HOW TO DETERMINE IF TUBING IS UNANCHORED IN ROD PUMP WELLS BY ANALYZING DYNAMOMETER DATA

O. Lynn Rowlan, Gustavo Fernandez, and Carrie Anne Taylor, Echometer Company
Sheldon Wang, Ph.D.,P.E., McCoy School of Engineering, MSU Texas

ABSTRACT

A frequent question that is asked when analyzing dynamometer data is "Does my pump card show that my tubing anchor is not set?" Both diagnostic and predictive software have the functionality to calculate and display the shape of the pump card during the expansion and compression portion of the pump cycle. This paper discusses a simple method that can normally be used to determine if the tubing anchor is set. Estimating the amount of pump stroke lost to slippage is proposed to provide an improved guide to determining if the tubing is unanchored.

Introduction

Slow strokes per minute, open pump clearances in a deep well have impacted the shape of the pump card and frequently results in the question: "Is my tubing unanchored?". The Coefficient of Tubing Stretch, Kt, and the downhole pump dynamometer card can be used to help identify unanchored tubing. The Unanchored Kt and Anchored Kt lines plotted on the left side of the pump card shape are the first step in resolving if tubing is anchored.

Excessive mechanical friction from doglegs created when drilling the well in the upper section of the wellbore can result in erroneous load measurement when initially setting the tubing anchor. Setting a tubing anchor should be done by pulling inches of stretch and should not be done using a load measurement gage.

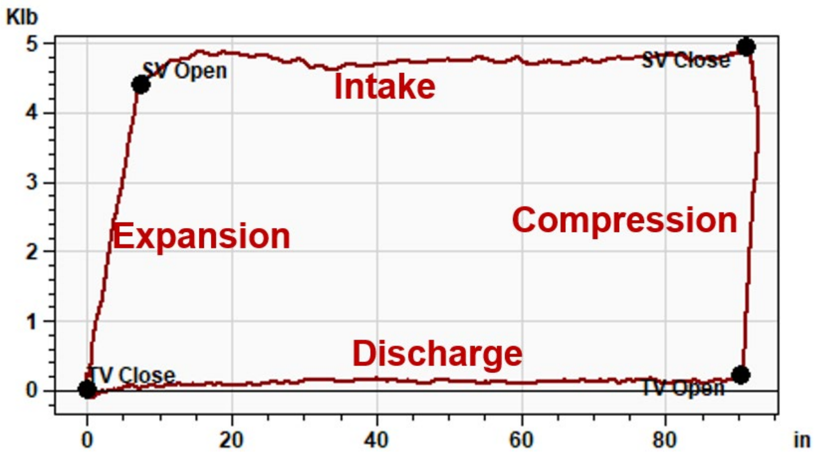
Slippage and/or a leaky pump can make identifying unanchored tubing difficult, because the left side of the pump card dynamometer card leans to the right in a similar fashion as unanchored tubing. A static traveling valve load test is a common field technique to determine if a leaky pump is present. The Patterson Slippage equation was developed to calculate pump slippage for the entire stroke. If a portion of the Patterson slippage can be allocated to the left side of the pump card stroke, where the fluid load is transferred from the tubing to the sucker rods; then a pump slippage line could be plotted and be used as an additional aid in identifying slippage plus anchored or unanchored tubing.

Understanding if tubing anchor is properly set is important for long sucker rod and tubing run life. This paper will use many example pump cards acquired from various sucker rod lifted wells to explain if tubing is unanchored or does the pump card shows tubing movement, unanchored tubing, excessive slippage or does this shape show some other issue.

Cyclic Loading

In a sucker rod lifted well both the sucker rods and the tubing have cyclic loads applied by the pump during one stroke. Figure 1 is stroke #18's pump card calculated by the TAM[1] diagnostic software and acquired at 120 HZ using a calibrated 50K horseshoe load cell at the Texas Tech Red Raider #1 on 07/09/2002 07:30:54 PM during the Slippage Testing Project.

