrated by conventional perforation practices in cased and cemented vertical completions) may substantially impede flow. Drilling induced damage may include fines mobilization, invasion of mud solids, mechanical glazing, phase trapping or chemical reactivity between invading fluids and the formation matrix or in-situ fluids. Underbalanced drilling is discussed as a solution to some horizontal well formation damage problems, and the importance of maintaining a continuous underbalance pressure condition during the entire drilling operation to obtain optimum results is emphasized.

Introduction

Horizontal wells are in use throughout the world in an ever increasing fashion to attempt to increase production rates by maximizing reservoir exposure, targeting multiple zones, reducing drawdowns to minimize premature water or gas coning problems, exploit thin pay zones and, more recently, in such processes as steam-assisted gravity drainage and as injectors and producers in secondary and tertiary enhanced oil recovery processes. Underbalanced drilling using horizontal well technology has also increased in frequency as a means of attempting to increase productivity from horizontal wells by reducing formation damage, improve ROP and reduce drilling and stuck pipe problems in severe lost circulation zones.

The use of conventional technology to drill and complete horizontal wells has resulted in disappointing results in many applications, due to what is believed to be formation damage effects. This paper reviews why formation damage effects may be more significant in horizontal versus vertical well applications. It also reviews current technology levels to reduce formation damage in horizontal well applications as well as applications of CT drilling technology to improve the performance of underbalanced drilling (UBD) operations.

Mechanisms of Formation Damage During Drilling of Horizontal and Vertical Wells

Mechanisms of formation damage which may be operative in reducing the productivity of horizontal and vertical wells have been discussed in the literature by various authors1,2.

These damage mechanisms can be grouped into several major categories, these being:

**Fines Migration.** Fines migration is the motion of naturally pre-existing particulate matter in the pore system. This may be induced during the drilling process by high fluid leakoff rates of water or oil-based mud filtrate into the near wellbore region caused by elevated hydrostatic overbalance pressures or excessively high underbalance pressures3.

**External Drilling/Mud Solids Invasion.** The invasion of artificial mud solids (weighting agents, fluid loss agents or bridging agents), or naturally generated mud solids produced by bit-rock interactions and not removed by surface solids control equipment into the formation during overbalanced drilling conditions2.

**Phase Trapping.** The loss of both water or oil based drilling mud filtrate to the formation in the near wellbore region due to leakoff during overbalanced drilling operations, or due to spontaneous imbibition in some situations during underbalanced drilling operations4, can result in permanent entrapment of a portion or all of the invading fluid resulting in adverse relative permeability effects which can reduce oil or gas permeability in the near wellbore region5.
Chemical Incompatibility of Invading Fluids with the In-situ Rock Matrix. Many formations contain potentially reactive material in-situ in the matrix, including reactive swelling clays such as smectite or mixed layer clays, and deflocuclatable materials such as kaolinite or other loosely attached fines. Expansion or motion of these materials within the pore system, which may be induced by the invasion of non-equilibrium water based mud filtrates into the near wellbore region, can cause considerable reductions in permeability.

Fluid-Fluid Incompatibility Effects Between Invading Fluids and In-Situ Fluids. Oil or water based mud filtrates invading into the near wellbore region during overbalanced drilling processes can react adversely with in-situ hydrocarbons or waters present in the matrix with detrimental results which may reduce permeability. Problems would include the formation of insoluble precipitates or scales between incompatible waters, de-asphalting of the in-situ crude or hydrocarbon based drilling fluid caused by blending of incompatible oils, or the formation of highly viscous stable water in oil emulsions due to turbulent blending of invaded filtrates with either in-situ water or oil.

Near Wellbore Wettability Alteration and Surface Adsorption Effects. Many drilling fluid additives used for mud rheology, stability, emulsion control, corrosion inhibition, torque reduction or lubricity contain polar surfactants or compounds which can be preferentially adsorbed on the surface of the rock. The physical adsorption of these compounds can cause reductions in permeability by the physical occlusion of the pore system, in the case of high molecular weight long chain polymers, particularly in low permeability porous media where the small pore throats may be easily bridged by long chain polymer molecules. Polar compound adsorption may alter the wetting characteristics of the matrix in the near wellbore region, generally in most cases to a preferentially more oil-wet state. This causes a potentially significant increase in water phase relative permeability in this region, which may adversely elevate producing water oil ratio for the well if the completion is in a zone where a mobile water saturation is present.

