USE OF THE PUMP SLIPPAGE EQUATION TO DESIGN PUMP CLEARANCES

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Abstract

Test data collected from the TTU test well plus field data will be used to show the impact of pump clearance and pumping speed on pump slippage. Pump slippage significantly increases with increased well depth due to high temperature reducing water viscosity and increased differential pressure acting across the plunger. Specifying plunger length and other recommended practices will be discussed. A procedure to design the pump clearances based on sensitivity of the various correlating parameters will be presented.

The Patterson Pump Slippage equation is discussed and a totally theoretically equation is shown to give similar slippage results which only adds to the credibility of the method. Pump efficiency can dramatically decreases at slow pumping speed when pump clearances are large. Additional energy must be input to the sucker rod pumping system to re-pump the portion of the pump's displacement lost to slippage. Even with the equations and guidelines available, the operator frequently uses too large of pump clearances for the well conditions and the reason for the low resulting production rate can be difficult to identify. Use of open or tight pump clearances should be based on well conditions. For large clearance pumps the efficiency decreases as the pumping speed is decreases plus the efficiency decreases when pumping from deeper depths.

Introduction

Pump slippage is the liquid that slips between the plunger outside diameter and the pump barrel inside diameter into the pump chamber between the standing valve and traveling valve when the traveling ball is on seat. A slippage formula called the Patterson equation is available to calculate the slippage volume and used to determine impact of slippage on pump efficiency and pump production. 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. If well configuration and well conditions are ignored in the selecting of pump clearances, then slippage rates may be larger than expected and pump efficiencies may be too low.

Texas Tech University, along with about a dozen companies, both operators and service companies, developed and funded a slippage field test which was performed at the Texas Tech test well facility, Red Raider # 1. See **Table 1** which contains a summary of the Slippage testing done by Echometer in 2005 and 2006, this is a subset of the original data presented at the SWPSC 2007[1] , these tests were conducted over a range of pumping speeds in order to evaluate the effects pumping speed and pump diameter and plunger clearances. In the first test at Texas Tech, a 2 inch pump with a 0.009 inch clearance and a 76 string consisting of 1468 ft of 7/8, 2000 ft of 3/4, and 400 of 7/8 rods was run at various speeds. In the second test at Texas Tech, a 2 inch pump with a 0.009 inch clearance and an 88 string consisting of 3852 ft 1 inch rods was run at various speeds. In the third test at Texas Tech, a 1.5 inch pump with a 0.005 inch clearance and a 76 string consisting of 1950 ft of 7/8 and 2002 ft of 3/4rods was run at various speeds. By combining all sets of test data, it was possible to develop an empirical equation that combines the effect of both pump clearance and pumping speed.

The equation for one theoretical approach to calculation pump slip is listed below:

$$\begin{aligned}\mathrm{BPD,\,slip} &= .11655\,\mathrm{SL\,SPM\,D\,C} + 83745\,\mathrm{D\,C}^3 DP/L\mu \\ &= 41.96\,\mathrm{U\,D\,C} + 83745\,\mathrm{D\,C}^3 DP/L\mu\end{aligned}$$

The above equation shows slippage varies with the clearance to the third power. For other historical approaches to the slippage problem, see references mentioned and discussed in the references 2 and 3 in the References cited below. There one historical slippage equation has the slippage varying by C $^{3.3}$ and another has the slippage varying by C $^{1.9}(do^2\text{-}di^2)$ See the Appendix for a detailed discussion and definition of terms to the simple Theoretical approach presented here for pump slippage. As will be seen below the new approach shows less leakage at the higher clearances with a smaller exponent developed for the C or clearance term.

What Has Been Published Previously Concerning Pump Slippage

In the SWPSC 2007 paper[1] the following empirical equation was presented as being the best predictive tool for rod pump slippage. By unanimous consent of all test participants, it is agreed that **Eq. 1** should henceforth be referred to as the "Patterson Equation" in honor of John C. Patterson who has spearheaded the effort since the inception of slippage research beginning in 1996.

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

Based on the Patterson Slippage Equation and previous work, the following minimum pump clearances were recommended in the 2007 paper[1] for a 48" plunger with a "+1 Barrel". These clearances have become widely used in the Permian Basin for well depths up to 8000 feet.

- 1.25" pump = -3 to -4 plunger (0.004" to 0.005" total clearance)
- 1.50" pump = -4 to -5 plunger (0.005" to 0.006" total clearance)
- 1.75" pump = -5 to -6 plunger (0.006" to 0.007" total clearance)
- 2.00" pump = -6 to -7 plunger (0.007" to 0.008" total clearance)

When Does Pump Slippage Occur

Sucker rod pumps typically consist of a plunger/traveling valve assembly connected to the rod string and barrel/standing valve assembly attached to the tubing. The traveling valve is considered to be the discharge valve and moves with the rod string. The closed traveling valve acts as a check valve to keep well fluid in the tubing on the upstroke. Standing valve acts as the intake valve, fixed to tubing, and acts as a check valve to keep well fluid in the tubing on the downstroke. The outside diameter of the plunger is less than the inside diameter of the barrel. This difference in diameter is called pump clearance and is usually expressed in thousands of an inch. When the traveling valve is open the fluid in the pump barrel is displaced into the tubing by the plunger moving into the pump barrel on the downstroke. **Figure 1** is a pump card representing the load the pump applies to the rod string. On the pump card the standing valve is closed from C-D, D-A, and A-B; and the standing valve is only open from B-C. Before the beginning of the upstroke the pressure from the tubing fluid is applied to the closed standing valve and the traveling valve is open as fluid is displaced from inside the pump into the tubing (D-A). At the start of the upstroke, A, the traveling valve and standing valve are both closed and the pressures above and below the plunger are equal. During the upstroke (A-B-C-D) the fluid load applied to the rod string is due to differential pressure acting on the plunger and is equal to the pump discharge pressure minus the pump intake pressure times the area of the pump plunger. The fluid load is gradually transferred from the tubing (A-B) as the rods stretch to pick up the fluid load. The standing valve begins to open at B when the pressure in the pump drops below the pump intake pressure, allowing fluid to enter the pump chamber. From point B to C, the rods carry the fluid load while well fluids are drawn into the pump. At C, the standing valve closes, and the traveling valve remains closed until the pressure inside the pump is slightly greater than the pump discharge pressure. From C to D, gas in the pump (if present) is compressed as the plunger moves down to increase pressure on the fluid from the intake pressure to the static pressure in the tubing. As the fluid in the pump barrel is compressed, then the fluid load is gradually transferred from the rods to the tubing. At D, the pump barrel pressure equals the static tubing pressure, and the traveling valve opens.