Figure 1 - Stroke #18's Pump Card



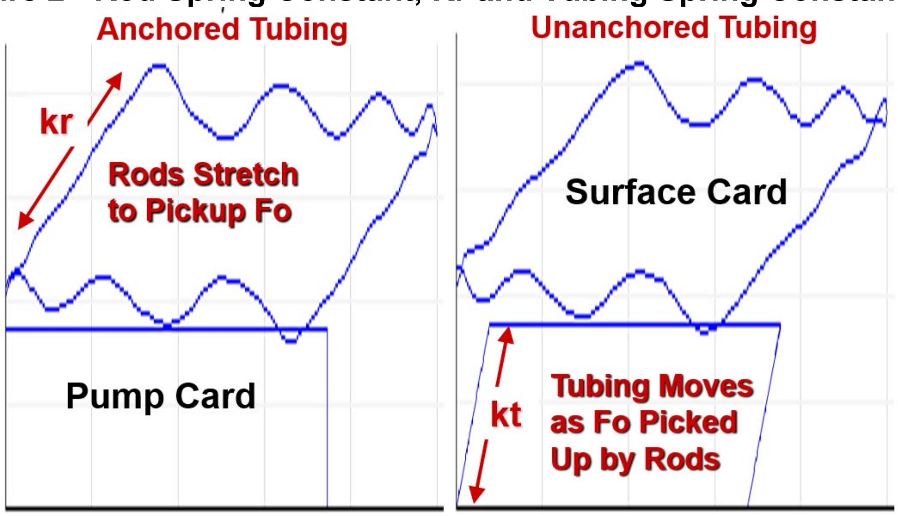
The stroke #18's pump card's load and position plot are labeled to show the pump cycle where expansion, intake, compression and discharge of the fluid occurs to create the cyclic loading on the rods and the tubing. In **Fig. 1** TV Close identifies the beginning of the upstroke, from TV Close to SV Open the pump plunger relative to the tubing appears to move up approximately 7.7 inches while the rods gradually stretch expanding the pump chamber volume until the fluid load, Fo, is transferred from the tubing (SV, standing valve) to the stretched rods (TV, traveling valve). If the tubing is "Not Anchored" then the slope of the pump card load versus position can indicate tubing movement. At point "SV Open" the standing valve opens due the expanded pressure inside the pump barrel being less than the well pressure on the bottom of the pump intake. At point "SV Open" the force exerted by the stretched rods balances the Fo and the plunger begins to move upward in the barrel of the pump. During the upstroke from SV Open to SV Close the stretched rods carry the fluid load as the rods and plunger move upward on the upstroke. Point "SV Close" is identified as the top of the plunger upstroke and where the standing valve ball goes on seat. After point "SV Close" as the plunger moves down to compress the fluid inside the pump barrel, the load is being transferred from the rods to the closed SV attached to the tubing. If the tubing is "Not Anchored" then the slope of the pump card load versus position can indicate tubing movement during the compression portion of the stroke. At point "TV Open" the TV ball comes off the seat as the pressure inside the pump barrel exceeds the discharge pressure at the bottom of the tubing; the plunger is completely unloaded and slides through the fluid in the barrel. During the downstroke both plunger and polished rod move nearly together due to the absence of load at the bottom of the rod string. This cycle is repeated for each stroke.

The sucker rods stretch when picking up the fluid load during the upstroke and the sucker rods unstretch when releasing the fluid load onto the tubing by opening the traveling valve on the down stroke. If the tubing is anchored then the tubing does not move during the pump cycle. If the tubing is "Not Anchored" or unset then the tubing unstretched when the plunger is picking up the fluid load during the up stroke and the tubing stretches when at the beginning of the down stroke compression of fluid inside the pump chamber transfers the fluid load off the plunger onto the tubing by opening the traveling valve on the down stroke.

Elastic Stretch

Tubing and rods are operated (elastically stressed) below the yield point in the elastic region of the stress strain curve. A constant cross-sectional area, **A**, of fiberglass or steel sucker rod or length, **L**, of tubing has a linear elastic change in length, **ΔL**, or stretch, in response to a proportional equal amount of change in load, **F**. This property is called the modulus of elasticity, **E,** where **E=(F/A)/(ΔL/L)**. Recommended loading on tubing is limited with a minimum design factor of 1.25 in tension for pulling and a simple approach is to assume a relatively high design factor of 1.6 based on the tubing weight in air. The tapered rod string is never loaded to more than 25% (Modified Goodman) or 35.7% (1/2.8 the current recommended practice) of the elastic tensile stress range; sucker rods do not fail in tension due to a maximum load because the rod string is designed for a long operational life with the expected failure mode of fatigue. Tubing and/or Rod stretch is a function of the lengths and area of various sections of sucker rods/tubing making up the entire string.