Mechanical Near Wellbore Damage Effects. Mechanical action of the bit, combined with fine cuttings, poor hole cleaning and a poorly centralized drill string may result in the formation of a thin "glaze" of low permeability surrounding the wellbore. This problem is believed to be aggravated by straight gas drilling operations, where a large amount of heat is generated at the rock-bit interface due to the poor heat transfer capacity of the gas based drilling fluid system in comparison to a conventional drilling fluid. Open hole completions in low permeability elastic formations tend to be the most probable candidates for this type of damage. Glazing will not generally occlude large permeability features, such as fractures or vugs, and the glaze is usually readily removable in carbonate based formations with a light acid wash due to its highly soluble nature.

Factors Which Will Tend to Increase the Severity of Near Wellbore Damage

The overriding factor which will increase the severity of near wellbore damage will be the extent of incursion of fluids and solids into the reservoir and how these materials will react with the formation once they come into contact with the rock matrix. Factors which will tend to increase the fluid/solid loss performance of a drilling mud in a horizontal drilling application may include:

Overbalance Pressure. The greater the density of the hydrostatic fluid column and resulting downhole pressure generated in comparison to the net effective reservoir pore pressure, the greater the tendency for losses of both fluids and mud solids to the formation. Highly weighted mud systems (due to either deliberate high concentrations of weighting agents for well control or poor surface solids control resulting in a undesirable build-up of a high concentration of dense natural silicate or carbonate based formation drill solids in the fluid system), high backpressures or drilling operations in significantly pressure depleted formations (particularly in deep zones) may all contribute to high overbalance pressures. Overbalance pressures in excess of about 7000 kPa (1000 psi) are generally considered to be severe and may cause serious losses of filtrate and associated solids to the formation, particularly in zones of high reservoir quality.

High Solids Content. A high concentration of artificial or natural solids in the mud system, which are inappropriately sized to form a low permeability filter cake, can both invade into the rock matrix (if the solids are too small, that is, less than approximately 30% of the median pore throat aperture), or may screen off the formation face forming porous, high permeability, thick filter cakes which may result in long-term filtrate seepage and stuck pipe problems if the solids are too large. For an open hole completion scenario, an appropriate size distribution of particulate matter in the mud is essential to establish a sealing, low permeability filter cake rapidly on the face of the formation. This will minimize solids invasion directly at the wellbore-formation interface where it can be readily removed, either by direct mechanical backflow or some type of very localized chemical or mechanical stimulation treatment.

Poor Fluid Rheology. The use of high API fluid loss, low viscosity fluids will generally increase the potential for filtrate losses to the formation. Consideration is often given to the use of so-called "clear" fluids with no added solids in the hope that, if the base fluid is compatible with the formation, no damage will occur, even if significant fluid losses occur during the drilling process. Unfortunately, the presence of naturally generated drill solids in clear fluid systems often results in near wellbore mechanical damage as large volumes of the base fluid, along with the often inappropriately sized naturally generated cuttings from the drilling process, are carried off into the formation. The use of appropriate
viscosifiers/polymers can assist in the reduction of uncontrolled fluid losses to the formation in some cases, and should be evaluated for each specific situation under consideration.

**Poor Base Fluid Compatibility.** Even in the best designed overbalanced drilling operation, and often in many so called "underbalanced" drilling operations, some unavoidable losses of mud filtrate to the formation occur. Shallow invasion may not be significant for cased/perforated completions, but may be quite problematic for open hole situations. This being the case, it is usually prudent to design the base mud filtrate with full compatibility with the formation matrix in mind. This would include anticipating problems with reactive clays, in-situ fluids (emulsion potential and precipitation ability) and phase trapping (possibility of including IFT reducing agents such as surfactants or alcohols to lessen the impact of phase trapping if fluid losses do occur).