Pump slippage can only occur when the traveling ball is on the seat during the stroke from A-B and B-C and C-D. Slippage through the pump clearances can only occur when the traveling valve ball is on the seat and differential pressure is acting across the plunger. Slippage is the liquid that slips between the plunger outside diameter and the pump barrel inside diameter into the pump chamber between the standing valve and traveling valve when the traveling ball is on the seat. Normally for a well that produces water, the liquid that slips back into the pump is usually water because the lighter oil and gas slip away from the top of the plunger on the up stroke and only the heavier water tends to remain on the top of the plunger. Liquid slippage into the pump barrel on the upstroke fills a portion of the pump chamber with liquids from the tubing and results in less well fluids entering the pump chamber, so the result is reduced pump displacement.

Results from Prior Slippage Test

Fig. 2 plots the pump slippage volume in BPD as a function of increasing pumping speed, SPM. **Fig. 2** shows for all clearances and plunger diameters tested that the volume of slippage increases as the SPM increases. Pump faster and more BBLS are leaked due to slippage. As the pumping speed, SPM, increases, then the slippage volume increases because more strokes per day results in more slippage volume. **Fig. 3** plots pump efficiency as a function of increasing speed, SPM. **Fig. 3** shows for all clearances and plunger diameters tested that the efficiency of the pump increases as the SPM increases. Pump faster and less BBLS are leaked through the clearances when compared to total pump displacement. With increasing pumping speed the pump displacement increases faster than pump slippage resulting in greater pump efficiency with increasing speed. As the pumping speed increases then the corresponding pump efficiency increases, because the slippage volume is a smaller fraction of the pump displacement.

What is a Reasonable Amount of Pump Slippage

The normal recommended amount of pump slippage is from 2 to 5 percent of a sucker rod pump's displacement. For the purposes of lubrication 2 to 5 percent slippage of the pump's down hole displacement is considered to be sufficient. It is recognized that if the rate is low (small pump for instance) and the percent slippage is high, it is possible to increase SPM to account for slippage but for larger rates and larger pumps, extra SPM creates significant extra loads and loss of energy. **Fig. 4** displays the surface and pump dynamometer cards for stroke number 6 which was acquired on 07/28/2005 15:10:46 at the Texas Tech test well during slippage testing. Some parameters about the well are the surface stroke length is 105.6 inches, plunger diameter is 2 inches, pump clearance is 0.009 inch, 1" diameter steel sucker rod string, and the pump slippage during this stroke was determined to be 63 BPD. During this test at 8.22 SPM 63 BPD slippage was measured, which is equal to 17 percent of the 372.6 BPD down hole pump displacement. The Patterson Slippage equation calculates 64.3 BPD slippage for the same conditions with an acoustically determined pump intake pressure of 149.9 psig and a 0.76 water viscosity. Pump Slippage % is defined as the percentage of slippage in BPD compared to the total pump displacement BPD and is shown in **Eq. 2**.

$$PumpSlippage\% = \frac{SlippageRate}{PumpDisplacment} \times 100 \qquad \textbf{Eq. 2}$$

Table 2 – Slippage % of 372.6 BPD

Patterson Equation Pump Slippage % vs Clearance @ SPM = 8.22						
	Plunger Diameter - Inches					
Clearance	1.25	1.50	1.75	2.00	2.25	2.75
0.003	2.0	2.4	2.9	3.3	3.7	4.5
0.004	3.2	3.8	4.4	5.0	5.7	6.9
0.005	4.4	5.3	6.2	7.1	8.0	9.7
0.006	5.8	7.0	8.2	9.3	10.5	12.9
0.007	7.4	8.9	10.3	11.8	13.3	16.2
0.008	9.0	10.9	12.7	14.5	16.3	19.9
0.009	10.8	13.0	15.1	17.3	19.5	23.8
0.010	12.7	15.2	17.8	20.3	22.9	27.9
0.011	14.7	17.6	20.5	23.5	26.4	32.3
0.012	16.8	20.1	23.5	26.8	30.2	36.9

Table 2 was calculated using the Patterson Slippage equation using the well parameter for **Fig. 4** and shows percentage of pump displacement lost to slippage due to clearances for various size plungers. The 17.3 percent slippage as measured during the slippage testing should be considered excessive and this large volume of slippage is primarily due to the 0.009 inch plunger/barrel clearances. For this well's specific operating conditions the 2 inch diameter plunger would require a pump clearance of 0.004 inch, highlighted in red, if 5% slippage is needed for plunger/barrel lubrication. The proper technique to specify plunger/barrel clearance would be to calculate the gross downhole pump displacement without slippage and select the plunger/barrel clearance which would calculate a pump slippage volume less than or equal to 5% of the gross pump displacement.

Table 3 – Pump Efficiency and Slippage % as Function of SPM

Anchored Tubing - 105.6 Inch Stroke - 1 Inch Rods - Clearance - 0.009								
	Plunger Diameter - Inches							
	1.50	1.50	1.50	1.50	2.00	2.00	2.00	2.00
SPM	Calc Pump BPD	Slippage BPD	Slippage %	Pump Eff %	Calc Pump BPD	Slippage BPD	Slippage %	Pump Eff %
6.22	165.0	42.0	25.4	74.6	283.0	56.0	19.8	80.2
6.72	180.0	43.5	24.2	75.8	309.0	58.0	18.8	81.2
7.22	195.0	45.1	23.1	76.9	331.0	60.1	18.2	81.8
7.72	208.0	46.7	22.4	77.6	352.0	62.2	17.7	82.3
8.22	220.0	48.2	21.9	78.1	378.0	64.3	17.0	83.0
8.72	235.0	49.8	21.2	78.8	407.0	66.4	16.3	83.7
9.22	252.0	51.4	20.4	79.6	436.0	68.5	15.7	84.3
9.72	269.0	53.0	19.7	80.3	462.0	70.6	15.3	84.7
10.22	283.0	54.5	19.3	80.7	483.0	72.7	15.1	84.9
10.72	295.0	56.1	19.0	81.0	495.0	74.8	15.1	84.9

Using the parameter for the well shown in **Fig. 4, Table 3** was calculated for a range of SPM from 6.22 to 10.72 in 0.5 SPM steps: 1) using the Patterson Slippage equation to calculate slippage BPD, 2) using the simple predictive program QRod[5] to calculate pump displacement, BPD, assuming 100% liquid fillage, 3) calculated Slippage % equal to the ratio of slippage divided by pump displacement and 4) calculated Pump Efficiency % equal to 100% minus Slippage %. Pump Efficiency % is defined by **Eq. 3**.

$$PumpEfficiency\% = \frac{SurfaceRate}{PumpDisplacment} \times 100 \qquad \textbf{Eq. 4}$$

Table 4 shows slippage percentage gets less (pump leaks less) as the pumping speed, SPM, is increased. When a pump is worn out and the production rate from the well has dropped off and the pump needs to be pulled and replaced with new; then increasing the pumping speed of a leaky worn pump will increase pump efficiency and likely increase liquid produced to the surface. The operator should recognize that pump efficiency increases with increased SPM. Although increasing the pumping speed from 6.22 SPM by 4.5 SPM to 10.72 SPM reduces pump slippage by only 5-6% and may result is a temporary increase in the production rate, the higher pumping speed can also result in increased failures and the temporary increase in oil production make not pay off any damage caused by a failure due to pumping too fast.