Figure 2 - Rod Spring Constant, Kr and Tubing Spring Constant, Kt



Coefficient of Stretch, K, for a constant area A and is defined as the required load in pounds applied to a tubing or rod string of length L to stretch the entire string equal to 1 inch. **Figure 2** displays predicted surface and pump dynamometer cards annotating the spring constant, K, to identify the slope of the pump chamber expansion portion of the pumping cycle on the pump card when the tubing, Kt, is unanchored and to identify the stretch of the sucker rods, Kr, in the plot of the surface dynamometer card with anchored tubing. These predicted pump dynamometer card shapes are for a pump filled with liquid, no gas inside the pump chamber and the pump is functioning properly. Notice Kr aligns with left side of the surface dynamometer with anchored tubing and Kt aligns with the expansion portion of the pump card having unanchored tubing.

In a vertical well the pump applies the fluid load at the bottom of the rod string, and the increasing pump load results in the rod string elastically stretching in response to the applied load. A rod string in a well consists of one or more diameters, with the largest diameter rods typically located at the top of the rod string. The top rod diameter is large enough to elastically stretch to support the weight of all of the rods connecting from the surface to the pump; plus supports the pump loads applied at the bottom of the rod string. The diameter of the rod string decreases at depth as the weight of the rod string decreases, creating a tapered rod string. A normal design of a tapered rod string results in the maximum stresses being equal at the top rod of each of the different-sized sections of the tapered rod string. Stretch of the rod string occurs due to the fluid load being applied by the plunger to the bottom of the rod string during the upstroke. Rod unstretch occurs by the release or transfer of the fluid load from the rod string to the tubing during the down stroke. **Equation 1** defines the Coefficient of Rod Stretch, Kr, for a single rod of area A and is defined as the required load in pounds applied to the rod of length L to stretch the entire rod string equal to 1 inch.

$$K_r = AE/L \qquad \text{… Eq. 1}$$

Equation 2 defines the Coefficient of Rod Stretch, Kr, for a tapered rod of area A_1, A_2, A_3, … and applied to the rod of length L_1, L_2, L_3, …

$$K_r = 1 / (L_1/A_1/E_1 + L_2/A_2/E_2 + L_3/A_3/E_3 + \ldots) \qquad \text{… Eq. 2}$$

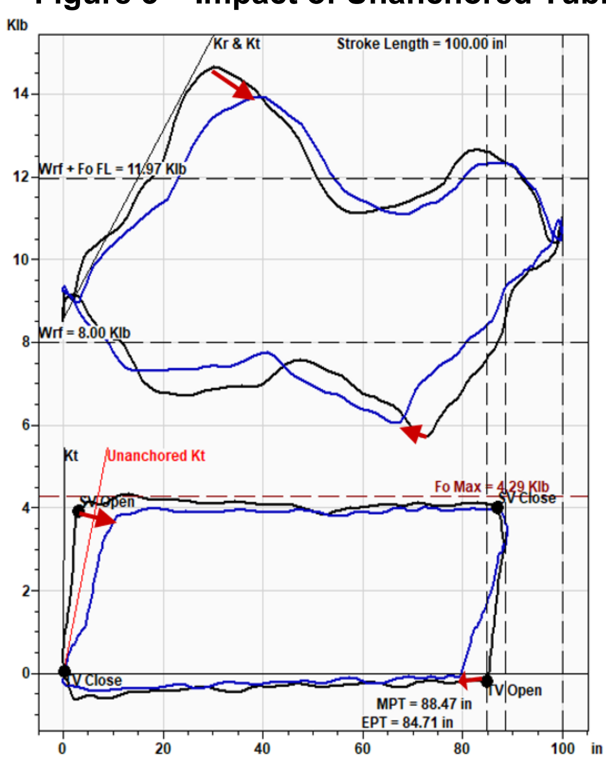
The tubing string is typically a constant diameter and if no anchor is installed or the if the anchor has become unset or if the anchor is set above the pump, then for the Lu, length of the unanchored section of tubing and for a constant diameter the Tubing String Spring constant, K_t, is defined by **Equation 3**:

$$K_t = AE/L_u \qquad \text{… Eq. 3}$$

In some unconventional wells having a liner below the kickoff point with the pump set below the kickoff, then two different sizes of tubing may be used. In the large diameter casing the larger tubing may be ran, then an anchor a short section of larger tubing, then a cross-over to smaller tubing that is ran to the pump. The unanchored length, Lu, is from the anchor set depth to the seating nipple, Lu_1 would be the large diameter below the anchor and L2 would be the length, Lu_2, from the cross-over down to the seating nipple. **Equation 4** defines the Tubing String Spring constant, K_t:

$$K_t = 1 / (Lu_1/A_1/E_1 + Lu_2/A_2/E_2 + \ldots) \qquad \text{… Eq. 4}$$

Figure 3 – Impact of Unanchored Tubing



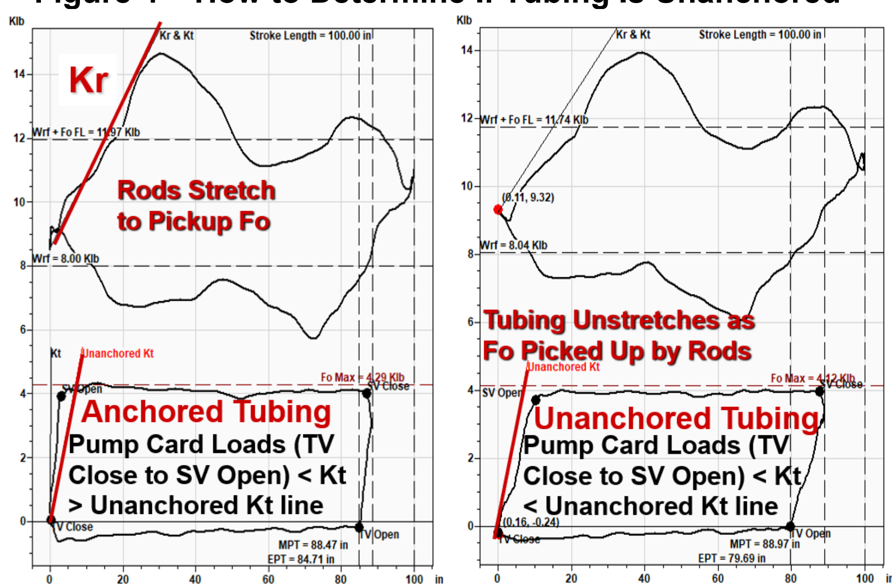
Impact of Unanchored Tubing on Dynamometer Analysis

When the tubing is unanchored, anchor becomes unset, or the tubing is partially anchored, then during the expansion portion of the pumping cycle (TV Close to SV Open) the tubing unstretches as the fluid load transfers off the Closed SV onto the Closed TV; resulting in the SV Opening. **Fig. 3** dynamometer data was acquired on a well having a pump depth of 5226 ft, approximate pump intake pressure of 200 Psig, and 8.3 SPM. The unanchored data shown in blue was acquired at 11:02:56AM on 01/24/2006. and the anchored data shown in black was acquired at 03:57:19PM on 03/24/2014. The K_t line is plotted on the left side of the pump card for both the anchored and unanchored tubing. The red arrow displays the impact of being unanchored for both the surface and pump card. Unanchored tubing results in the pump card leaning more to the right, past Unanchored Kt and the tubing movement causes less pump displacement (EPT, Effective Plunger Travel is reduced). The Peak Polished Rod Load is decreased and minimum Polished Rod load increases; resulting in reduced stress range (potentially longer rod life). Usually within a short time period tubing movement due to unanchored tubing increases rod-on-tubing wear (increases rod and tubing failures).

