Vibration and Rotation To Extend Coiled-Tubing Reach

In recent years, there has been increased use of coiled tubing (CT) to drill shallow wells or to drill laterals from existing wellbores. Often the weight on bit (WOB) that can be applied with CT is limited as a result of friction between the CT and the wellbore, making some drilling operations impossible. Two methods proposed to reduce this friction are CT vibration and rotation. The full-length paper presents research performed to determine the effectiveness and practicality of these two means of friction reduction.

Introduction

The US Dept. of Energy (DOE) funded research in microhole drilling with CT. A portion of this funding was devoted to researching methods for mitigating downhole friction to enable CT to be used for extended-reach-drilling applications. Small-diameter CT (used for microhole drilling) helically buckles easily when in compression. Once helically buckled, additional wall-contact forces (WCFs) are caused by CT contact with the wellbore. These additional WCFs increase friction between the CT and the wellbore. This friction increases exponentially with the compressive force in the CT until no additional force can be transmitted to the bit. This situation is known as helical lockup. When the axial force reaches the helical-bucking load (HBL), the additional WCF caused by buckling far exceeds the WCF resulting from weight.

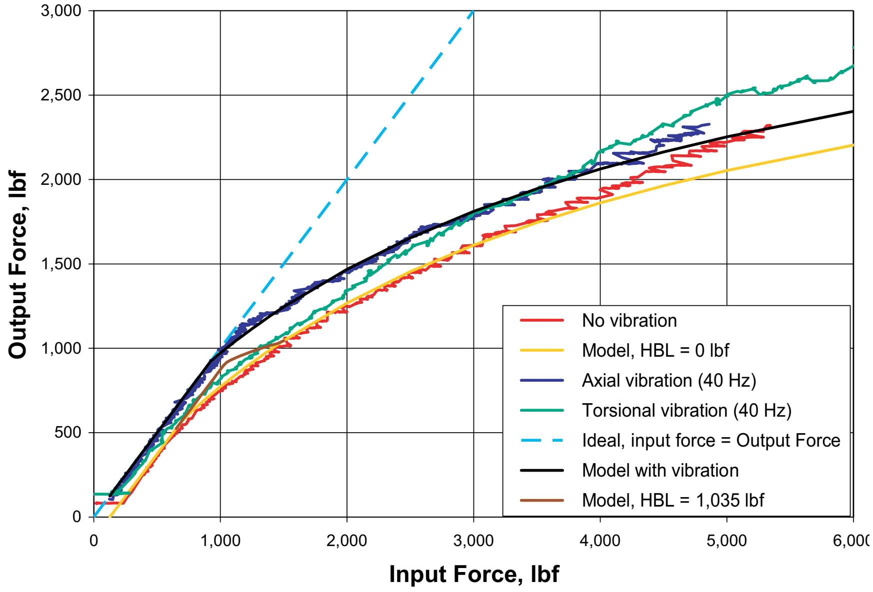

Fig. 1—Vibration-test results for 1-in. straight simulated horizontal wellbore.

Methods To Increase WOB. ***Geometry Changes.*** Increasing CT diameter or decreasing hole diameter is an effective way to increase WOB. Increasing CT wall thickness may increase WOB, especially in vertical wells.

Lubricants. Various lubricating fluids have been used to reduce the friction coefficient between the CT and well tubulars or the wellbore. These lubricants have been somewhat successful in cased-hole workover applications. However, in drilling applications, the drilling fluid must turn the downhole motor, maintain well control, and carry the cuttings out of the hole. It is difficult to design a drilling fluid that will perform all of these functions and also provide significant lubrication.

Tractors. Downhole tractors are available for CT-drilling (CTD) applications. Tractors provide the WOB so the CT can remain in tension. However, a downhole tractor adds additional deployment logistics, risk, and expense. Currently, tractors are not available in sufficiently small diameters to perform microhole drilling.

Rollers. Various types of rollers have been developed that can be attached to the CT and to the drilling bottomhole assembly. The time and logistics associated with attaching and removing rollers make them undesirable.