For the same pump clearance, 0.009 inch, **Table 3** shows there is less total liquid BPD slippage for a smaller 1.5 inch plunger diameter when compared to a larger 2.0 inch plunger diameter. But, it is important to note that the pump displacement increases by the square of the plunger diameter, while slippage volume increase is directly proportional to the plunger diameter. So at the same SPM the larger 2.0 inch diameter plunger diameter is approximately 5 % more efficient than the 1.5 inch diameter pump, but leaky a higher total slippage BPD volume.

Field Case Study

Fig. 5 shows the surface and pump card acquired on a Permian Basin oil well having a 2.25 inch plunger diameter with 0.009 inch clearances. The pump card is displaying a pump stroke filled with liquid with an effective pump stroke length of 103 inches (calculated from the measured surface dynamometer card). The calculated pump displacement for the selected is equal to 580 BPD (without correction for pump slippage or liquid swell due to gas in solution). The tested liquid production BPD rates of 106 BPD oil and 296 BPD water are equal to 178 BPD less than the 580 BPD pump displacement. Not much of this 178 BPD difference should be attributed to leakage from a worn or damaged pump, since this is a new pump installed a few weeks prior to acquiring the data. This pump's clearance between the 4 foot plunger and barrel are 0.009 inch and the Patterson Slippage Equation **Fig. 6** calculates 169.8 BPD slippage for this 2.25 inch diameter pump. The loss of 30% of the pump displacement was considered excessive by the operator.

51 MscfD of gas was produced from the well with 26 MscfD produced up the tubing and all gas appears to be in solution because the pump card does not show any gas interference. The fluid level shot shows a 911 ft gaseous fluid column above the pump intake. 25 MscfD of the produced gas flows to the surface up the casing annulus as calculated from the 0.9 psi casing pressure buildup rate over 2 minutes. This rate of pressure buildup means that the gaseous fluid column above the pump is equivalent to a 35% liquid liquid gradient and correcting for the annular gas flow rate the pump intake pressure is 151 psig. 26 MscfD is equal to a 245 GOR produced up the tubing, and assuming that all of the gas is in solution in the oil, then at the discharge pressure of 3155 psi based on PVT correlations the oil volume would be swelled 4.4% higher due to gas in solution. 4.4% of 106 BOD is equal to 5 BPD of additional oil volume due to swell of the oil due to gas in solution.

Actual stock tank production is 174 BPD less than the 576 BPD pump displacement, where ((106+296)/576) the pump efficiency is 70 % in a new pump installation. Most of the loss in efficiency can be attributed to slippage. The operator selected the pump clearance based on the table of recommended pump clearances that was published in 2007 SWPSC[1]. If the table is used to specify pump clearances without regard of well configuration and well conditions, then (as in this actual example) the pump efficiency can be too low due to excessive pump slippage.

Recommended Procedure to Select Pump Clearances

Fig. 7 shows a QRod wave equation analysis which predicts a pump displacement of 655 BPD for the Permian Basin oil well. **Fig. 8** is a plot of pump slippage versus various size pump clearances for the well conditions shown in **Fig. 6**. Examine Fig. 8 and select the pump clearance of 0.005" to achieve 90% pump efficiency with 65 BPD slippage, highlighted in red. Tighter pump clearances would be required if 5% slippage is allowed only for plunger/barrel lubrication. Following are the steps to select correct pump clearances:

1. Use predictive sucker rod design program to calculate pump displacement, assume 100% liquid pump fillage.
2. Input correct well parameters into "Pump Slippage Calculator_SPM_PattersonEq.XLS"[6], be sure to adjust water viscosity for the temperature at the pump
3. Examine "Plot Slippage Table" tab and select pump clearance that gives the desired percentage of pump slippage.

Summary and Conclusions

Pump Clearances should be specified by the operator to the pump shop. The above recommended "Procedure to Select Pump Clearances" should be followed or the pump that is ran in a well may be inefficient due to too open clearances and too much slippage. The Patterson equation is available to calculate the pump slippage volume and should be used to determine impact of slippage on pump efficiency and pump production. 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.

Nomenclature:

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

References:

1. John Patterson, Kyle Chambliss, Lynn Rowlan, Jim Curfew: "Progress Report #4 on "Fluid Slippage in Down-Hole Rod-Drawn Oil Well Pumps" ", SWPSC, Lubbock, Texas (2007)
2. Chambliss, R. Kyle: "Developing Plunger Slippage Equation for Rod-Drawn Oil Well Pumps," Dissertation, Texas Tech U., Lubbock, Texas (2005)
3. Chambliss, R. Kyle, James Christian Cox and James F. Lea: "Plunger Slippage for Rod-Drawn Plunger Pumps," Trans. of the American Society of Mechanical Engineers – J. of Energy Resources Technology (September 2004) vol. 126, 208-214.
4. Gibbs, S.G.: "Predicting the Behavior of Sucker-Rod Pumping Systems," JPT (July 1963) 769-778.
5. Pump Slippage Calculator_SPM_PattersonEq.XLS, contact info@echometer.com
6. QRod Design Program Download, http://www.echometer.com/software/qrod/index.html

APPENDIX I

Leakage through the Barrel-Plunger Interface on Upstroke

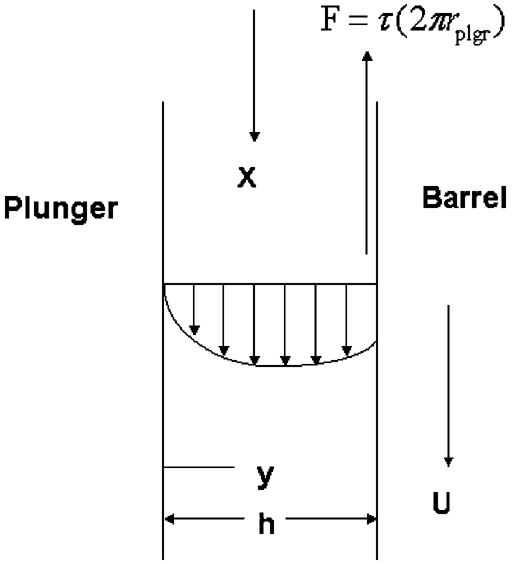
Schlichting 6th Edition, page 77, flow through two flat plates, top place moving at U to the right (or up) representing the plunger, top plate distance h from lower plate.

u = the local velocity at any y, ft/sec
U = the velocity of the top plate, ft/sec
h = the distance between plates, ft
x = the distance along streamline between plates, ft
μ = the viscosity of the fluid
μ = Viscosity, cp x .0000209 lbf-sec/ft^2
dp/dx = lbf/ft^3
τ = shear stress, lbf/ft^2

$$u = \frac{y}{h}U - \frac{h^2}{2\mu}(\frac{dp}{dx})\frac{y}{h}(1-\frac{y}{h})$$

$$\frac{du}{dy}@_{y=h} = \{\frac{U}{h} + \frac{h}{2\mu}(\frac{dp}{dx})\}$$

$$\tau_{y=h} = -\mu\frac{du}{dy} = -\mu[\frac{U}{h} + \frac{h}{2\mu}(\frac{dp}{dx})]$$



In the above figure, the drawing is relative to being on the Plunger. Then on the upstroke as the plunger moves upward, the barrel appears and is moving downward relative to the plunger as above. The leakage is relative to the plunger, or what passes beneath the plunger is leakage from above the plunger to below the plunger.