Determine if Tubing is Anchored or Unanchored (Simple Method)

Fig. 4 displays a simple method that can usually be applied to determine if the tubing is anchored or unanchored. Plotting the tubing stretch line, Kt, and the completely Unanchored Kt line on the left side of the pump card provided two reference lines to compare the (TV Close to SV Open) pump card loads over the expansion portion of the pump cycle. If the tubing is **Anchored** and set, then the pump card loads from TV Close to SV Open should plot to the right of the Kt line, but the pump card loads from TV Close to SV Open should plot to the left of the Unanchored Kt line. If the tubing is **UnAnchored**, NOT set, or slipping then the pump card loads from TV Close to SV Open should plot to the right of the Kt line and to the right of the Kt Unanchored line. The plunger moves relative to the tubing as the fluid slips between the barrel due to decreasing chamber pressure created due to the expanding volume of the pump chamber as the fluid load gets picked up by the rod stretch, pump slippage increases as the differential pressure acting across the plunger increases.

Figure 4 – How to Determine If Tubing Is Unanchored



Pump Slippage

In the SWPSC 2007 paper[2] the following empirical **Eq. 5** was presented as being the best predictive tool for rod pump slippage. General observations determined by examining the slippage equation are 1) slippage volume increases as SPM increases, 2) slippage increases exponentially as clearance increases, 3) slippage increases as plunger diameter increases, 4) slippage increases as the differential pressure across the plunger increases, 5) slippage decreases as the plunger length increases, 6) slippage decreases as the fluid viscosity increases. The expansion portion of the pump card tends to lean more to the right as slippage increases.

$$Slippage = [(0.14 \cdot SPM) + 1]453 \frac{DPC^{1.52}}{L\mu} \qquad \textbf{Eq. 5}$$

SWPSC 2012 paper[3] recommended that Pump Clearances should be specified by the operator to the pump shop. Total barrels per day of pump slippage increases with increasing pump speed. Pump displacement increases faster than pump slippage resulting in greater pump efficiency with increasing speed. Proper selection of pump clearances is important in sucker rod pump design. Pump slippage may be excessive for large clearance pumps when pumping from deeper depths with high temperatures. System efficiency can be significantly reduced at slow SPMs with "large" pump clearance. The Patterson slippage equation should be used to design pump clearances, using the procedure is much better than using a Rule-of-Thumb table recommended in the 2007 paper. The Patterson equation is available in QRod[4] and TAM[1] to calculate the pump slippage volume and should be used to determine impact of slippage on pump efficiency and pump production, but Patterson Slippage calculates total slippage for a selected stroke. To determine the slippage and corresponding pump displacement the slippage for one stroke needs to be allocated to the individual segments of the pump cycle where the traveling valve ball is on the seat.

Allocation of Pump Slippage to Expansion Portion of Pump Cycle

Reference 5 discusses super-imposing Couette(moving) and Poiseuille (pressure) flows through the pump clearance to generate the composite slippage velocity profile. The two types of leakage that apply to the Sucker Rod Pump, Couette flow and Poiseuille Flow. Poiseuille flow occurs when there is a difference of pressure on two ends of a pipe, the flow is greatest in the middle, or at the maximum distance away from all sides of the pipe. Couette flow occurs when there is liquid between two surfaces, and one of the surfaces is moving, i.e. the plunger. The highest velocity, or most liquid movement takes place adjacent to the moving surface and in the direction of the motion. These two flows need to be added together in order to determine the total maximum leakage flow [5]. The pressure difference across the plunger drives fluid from the high pressure area, on top of the plunger to the low pressure area, which is below the plunger and inside the pump chamber, this leakage is modeled by Poiseuille flow. Couette flow is a steady-state, incompressible, one-dimensional flow of viscous fluid through two horizontal parallel plates. In a sucker rod pump, Couette flow occurs due to plunger motion. The Couette flow is caused by the movement of the plunger at a known velocity of the plunger calculated by the wave equation. The Couette flow occurs closest to the moving plunger, as the fluid is dragged through the system. In the sucker rod pump, this flow type is a result of the upward drag of fluid during the upward stroke.