**Presence of Zones of Extreme Permeability.** Fluid losses and potential damage will generally be more significant in zones of high permeability, such as high perm intercrystalline streaks, fractures or interconnected vugular porosity which may be penetrated by the horizontal well. Conversely, if invasion depth is not too significant, these zones may be the most forgiving and easy to clean up in some respects due to more favourable capillary pressure relations and larger pore sizes.

Why is Damage More of a Concern in Horizontal Versus Vertical Wells?

There are a number of reasons why horizontal wells appear to be more susceptible to formation damage than their vertical well counterparts. One of the major reasons is related to the completion practices used for most horizontal wells. The fact is that the majority of horizontal wells are completed in either a direct open hole fashion, or with some type of slotted or prepacked liner, which, as far as produced fluids are concerned, is equivalent to an open hole completion. This is in comparison to vertical wells where most of the wells are cased, cemented and perforated. One can thus see that a degree of relatively small invasive formation damage, several centimetres in depth about a vertical wellbore may be insignificant, as a normal perforation charge will penetrate beyond the damaged zone and access undamaged reservoir matrix to facilitate reasonable production rates if a permeable formation is present. Many types of damage, such as solids invasion, do, in fact, tend to be very localized about the wellbore in this limited type of radius, particularly in the absence of zones of extreme permeability (such has highly fractured or vugular porosity systems).

It can be observed in an open hole horizontal completion, however, that the produced reservoir fluids must pass completely through the zone of damage which may have been created about the wellbore during the drilling process. Although shallow in some cases, the permeability of this affected zone may be extremely low, creating a very high zone of what is referred to as "skin" damage about the wellbore. Thus, even relatively shallow invasive damage, which may be insignificant in a cased and perforated completion, can be very substantial in an open hole scenario. Other reasons contributing to increased severity of damage in horizontal versus vertical wells could include:

**Greater Depth of Invasion.** Drilling times for horizontal wells are usually greater than conventional vertical wells. Fluid exposure time at the heel of the well may be significant if poor mud rheology is present in an overbalanced condition, or if the mud filter cake is continuously disturbed by a poorly centralized drill string or multiple tripping operations, invasion depth of damaging mud filtrate and solids into the near wellbore region may be substantially greater than in a conventional vertical well application.

**Selective Cleanup/Damage.** The large exposed length of a horizontal well often results in zones of highly variable reservoir quality being penetrated. High permeability streaks may preferentially clean up upon drawdown resulting in minimal drawdown pressure being applied to more heavily damaged and invaded portions of the well, making it difficult to obtain an effectual clean up. Production logs on horizontal wells often indicate the majority of the produced fluid is being sourced from only a very small section of the total length of the well.

**Difficulty of Stimulation.** Damaged vertical wells may often be effectively stimulated economically using a variety of penetrative techniques such as hydraulic or acid fracturing, acid or other types of chemical squeezes, heat treatments, etc. These types of processes are not readily economically applied to horizontal wells due to cost and technical considerations associated with attempting to stimulate a section hundreds of meters in length (instead of only a few meters in length as often is the case in a vertical well). Therefore, most horizontal well stimulation treatments tend to be relatively non-invasive in nature, such as acid washes, and may only be effective in penetrating shallow near wellbore damage.

**Anisotropic Flow.** The flow patterns into a horizontal well are completely different than a vertical well, this is schematically illustrated as Figure 1. It can be seen that a vertical well in a uniform strata of cross bedded planes which it penetrates in an orthogonal fashion will drain the reservoir in a uniform planar radial fashion. Conversely, a horizontal well sources fluids from both the vertical and horizontal planar directions and hence is much more radically affected by variations in the vertical permeability of the reservoir. This shall be described in greater detail in the following sections of the paper.

In a similar fashion, invasion occurring during an overbalanced drilling operation is governed by directional permeability which exists in the reservoir. This is illustrated for a vertical and horizontal well as Figure 2. It can be seen that invasive damage about a vertical well in a situation of uniform non directional horizontal permeability will be in a cylindrical pattern, with the depth of invasion in an unimpeded fluid loss situation being governed by the variable permeability of the strata under consideration. In a horizontal well, due to the frequent anisotropy
of horizontal versus vertical permeability in many reservoir systems, the invasion pattern will be elliptical in nature, with the direction of the primary axis of the invasion ellipsoid being oriented in the direction of highest permeability.