<u>Upstroke: Leakage Analysis:</u>

$$\bar{u} = \frac{\int_0^h u(dy)}{h} = \frac{\int_0^h \frac{y}{h}U - \frac{h^2}{2\mu}(\frac{dp}{dx})\frac{y}{h}(1-\frac{y}{h})dy}{h} = \frac{U}{2} - \frac{h^2}{12\mu}(\frac{dp}{dx}) \text{ , ft/sec}$$

$\bar{\text{u}}$ = average velocity through plunger – barrel interface, ft/sec

$\text{Aflow} = \pi(do^2 - di^2)/(144x4)$, ft^2

BPD, leakage (rate on upstroke) = $\bar{\text{u}}$ x Aflow x 24 x 3600 / 5.615

BPD ,leakage ≅ above / 2 to account for only upstroke

The pressure decreases in the direction of the positive U and X, so the pressure gradient is a negative value. Therefore the sign of the second term becomes a positive term when Δp/L is inserted below for dp/dx:

Final form of leakage formula:

$$\text{const} = \pi / (144 \text{ x } 8) \text{ x } 24 \text{ x } 3600 / 5.615 = 41.96$$

$$\bar{u} = \frac{U}{2} + \frac{h^2}{12\mu}(\frac{dp}{dx}) = \frac{U}{2} + \frac{144(\text{do}-\text{di})^2\Delta\text{p}}{144.\text{ x }12 \text{ x } .0000209 \text{ x } \mu \text{ x L}} = \frac{U}{2} + \frac{3991.67(do-di)^2\Delta p}{4\mu L} \text{ , ft/sec}$$

$$BPD, leakage = \text{Aflow x } \bar{\text{u}} = \text{const x } (do^2 - di^2)\{\frac{U}{2} + \frac{3991.67(do-di)^2\Delta p}{4\mu L}\}$$

$$\text{or : BPD, leakage} = 41.96 \text{ U D C } + 83745\text{D C}^3 \text{ P } /\{\mu/\text{L}\}$$

With U in ft/sec, D in inches, with C in inches and P in psi and L in ft and μ in cp :

First term above is for the leakage due to plunger movement and the second is for viscous leakage under pressure between the plunger and barrel.

Summary:

BPD, leakage = (41.96)UDC + (83745) DC^{3}P/μL

Where first term is due to plunger velocity and the second term is for the viscous leakage due to the pressure across the plunger-barrel interface.

Where:
U = velocity of plunger, up, ft/sec
D = diameter, in , (do + di)/2 = D
C = diameter clearance of barrel ID – plunger OD, in, C= (do-di)
P = pressure difference across pump, psi (Δp)
μ = viscosity of fluid, cp
L = length of plunger, ft
Replacing U by SL SPM/360 where SL is stroke length, inches gives:

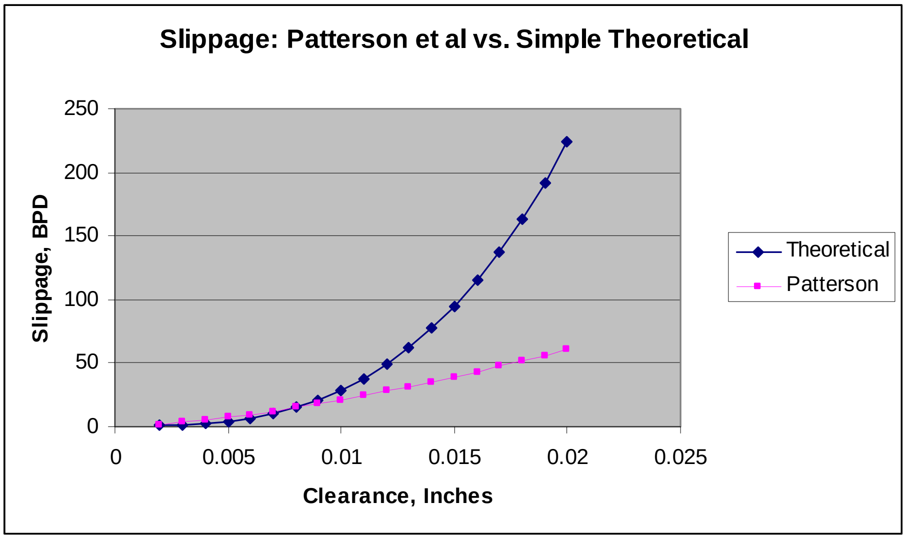
BPD, leakage = (0.11655)SL SPM DC + (83745) DC^{3}P/μL

The Patterson Equation, fit to test data, is as follows:

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

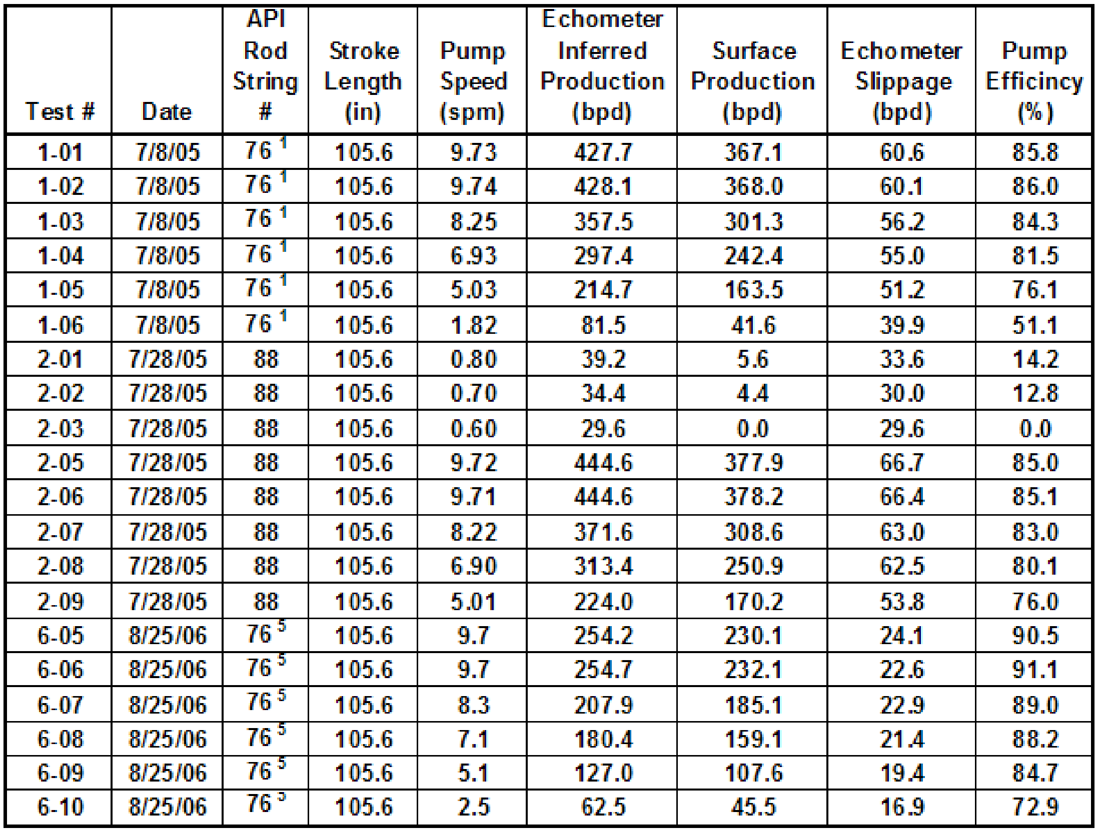
Leakage Example Calculations:

$D = 2.00$ inches
$C = .002, .006,$ and $.009$ inches
$\Delta p = P = 2000$ psi
$L = 4$ ft
$\mu = 3$ cp
$SL = 144$
$SPM = 6$
$U = 6\ 144 / 360 =$ 2.4 ft/sec average velocity



So the comparison is not exact but results are somewhat close at the lower clearances and both equations contain the same variables. The Patterson Equation fits test data and the Theory is not adjusted to any results. The biggest difference is that the new equation fit to data results show the clearance varying with an exponent of 1.52 and the theory predicts an exponent of 3 so at larger clearances the theoretical approach shows much bigger leakage rates.

Table 1 – Slippage Data – Originally Presented SWPSC 2007 Echometer Subset Only



Test #	Date	API Rod String #	Stroke Length (in)	Pump Speed (spm)	Echometer Inferred Production (bpd)	Surface Production (bpd)	Echometer Slippage (bpd)	Pump Efficincy (%)
1-01	7/8/05	76 [1]	105.6	9.73	427.7	367.1	60.6	85.8
1-02	7/8/05	76 [1]	105.6	9.74	428.1	368.0	60.1	86.0
1-03	7/8/05	76 [1]	105.6	8.25	357.5	301.3	56.2	84.3
1-04	7/8/05	76 [1]	105.6	6.93	297.4	242.4	55.0	81.5
1-05	7/8/05	76 [1]	105.6	5.03	214.7	163.5	51.2	76.1
1-06	7/8/05	76 [1]	105.6	1.82	81.5	41.6	39.9	51.1
2-01	7/28/05	88	105.6	0.80	39.2	5.6	33.6	14.2
2-02	7/28/05	88	105.6	0.70	34.4	4.4	30.0	12.8
2-03	7/28/05	88	105.6	0.60	29.6	0.0	29.6	0.0
2-05	7/28/05	88	105.6	9.72	444.6	377.9	66.7	85.0
2-06	7/28/05	88	105.6	9.71	444.6	378.2	66.4	85.1
2-07	7/28/05	88	105.6	8.22	371.6	308.6	63.0	83.0
2-08	7/28/05	88	105.6	6.90	313.4	250.9	62.5	80.1
2-09	7/28/05	88	105.6	5.01	224.0	170.2	53.8	76.0
6-05	8/25/06	76 [5]	105.6	9.7	254.2	230.1	24.1	90.5
6-06	8/25/06	76 [5]	105.6	9.7	254.7	232.1	22.6	91.1
6-07	8/25/06	76 [5]	105.6	8.3	207.9	185.1	22.9	89.0
6-08	8/25/06	76 [5]	105.6	7.1	180.4	159.1	21.4	88.2
6-09	8/25/06	76 [5]	105.6	5.1	127.0	107.6	19.4	84.7
6-10	8/25/06	76 [5]	105.6	2.5	62.5	45.5	16.9	72.9

Note:

- **2.00 in pump with a 0.009 in clearance and 4 ft plunger was used for tests 1 thru 5**
- **1.50 in pump with a 0.005 in clearance and 4 ft plunger was used for test 6**

1. 76 string has 1468 ft of 7/8, 2000 ft of 3/4, and 400 of 7/8 rods
5. 76 string has 1950 ft of 7/8 and 2002 ft of 3/4

Figure 1 – Typical Pump Card with Point ABCD Labels Showing Where Valves Open or Close