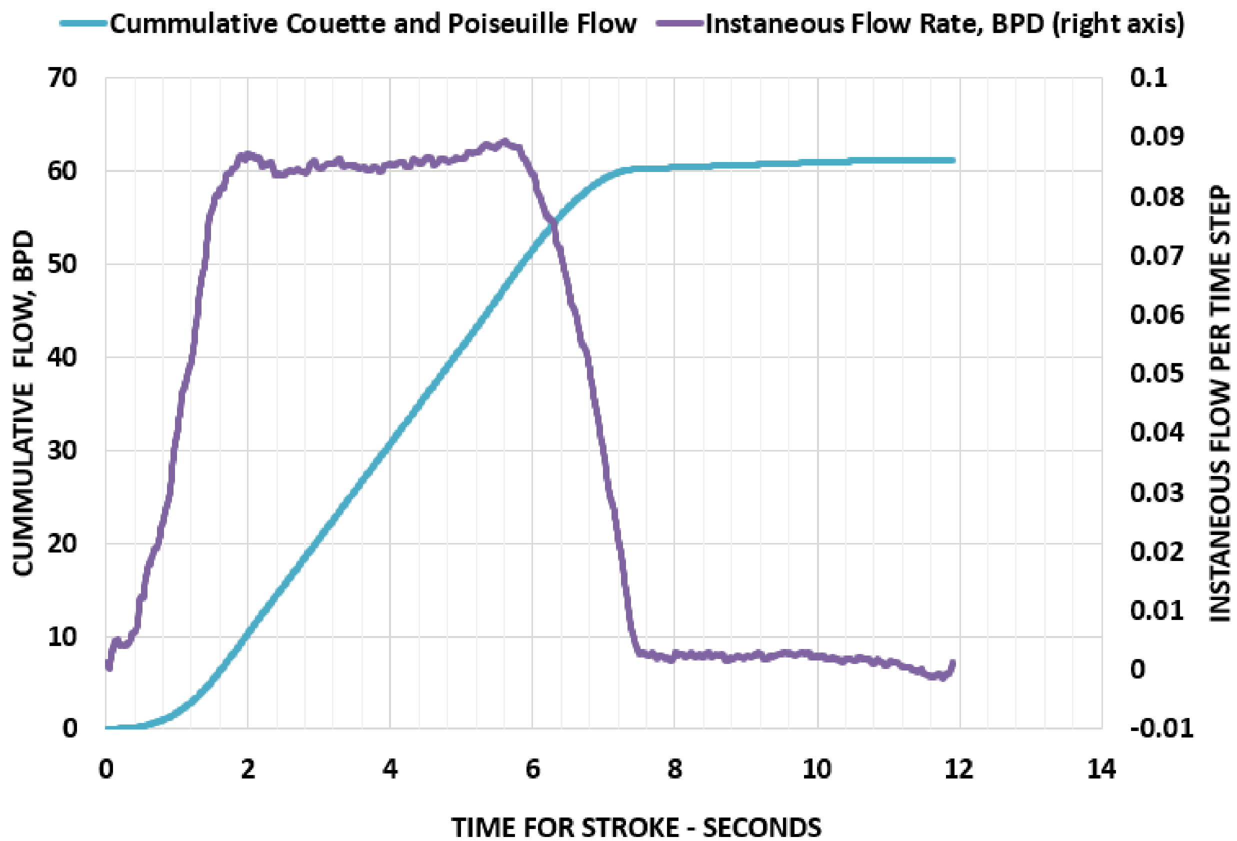
Couette Flow $$Q_c = (\pi V D_i \delta)/2$$ **Eq. 6**

Poiseuille Flow $$Q_p = \frac{\pi(p_A - p_B)}{12\mu L} D_i \delta^3$$ **Eq.7**

where μ is the dynamic viscosity of the hydraulic fluid, p_A and p_B stand for the pressures at both ends of the plunger, and δ is the gap between the outer diameter of the plunger Di and the inner diameter of the barrel D_o, denoted as (D_o -Di)/2.