CT Straightening. CT has residual curvature because of the bending it undergoes on the reel and guide arch. A device that causes a small reverse bend to straighten the CT can be used, so the CT in the well is straight (or nearly straight). This device does not remove the residual stresses; instead, it modifies

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the residual stresses so that they result in nearly straight pipe. Some work has been done that shows that straightened CT can be pushed farther in a horizontal well before reaching helical lockup. Other work has shown that the maximum WOB provided by straightened CT is the same as the maximum WOB provided by curved CT. Thus, it appears to be inconclusive that straightening is beneficial. It is clear that straightening CT exacerbates fatigue damage.

Vibration. Downhole devices to vibrate the CT have been used to decrease friction and increase WOB. In some cases, the vibration helped; in other cases, there appeared to be little benefit.

Rotation. The idea of rotating the CT has been discussed for many years. At one point, a rotating-CT unit with the reel above the injector was designed, but it was never built. Currently, a rotating-CT unit is being developed that stores the CT in a carousel above the injector. In either case, the entire CT length is rotated with the injector. Other concepts have been discussed in which a motor is inserted in the CT string below the injector to rotate the CT in the portion of the well below the motor. To date, none of these systems have been commercialized.

Research. A DOE-funded research project was undertaken to determine if vibrating the CT from surface would be a practical means to mitigate friction to provide sufficient WOB while drilling 3,000 ft or more of horizontal displacement in a $3^1/2$-in. wellbore. This project involved design and fabrication of a test facility and performing CT-vibration tests in simulated horizontal wellbores. In addition, some analytical work has been performed to evaluate issues associated with CT rotation for CTD applications.

Test Facility

Two 558-ft-long, $2^7/8$-in. corrosion-resistant-alloy (CRA) CT strings were straightened and laid out to represent horizontal wellbores, one straight and the other with a 45° bend. These wellbores were held in place with cement blocks poured at intervals along the string. Either a 1- or $1^1/2$-in.-outside-diameter CRA CT string was placed inside one of the simulated horizontal wellbores, and a load was applied to the CT to simulate CTD applications. An axial-force piston and load cell were used to apply a known input force to one end of the CT string. Electric vibrators were used to vibrate the string adjacent to the axial-force piston. Another load cell at the other end of the simulated wellbore measured the output force, that would be equivalent to the WOB in a drilling operation. Until the HBL point is reached, all of the applied input force was expected to be observed as output force, except for the force needed to overcome the CT-weight friction, which was constant. Thus, once the input force was greater than the weight friction force, an incremental increase in input force yielded the same incremental increase in output force. This is referred to as 100% force transfer. Once the CT helically buckles, the additional WCF and associated friction reduce the amount of force transfer. Helical lockup is defined as the point at which the force transfer declines to 1%.

Testing

Vibration. *Lateral.* Lateral vibration is vibrating the CT back and forth, perpendicular to the CT axis. Lateral vibration did little to reduce friction, even when vibrational forces sufficiently large to break the CT were used. Thus testing with lateral vibration was discontinued.

Torsional. Torsional vibration is rotationally vibrating the CT the way that a downhole motor would vibrate the pipe if the bit was sticking and slipping.

Axial. Axial vibration is vibrating the CT along its axis, the way a downhole hammer would vibrate the pipe.

Fig. 1 shows a typical set of test results for 1-in. CT inside of the straight, simulated horizontal wellbore. The dashed light-blue line shows the ideal situation in which the output force is equal to the input force (zero friction). The yellow curve is the theoretical force-transfer curve, with the exception that the pipe is assumed to be helically buckled as soon as compression is applied. A 0.2 friction coefficient was used to generate this theoretical curve. The small brown portion of a curve is the modification that would be made to the yellow curve if the CT does not buckle until the HBL is reached. The red curve is the test results with no vibration applied to the CT. These results match the yellow curve. It is interesting to note that the red curve does not follow the small brown curve. This means that the CT behaved as though it was helically buckled as soon as compression was applied. This result does not agree with the theory and currently is not understood.