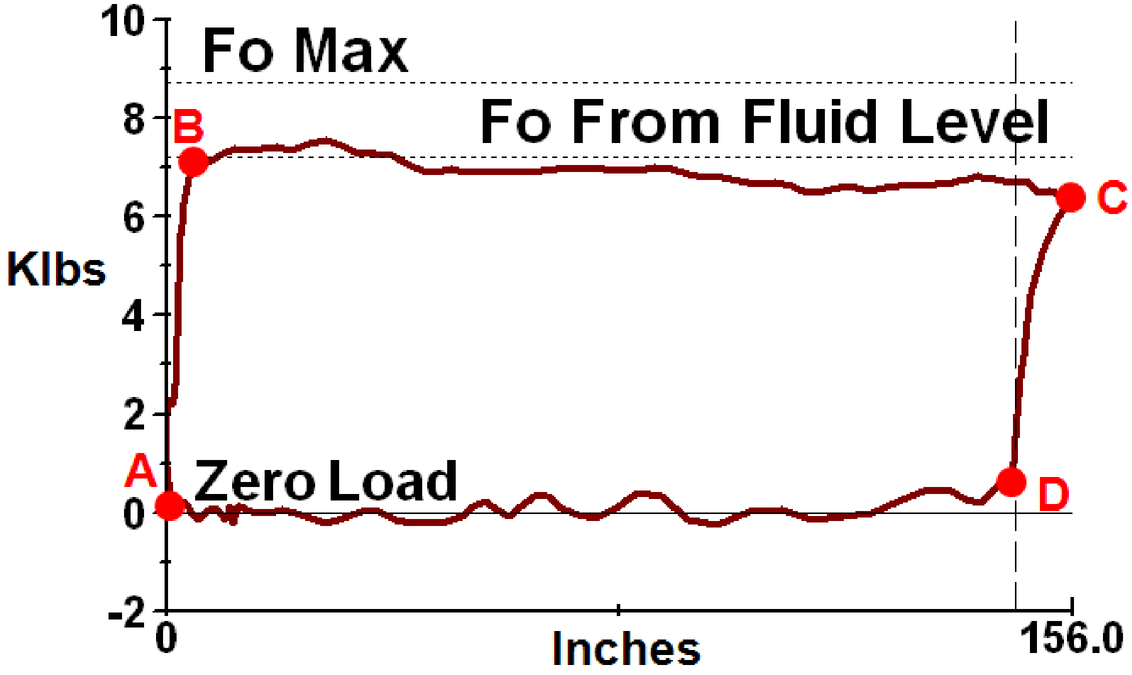


Figure 2 – Slippage BPD as Function of Increasing SPM

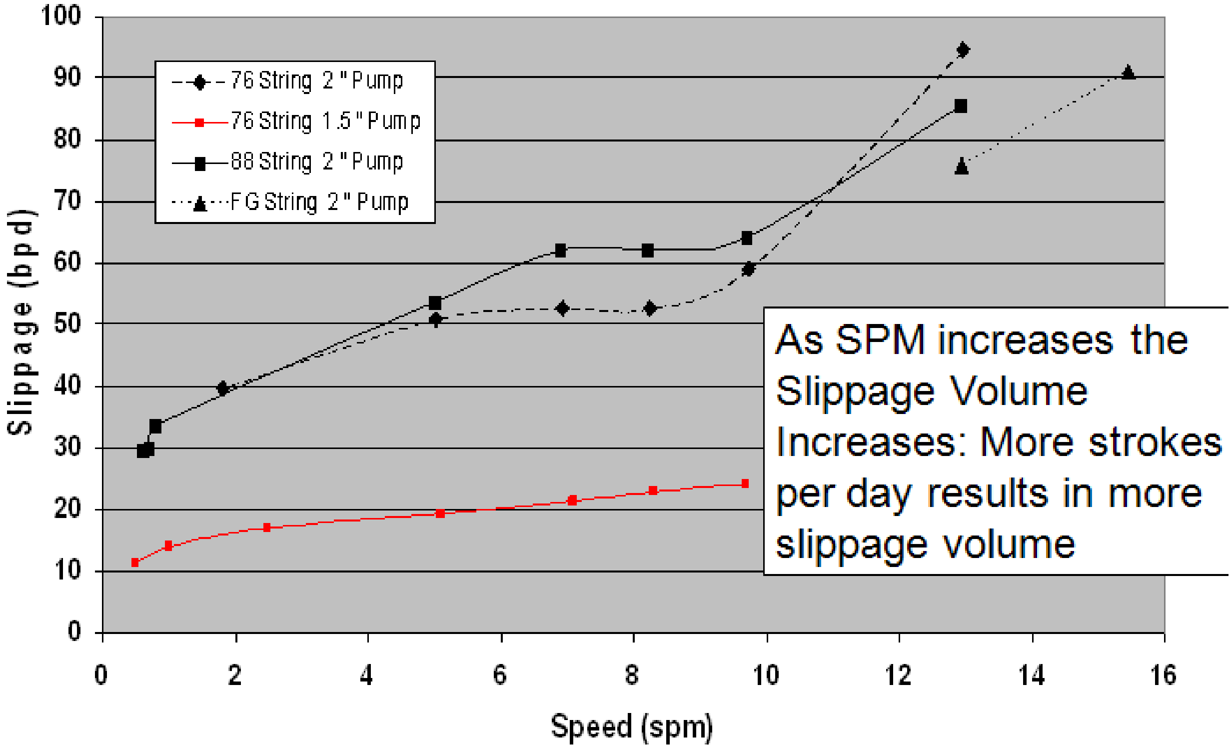
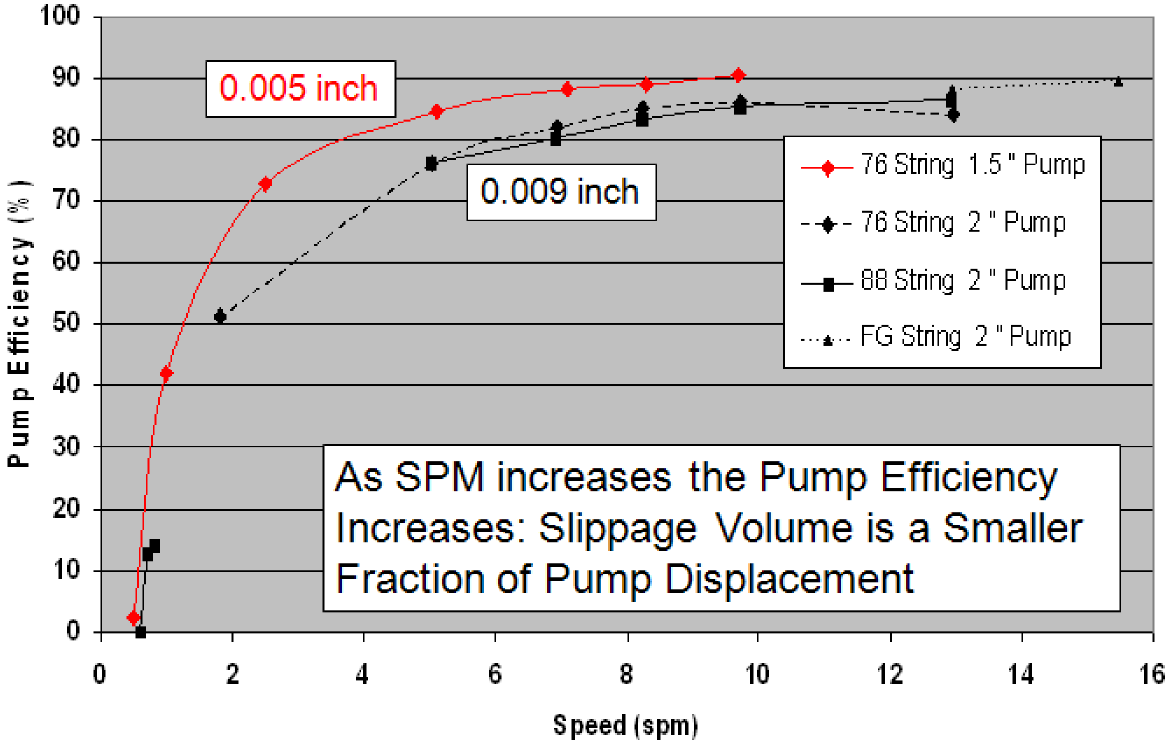
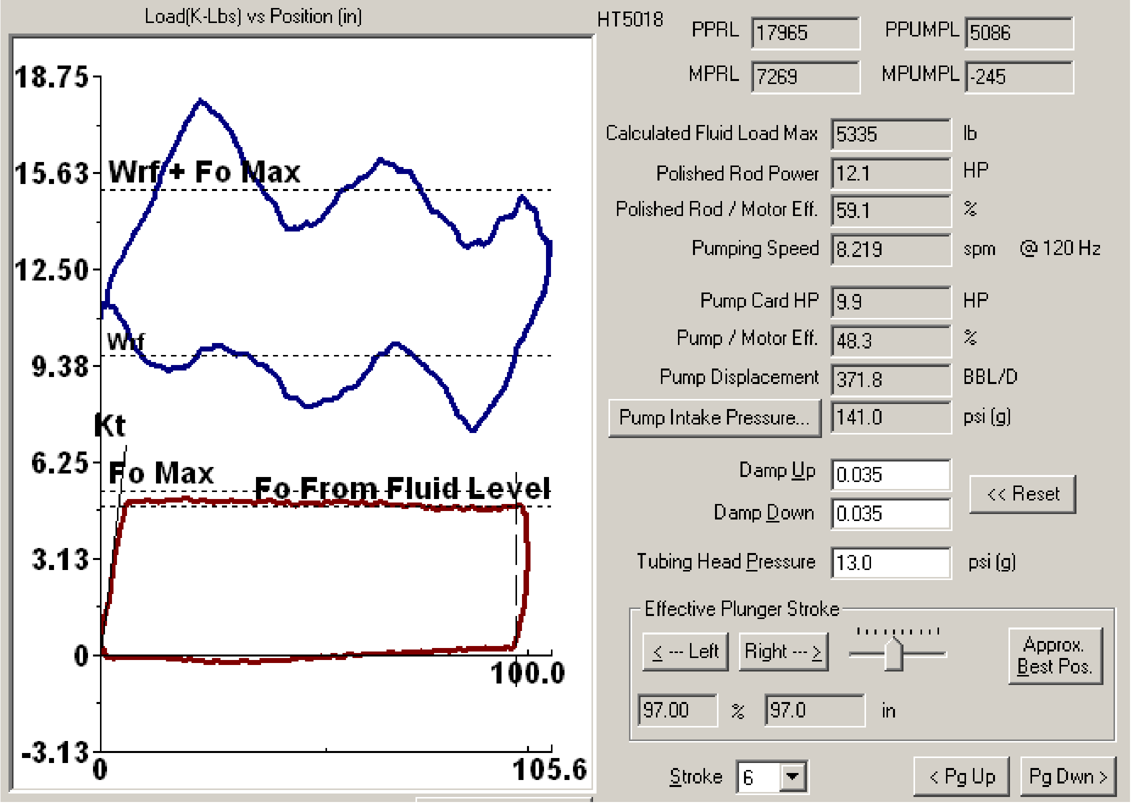