The calculated Couette Flow and Poiseuille Flow for the entire stroke shown in Figure 1 for Stroke #18's Pump Card is shown in the **Fig. 5** below:

Figure 5 – Cumulative and Instantaneous Couette + Poiseuille Flow

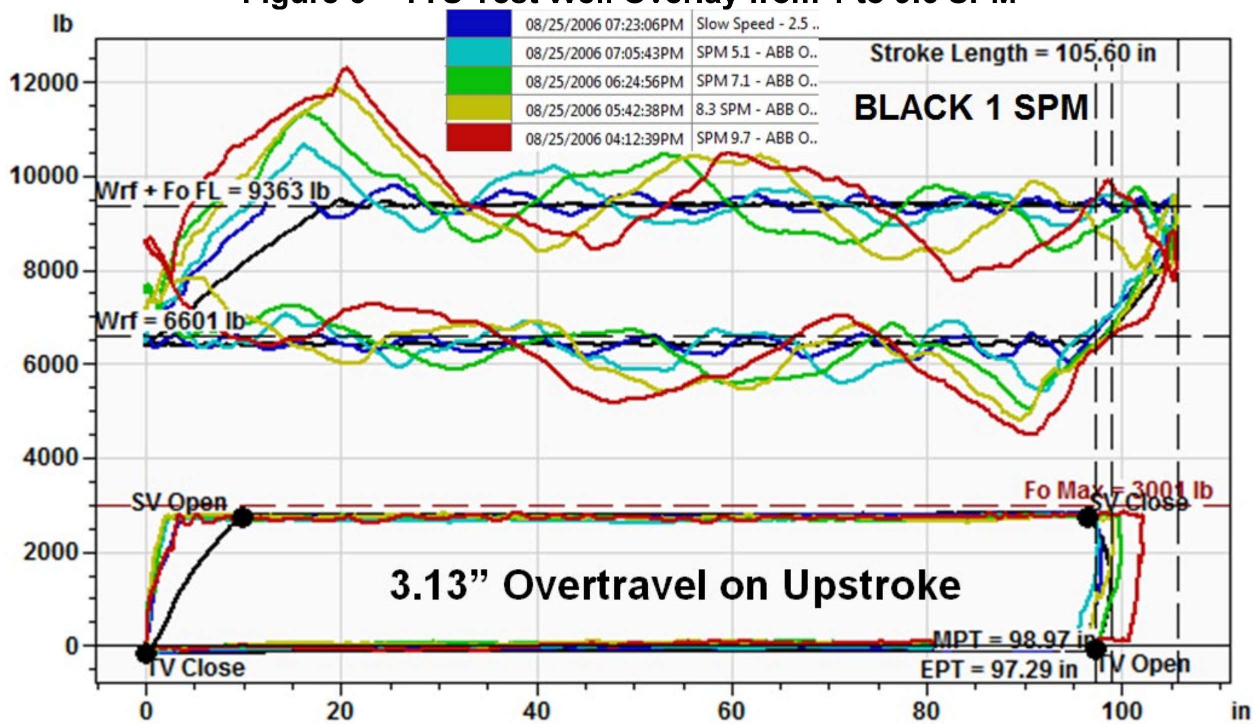


The above plot shows that Couette + Poiseuille Flow underestimates the slippage at the beginning of the upstroke and appears to be dominated by the differential pressure. The differential pressure is 0 at the beginning of the stroke and the pump card leaning to the right indicates slippage is occurring. If this technique were used to estimate the slippage at the beginning of the upstroke, then the slippage would be underestimated and allocation of the slippage from the Patterson slippage equation would not be reasonable..

Impact of SPM on Pump Slippage

All 6 dynamometer datasets data shown in **Fig. 6** were acquired at the same conditions on 08/25/2006 at the TTU Test Well (Stroke length:105.6", plunger diameter:1.5", pump clearance:0.005", API Rod String #: 76, and pump Intake pressure constant at 135 psi). The pumping speed for each surface and pump card was changed in discrete steps to 1, 2.5, 5.1, 7.1, 8.3, and 9.7 SPM. Notice that the fastest pumping speed of 9.7 SPM (red pump card) appears to show that the tubing is anchored, while at the slowest pumping speed of 1 SPM (black pump card) appears to show based on the left side of the pump card that the tubing is unanchored. The pump card shape is completely due to the decrease in efficiency of the seal between the plunger and the barrel decreases as the SPM slows and slippage increases.