Axial- and torsional-vibration testing was performed at multiple frequencies. With either type of vibrational energy, the higher the frequency the more the friction was reduced.

The dark-blue curve illustrates the axial-vibration-test results. The first portion of the curve is on the ideal input force equals output force line. This means that the axial vibration eliminated the friction, including the friction caused by CT weight. Slightly above the HBL, the dark-blue curve departed from the light-blue curve and ran parallel to the red curve. Once the pipe was helically buckled, the additional WCF resulting from helical buckling rapidly attenuates the vibrational energy. As the axial load is increased, there is a point along the length of the pipe where the vibration stops. As the load continues to increase, this point moves toward the input-force end. The black curve is an attempt to model the axial-vibration results by assuming that the vibration eliminates a fixed amount of friction from the end being vibrated.

The green curve illustrates that torsional vibration behaves differently from the other vibrational-energy modes and is less effective than axial vibration at friction mitigation. This may be attributed to the CT rolling back and forth slightly in the simulated wellbore, although the increase in force transmitted for input forces greater than 4,000 lbf could not be explained. This torsional-vibration result seems to be independent of helical buckling.

Conclusions From Vibration Testing.

1. Axial vibration is most effective in reducing friction
2. Before helical buckling occurs, vibration reduces friction significantly.
3. Once helical buckling occurs, the additional WCF causes the vibration to attenuate rapidly.
4. Significant vibrational energy is required to achieve friction reduction.
5. The friction-mitigation benefits from vibration do not justify the cost and maintenance issues associated with vibrating CT from the surface.

6. Downhole-axial-vibration tools should reduce friction up to the point where helical buckling occurs, but once helical buckling occurs, they will be less effective.

Rotation. Full-scale rotational testing has not been performed yet in the test facility. However, a miniature rotational test fixture was built. Two small tubes, representing simulated wellbores, were fixed to a wooden board. One tube was straight and the other curved. Two 0.125-in. rods (representing CT), one straight and one curved (representing residual bend), were placed into these tubes and rotated by hand. For the straight rod in the straight tube, there was almost zero friction. For the straight rod in the curved tube, there was a small amount of friction caused by the rod bending in the tube. For the curved rod in the straight tube, there was a small amount of friction (approximately the same as straight rod in curved tube) resulting from the rod straightening in the tube. For the curved rod in the curved tube, there was a large amount of friction when the curve of the rod was in a plane different than the curvature of the tube. When both were in the same plane, there was basically zero friction. Thus, the rod snapped and twisted when rotated at a constant speed. These miniature-test results may not be fully representative of the results that will be obtained with full-scale testing, but they were sufficiently dramatic to initiate an analytical study of the rotation of curved pipe in a curved well.

Rotational Analysis. The appendix of the full-length paper presents a theoretical analysis of the torsional behavior of pipe. The resulting equation from this analysis provides the change in torque along the length of the pipe. There are two components that cause torque to change. The first and most obvious component is any externally applied torque, such as the torque caused by friction when the pipe is rotating in the well. The second component is the one of interest. It provides a change in torque that is the product of three variables: pipe stiffness, wellbore curvature, and the pipe curvature caused by residual stresses.

Qualitatively, this means the following.

- There is no change in torque in a straight wellbore.
- There is no change in torque in a curved wellbore if there is no residual curvature in the pipe.
- There is no change in torque in a curved wellbore if the residual curvature of the pipe is in the same plane as the curvature of the well.
- There is a change in torque with bent pipe in a curved wellbore when the bend of the pipe is out of plane with the curve of the well.

Conclusions From Rotational Testing and Analysis.

1. Rotating bent pipe in a curved wellbore will cause variations in torque along the pipe.
2. These variations in torque will cause variations in rotational speed and likely will cause undesired dynamic effects.
3. If the pipe is straightened, these dynamic phenomena may be mitigated.
4. Full-scale testing is required to verify these results. JPT