Underbalanced Drilling

The previous discussion illustrated that near wellbore skin damage in a horizontal well can significantly reduce productivity to the point where, in some situations, the wells are uneconomic. Much of this damage is associated with invasion of fluids and solids during the conventional overbalanced drilling process. Underbalanced drilling has been used in recent years as a means to attempt to reduce invasive formation damage and improve the productivity of wells in high damage/high fluid loss prone scenarios. Success with underbalanced drilling operations has been mixed, primarily due to misapplication of the technology in many situations and a failure to maintain a continuously underbalanced condition at all times during the drilling operation. Since no protective filter cake is formed during a properly executed underbalanced operation, due to a net outflow of fluids from the formation, even relatively short periods of periodic overbalance pressure can result in significant invasion of fluids and solids into the formation and severe damage, sometimes of greater magnitude than would have occurred if a well designed and conceived overbalanced system with good fluid loss control had been used in the same situation (Figure 3). In certain conditions, damage may occur due to countercurrent imbibition, gravity drainage, mechanical glazing or drawdown effects, even if a continuously underbalanced condition is maintained during the drilling operation. A detailed discussion of problems associated with many underbalanced drilling operations and suggested screening criteria for the proper design of an underbalanced drilling program is contained in the literature 4,12.13.

The Use of CT in UBD Operations

Coiled tubing has been used with increasing frequency in some underbalanced drilling (UBD) situations because of perceived superiority to conventional jointed pipe drilling technology. Much of the success of an underbalanced drilling operation centres on the ability to maintain an underbalanced condition on a continuous basis, transmit effective survey and pressure data back to the surface in a unremitting fashion during the underbalanced drilling operation, clean the hole effectively and operate in a safe fashion with potentially high flow pressures at surface. Coiled tubing has distinct advantages in these areas over conventional jointed pipe due to the lack of requirements for connections, use of an internal wireline and capillaries for survey and geosteering purposes, and much higher operating surface pressure limitations than conventional jointed pipe.

Jointed pipe, however, is much less expensive to utilize and is readily available. Also, increasing experience and modifications in technology (such as EMT surveying tools) have reduced or eliminated many of the problems initially associated with its use for UBD applications. The common application of jointed pipe technology for drilling reduces problems associated with inexperienced crews implementing the relatively new technology of coiled tubing drilling. In addition, coiled tubing drilling technology is currently limited at approximately 2500 ft. of horizontal outreach and relatively small hole sizes in order to maintain sufficiently high annular velocity for adequate hole cleaning purposes. High frictional losses, associated with the necessity of injecting fluid through the entire length of the coiled tubing string at all times, may also be problematic.

Jointed Pipe vs Coiled Tubing For Underbalanced Drilling

The vast majority of wells drilled using underbalanced technology have utilized conventional jointed pipe technology and rotary rigs. More than 85% of the wells drilled using the "artificial" underbalanced type technology in Canada have been drilled using conventional jointed pipe. The fraction is even greater if low head and flow drill applications are considered on a worldwide basis. Major advantages and disadvantages with respect to coiled tubing vs jointed pipe applications can be summarized into the following categories:

Safety and surface pressure control issues
2. Continuous BHP maintenance issues
3. Rate of penetration issues
4. Hole cleaning issues
5. Total drilling time issues
6. Continuous circulation issues
7. Mud spillage and environmental issues
8. MWD capabilities
9. Rig/site considerations, footprint
10. Surface hole/casing considerations
11. Hole size limitations
12. Depth limitations
13. Rotation issues
14. Torque, drag and weight on bit issues
15. Downhole motor issues
16. Tubing life limitations
17. Torque limitations
18. Flow hydraulics limitations
19. Orientation and steering difficulties
20. BHA considerations
21. Availability issues
22. Experience issues
23. Economics
24. Hybrid rig applications

Some of the more significant of these areas with respect to formation damage issues will now be discussed in detail.