Figure 6 – TTU Test Well Overlay from 1 to 9.6 SPM



Set the Tubing Anchor Tension

The original work done on setting tubing anchor tension in sucker rod in pumping wells, its effects and means for controlling was presented by Arthur Lubinski of the Pan American Petroleum (then AMOCO, now OXY). Lubinski deduced that a column of steel (tubing, sucker rods, etc.) must be subjected to some compression in order to buckle; and also, that a structural member does not buckle if subjected to a tension. Lubinski also found that the buckling phenomenon is affected by inside or outside pressure [6]. In some cases, Lubinski found that when a column is subjected to more pressure inside than outside, a pipe may buckle under tension. In other cases, a pipe may remain straight, although subjected to a very large compression. The method of Lubinski accounts for tubing effects due to: 1) force due to fluid transfer from tubing to rods, 2) thermal expansion due to heat transfer from produced fluids, 3) change in fluid level from static to working levels in the annulus, and 4) casing pressure force. The first two items tend to elongate the tubing, while the latter two tend to contract the tubing. Although there are many parameters affecting tubing stretch calculations, the tendency is to "guess" at the effects due to temperature. Lubinski used 0.5 of the delta surface temperature, since the producing temperature profile in the tubing is somewhat parabolic, then using a 0.54 or higher factor is recommended to determine the tubing thermal expansion. Note that tubing tension should always be applied in inches [Inches] of stretch rather than in pounds of pull because of probable mechanical friction between the tubing and the casing, and possible inaccuracy of the pulling unit weight indicator. Consider running a hydraulic tubing anchor, because as the tubing stretches longer due to loading or increased temperature profile the hydraulic anchor will set at the deepest depth of tubing elongation.

Conclusion

This paper discusses a method to use the pump card shape to identify if the tubing is unanchored or if the anchor is not set. A simple method to identify if the tubing is unanchored can be seen when the expansion portion of the pump card is plotting to the right of the Unanchored Kt line. Slippage is shown in the pump card plotting to the left of the Unanchored Kt line and to the right of the KT line. Slippage from a leaky "pump", open clearance, and/or slow SPM can appear to be unanchored tubing, but the right lean of the left side of the pump card is often just slippage. Use QRod[4] (free predictive design program) to calculate Patterson slippage to determine the amount of pump slippage. Traveling Valve Load Test may not show slippage and can be misleading when Pump is not filled due to being pumped off, then NO TV Valve Test Load Change will occur until sufficient time passes for slippage into the pump chamber to increase the chamber pressure and create incompressible condition so that pump slippage can be seen. When setting Tubing Anchor tension always measure the pull in inches, NOT by reding pounds on a load indicator.

Steps to Determine if Tubing is Unanchored

1. Look at the left side of Pump Card Load expansion segment of pumping cycle, where fluid load is being picked up (pump load transfers to Closed TV lowering chamber pressure below intake pressure to open SV). Tubing is Anchored if (SV Close-TV Open) line to right of Kt but to the left of Unanchored Kt line.
2. If Kt is not plotted on your pump card by your diagnostic wave equation software, then use QRod to determine Kt and compare left side of your pump card to QRod Kt.
3. Tubing is "likely" Unanchored when Pump Card leans to the right of Unanchored Kt line.
4. Perform Traveling Valve Load Test: To identify large issue is a leaky pump with high TV leakage rate shown by the Polished Rod load dropping quickly after rods are stopped on upstroke.
5. Understand that excessive slippage from slow SPM, deep well with low PIP and open pump clearance can cause a Pump Card to Look Unanchored.

References

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Nomenclature:

Fo - Fluid load applied to Rods by plunger - Lbs
S - Surface Stroke Length - Inch
Kr - Rod String Spring Constant – Lbs/In
Kt - Tubing String Spring Constant – Lbs/In
A – Area of a Sucker Rod
E – Modulus of Elasticity
L – Length of a rod string segment
SV – Standing Valve
TV – Traveling Valve
D = nominal diameter, inches
C = diametrical clearance, inches
P = Pressure drop across the plunger, psi
L = length of the plunger, inches for Patterson, feet for the theoretical approach
SL = stroke length, inches
SPM = strokes per minute
U = pump velocity, ft/sec = SL SPM/360
μ=viscosity of fluids, cp