Figure 3 – Pump Efficiency as a function of Speed SPM



As SPM increases the Pump Efficiency Increases: Slippage Volume is a Smaller Fraction of Pump Displacement

Figure 4 – TTU Slippage Test 0.009 Clearance 1" Rod String 8.22 SPM



HT5018

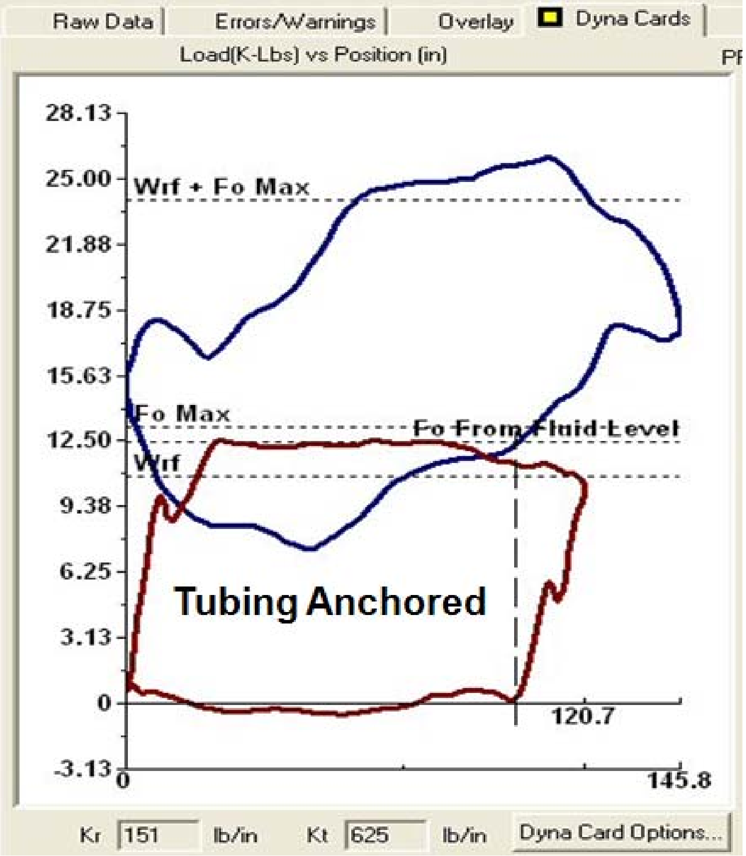
PPRL	17965	PPUMPL	5086
MPRL	7269	MPUMPL	-245

Calculated Fluid Load Max	5335	lb
Polished Rod Power	12.1	HP
Polished Rod / Motor Eff.	59.1	%
Pumping Speed	8.219	spm @ 120 Hz
Pump Card HP	9.9	HP
Pump / Motor Eff.	48.3	%
Pump Displacement	371.8	BBL/D
Pump Intake Pressure...	141.0	psi (g)
Damp Up	0.035	
Damp Down	0.035	
Tubing Head Pressure	13.0	psi (g)

Effective Plunger Stroke
97.00 % 97.0 in

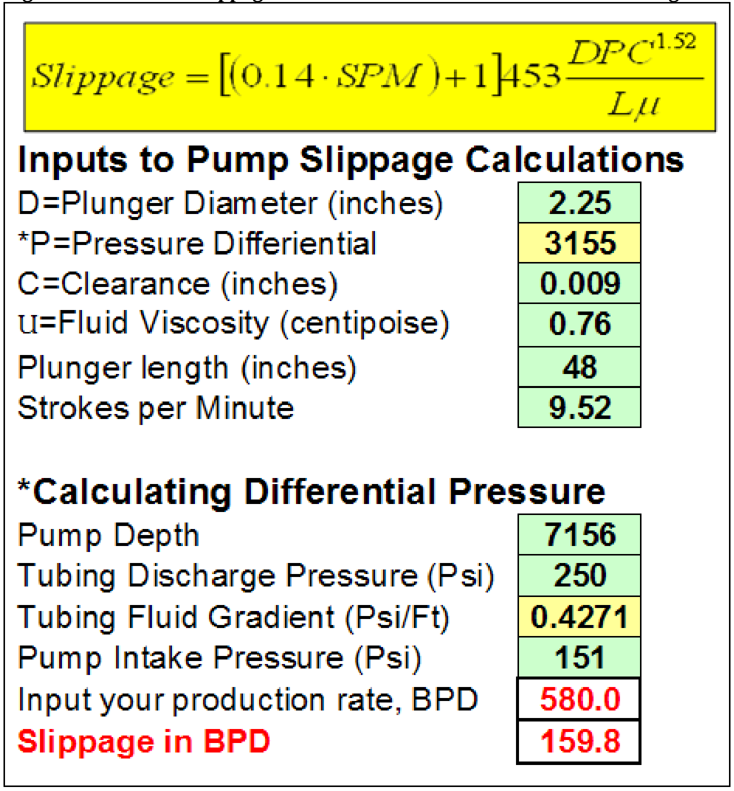
Stroke 6

Figure 5 – Surface and Pump Card from Permian Basin 2.25 in Plunger 0.009 Clearances