Continuous Maintenance of an Underbalanced Bottomhole Pressure Condition

One of the main motivations for underbalanced drilling, in many situations, is the elimination or minimization of invasive formation damage caused by fluid and solids losses to the formation under conventional overbalanced conditions. Much of
this benefit is negated if the underbalance pressure condition is periodically compromised. This phenomena is schematically illustrated as Figure 3. Coiled tubing has a major advantage over jointed pipe in this case, due to the fact that there is no necessity to break for connections. If standpipe injection of the non-condensible gas being used to generate an artificially generated underbalance pressure condition is occurring, this may result in bottomhole pressure fluctuations which may, if improperly handled, result in conditions of periodic hydrostatic overbalance pressure being encountered downhole. This may negate much of the benefit of the UBD operation (with respect to formation damage minimization). Damage may actually be worse in some cases in comparison to the same situation than if a well-designed overbalanced drilling fluid (which has the capability to form a stable and bridging and, hopefully, readily removable filter cake) had been utilized.

Bottomhole pressure fluctuations using jointed pipe can be minimized by making fewer connections (drilling with double or triple pipe stands - triples are becoming more common with the increasing use of top drive rigs for UBD jointed pipe applications), faster connections, circulating to pure gas to attempt to unload as much fluid from the horizontal and annular section as possible prior to making a connection, and leaving the annulus open during connections to allow bleedoff to prevent rapid fluid fallback in the vertical annular section of the wellbore. Bottomhole pressure fluctuations, however, in situations where significant volumes of liquid are being produced from the formation, can be minimized through application of these techniques but not totally avoided.

Alternate injection configurations, such a parasite tubing string or microannular injection techniques (see Figures 4 and 5) can provide stable and uniform bottomhole pressure profiles for jointed pipe operations similar to those seen during CT operations. These modified UBD operations increase expense of the well, however, both from an equipment perspective and also operationally due to the fact that more non-condensible gas is required to maintain the same bottomhole pressure in a concentric or parasite string application in comparison to a standpipe injection mode in the same situation.

Rate of Penetration (ROP) Issues

Generally, ROP is significantly increased by UBD operations. All factors being equal, ROP increases in CT vs jointed pipe operations are comparable, but this assumes that equivalent hole size, weight on bit, torque and drag considerations, etc. are present which is often not the case as will be discussed shortly. ROP may be compromised in some CT applications, particularly in extended reach applications, due to the fact that limited weight can be applied to the bit by the action of the CT injector at surface, and much of this force may be expended in drag effects as the CT string is forced around the horizontal bend and down the helical well path that is typically generated when attempting to drill horizontally with CT.

Hole Cleaning Issues

Hole cleaning presents a major problem in many UBD operations. Hole cleaning is affected by fluid rheology, cuttings size and concentration (which is in turn a function of bit type and ROP) and annular fluid velocity. The majority of CT operations are conducted using 2" or smaller CT strings, whereas hole size can be 6.25" or larger. This may result in high pump rates and frictional losses in the CT string being required in order to maintain sufficient annular velocity to maintain effective hole cleaning. Inability to rotate coiled tubing may further exacerbate the problems with hole cleaning. The use of larger CT strings (to reduce frictional drop in the string and increase corresponding annular velocity due to a reduction in annular size) may be useful. Increased use of aggressive bits (such as PDC's) to reduce cuttings size may also be useful, but may be offset by problems with torque generation and high amplitude torque variation.

The ability to continually or periodically rotate conventional jointed pipe may result in superior hole cleaning ability due to keeping a competent cuttings bed from forming. Working the CT string may also assist in hole cleaning ability in certain situations. Many CT applications for UBD are drilled slim hole which reduces the problems associated with low annular fluid velocities in the horizontal section, although problems may still be apparent in larger diameter uphole sections. The concentration of large amounts of drill solids in the hole, if the UBD condition is compromised, may increase near-wellbore invasive damage characteristics.

Total Drilling Time

Drilling times may be reduced using CT due to the fact that time for connections may account for up to 25% of the total drilling time (in soft formation applications) when drilling with conventional jointed pipe. Since connections are not required for a CT application, this represents direct reduced drilling time and cost savings for the drilling operation. CT can also be tripped much faster than conventional jointed pipe, which may also reduce on-site time if multiple trips are required in a particular job. A reduction in exposure time limits potential for invasive damage/imbibition to occur.

Continuous Circulation Issues

Due to the nature of coiled tubing, continuous circulation is possible both while drilling ahead, and also while tripping. The advantages of continuous circulation in maintaining a uniform BHP while drilling have been discussed previously. The ability to continuously circulate with CT while tripping, in general, reduces reaming requirements, allows for backreaming, while tripping out (if required) and allows the hole to be cleaned and maintained in a better condition.
Depth Limitations

Coiled tubing, due to the inherent helical buckling characteristics and limited power of the surface injector heads, is currently limited by both depth and horizontal outreach. Maximum horizontal outreach with current levels of technology is in the range of 2500 ft, which severely limits the use of CT applications in many horizontal situations where extended reach wells are required due to reservoir or surface location considerations or constraints.

Current research into the use of CT tractor units, which can be used to apply weight on bit in CT drilling applications, and the use of larger CT strings, may extend the reach capability of CT in the future, but this currently remains one area in which conventional drill pipe exhibits considerable advantages over CT.

Rotation Issues

A major disadvantage of CT over jointed pipe is that CT cannot be rotated. This means that a CT drilling operation is operated in a continuous sliding mode which results in considerable associated frictional drag effects and a reduced effective weight on bit, reduction in ROP and reduced outreach for horizontal applications. There may also be the need to add friction reducers to the drilling fluid to aid in the smooth operation of the CT drilling program. This increases the cost of the program, and many friction reducers can adversely affect the formation if the underbalance pressure condition is comprised and fluids are lost to the reservoir matrix.

Availability Issues

In many cases, CT drilling for an underbalanced drilling application is desirable, but a shortage of suitable CT units for the particular application under consideration, in comparison to conventional jointed pipe rigs, occurs. This results in many applications with undertrained crews attempting to operate equipment in a highly non-standard situation which can result in less than optimal performance and results. Once again, as more CT drilling units become available, this issue may become less problematic.

Experience Issues

Although there are many experienced coiled tubing operators, there are few highly experienced coiled tubing drilling operators, especially for UBD applications. This results in problems in many applications with undertrained crews attempting to operate equipment in a highly non-standard situation which can result in less than optimal performance and results. Once again, as more CT drilling units come into the market and the number of CT drilling operations increases, the mean expertise level of CT drilling crews will increase.

Economics

A combination of high demand, new, non-paid out equipment and limited life of CT strings may often adversely affect the economics of a CT drilling application in comparison to conventional drilling with jointed pipe. The large number of depreciated and readily available land rigs which can be used for UBD operations may often make CT an uneconomic alternative in many UBD cases. An increased number of CT units will foster a more competitive market with more depreciated equipment which may aid in reducing costs and improving the economics of CT drilling in comparison to jointed pipe in some situations.

Hybrid Rigs

There has been interest in the development of hybrid drilling rigs which incorporate the desirable features of both jointed pipe and CT drilling applications into a single unit. This is particularly appealing in some offshore applications where very limited footprint size is available for a given drilling operation. Once again, the cost of development and construction of these hybrid rigs may make their initial use prohibitively expensive except in certain special applications.

Conclusions

The use of coiled tubing for overbalanced or underbalanced drilling of vertical and horizontal wells may result in a reduction of formation damage in specific situations. Particular application for coiled tubing drilling occurs in situations where underbalanced drilling is under consideration, as coiled tubing has specific advantages with respect to the continuous maintenance of a more uniform, underbalanced bottomhole pressure condition as well as the ability to continuously circulate the hole while faster tripping times and the ability to run an internal water line for less problematic MWD problems during horizontal underbalanced applications.

潜在的不利因素与CT有关，在特定情况下，未平衡钻井可能与CT相关的不利因素有关，这可能导致较差的井下清洁能力与较小直径CT管并和一个更可能的潜在损害和有限的水平延伸，与当前的CT技术有关。

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