Kr 151 lb/in Kt 625 lb/in

Figure 6 – Patterson Slippage Calculations for Permian Basin Well having 2.25 in Plunger 0.009 Clearances



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

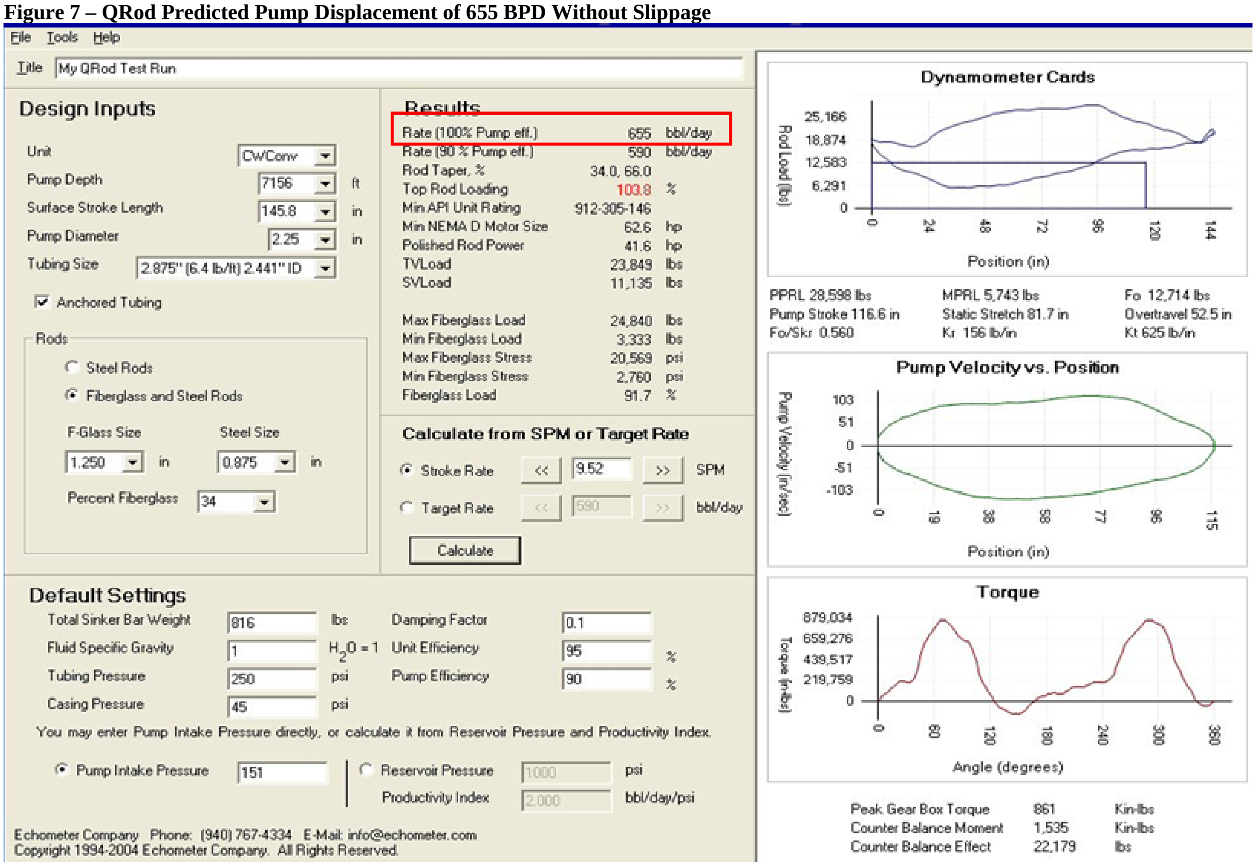
Inputs to Pump Slippage Calculations

D=Plunger Diameter (inches)	2.25
*P=Pressure Differential	3155
C=Clearance (inches)	0.009
u=Fluid Viscosity (centipoise)	0.76
Plunger length (inches)	48
Strokes per Minute	9.52

***Calculating Differential Pressure**

Pump Depth	7156
Tubing Discharge Pressure (Psi)	250
Tubing Fluid Gradient (Psi/Ft)	0.4271
Pump Intake Pressure (Psi)	151
Input your production rate, BPD	580.0
Slippage in BPD	159.8

Figure 7 – QRod Predicted Pump Displacement of 655 BPD Without Slippage



Title: My QRod Test Run

Design Inputs

Unit	CWConv	
Pump Depth	7156	ft
Surface Stroke Length	145.8	in
Pump Diameter	2.25	in
Tubing Size	2.875" (6.4 lb/ft) 2.441" ID	

☑ Anchored Tubing

Rods

○ Steel Rods
● Fiberglass and Steel Rods

F-Glass Size: 1.250 in
Steel Size: 0.875 in
Percent Fiberglass: 34

Results

Rate (100% Pump eff.)	655	bbl/day
Rate (90 % Pump eff.)	590	bbl/day
Rod Taper, %	34.0, 66.0	
Top Rod Loading	103.8	%
Min API Unit Rating	912-305-146	
Min NEMA D Motor Size	62.6	hp
Polished Rod Power	41.6	hp
TVLoad	23,849	lbs
SVLoad	11,135	lbs
Max Fiberglass Load	24,840	lbs
Min Fiberglass Load	3,333	lbs
Max Fiberglass Stress	20,569	psi
Min Fiberglass Stress	2,760	psi
Fiberglass Load	91.7	%

Calculate from SPM or Target Rate

● Stroke Rate: 9.52 SPM
○ Target Rate: 590 bbl/day

Default Settings

Total Sinker Bar Weight	816	lbs	Damping Factor	0.1	
Fluid Specific Gravity	1	$H_2O = 1$	Unit Efficiency	95	%
Tubing Pressure	250	psi	Pump Efficiency	90	%
Casing Pressure	45	psi			

You may enter Pump Intake Pressure directly, or calculate it from Reservoir Pressure and Productivity Index.

● Pump Intake Pressure: 151
○ Reservoir Pressure: 1000 psi
Productivity Index: 2.000 bbl/day/psi

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PPRL 28,598 lbs	MPRL 5,743 lbs	Fo 12,714 lbs
Pump Stroke 116.6 in	Static Stretch 81.7 in	Overtravel 52.5 in
Fo/Skr 0.560	Kr 156 lb/in	Kt 625 lb/in

Peak Gear Box Torque	861	Kin-lbs
Counter Balance Moment	1,535	Kin-lbs
Counter Balance Effect	22,179	lbs

Figure 8 – Design Pump Clearance of 0.005” to Achieve 90% Pump Efficiency with 65 BPD Slippage