THE MEASUREMENT OF DOWN STROKE FORCE IN ROD PUMPS

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Hypothesis: During the down stroke the plunger in a rod pump must descend through a barrel that is filled with fluid. A free plunger will establish a fall velocity that is determined by the pull of gravity and the forces resisting downward motion. The free fall of the plunger may not be large enough to correspond to the actual velocity necessary to match the pumping speed set by the pumping unit. In this case the plunger must be pushed down into the barrel by a compressive force in order to match the pumping velocity. The compressive force may be large enough to cause buckling in the pull rod and lowest section of sucker rods. The purpose of this paper is to test this hypothesis by presenting measurements of the free fall velocity of a plunger in a liquid filled barrel and the pushing force necessary to exceed the free fall velocity of the plunger in the barrel. The pull rod on the plunger was observed during the downward motion to see if buckling occurred in the pull rod. Simple models are shown to relate the measurements to practice.

Discussion: During the down stroke the plunger must overcome a variety of forces to move down in the barrel.

(1) Viscous friction caused by fluid flow through the traveling valve and the plunger.
(2) Viscous friction caused by fluid flow in the annulus between the outside of the plunger and the barrel.
(3) Mechanical friction if the plunger comes in contact with the barrel.

The viscous friction of the first two can be calculated using the mechanical energy balance (Bommer and Podio, 2015).

The mechanical friction is often neglected or assumed. In dynamometer analysis software a common value is 200 Lbf.

If the plunger must fall faster than is possible during free fall the extra force required to propel the plunger is supplied from the weight of the rod string above the plunger.

The pull rod and the lowest section of rods will buckle if the total force exceeds the critical force for the onset of buckling for the given rod. Should the pull rod buckle the mechanical friction will be greatly increased as the buckled shape is forced into the barrel. If the lowest section of rods buckle, tubing and rod wear and early fatigue rod failure will result.

The critical force for the onset of buckling can be calculated using the Euler equation shown as equation (1).

$$F_{cr} = \frac{\pi^2 EI}{4(144)L^2} \qquad (1)$$

$F_{cr} =$ critical load for the onset of buckling (lb_f)

$E =$ Young's Modulus $(30x10^6 \text{ psi for steel})$

$I =$ moment of inertia $(\text{in}^4) = \dfrac{\pi d^4}{64}$

$d =$ rod diameter (in)

$L =$ rod length (ft)

Other authors have proposed alternate formulas for sucker rods (Lea, et al, 1995) and made measurements of the force necessary to buckle a sucker rod (Cutler and Mansure, 1999). The alternative values are shown in Table 1 and are adapted from Bommer and Podio, 2015.

As can be seen in Table 1 the Euler equation presents the minimum buckling value. The measured data, at least for a rod in air, is more than likely the most accurate.

The maximum plunger velocity during the down stroke is best estimated by the solution of the one-dimensional wave equation used by the current generation of sucker rod design programs. Figure (1) is an example of this taken from the program QROD, available from the Echometer Company, using the example data set shown in Table 8.

Figure (1) shows a maximum down stroke velocity of 5.95 feet/sec which goes along with a pump rate of 204 BPD for the example data set using a pumping speed of 9.1 spm. This equals the free fall velocity measured for this plunger in the 3.7 cp viscosity liquid used in our experiments.

During the portion of the down stroke when the maximum plunger velocity from the calculations exceeds the free fall velocity the plunger must be pushed or forced into the barrel.

Measurements:

To make plunger velocity measurements we constructed a vertical test cell for the pump that is described in Table 2. The test cell schematic is shown in Figure 2.

The pull rod was raised to the top of the stroke by means of an electromagnet attached to a hoist. The accelerometer and potentiometer signals were digitized at a sampling rate of 5000 samples/sec and recorded on a computer versus time. The accelerometer data was integrated using the trapezoid rule to calculate the plunger velocity. The potentiometer data was differentiated using an appropriate curve fit to calculate the plunger velocity. A representative plot of plunger velocity using both instruments is shown in Figure 3. As an additional check on the two instruments the accelerometer data was integrated twice to create a position versus time calculation and the results plotted with the potentiometer position plot. This plot is shown as Figure 4 and demonstrates that both instruments gave essentially the same values. Since both instruments gave comparable results, the potentiometer was not used for some of the tests.

The test liquids used are shown in Table 3.

The test protocol was as follows:

(1) Fill test cell with test liquid.
(2) Measure the free fall of the plunger 3 times minimum. By comparing the raw accelerometer data after each test, it was determined that at least 3 trials were needed to ensure the data was repeatable.
(3) Add 2, 16, and 75 pounds of weight sequentially and repeat fall velocity measurement 3 times.
(4) Change out test liquid and repeat steps 1-3. The liquids tested are shown in Table 3.
(5) Change plunger to next clearance size and repeat steps 1-4.

During the testing, observations were made to see if the pull rod buckled and it did not. This result is not surprising because the Euler buckling force calculated using equation (5) for the pull rod was 302 Lbf.

The results of our experiment using the 1.5” pump are shown in Table 4 and Figure 5.

Figure 5 shows the plunger velocity dependence on liquid viscosity. The black error bars of plus or minus one standard deviation are shown for each data point. The plunger velocities in low viscosity fluids (water and 3.7 cp oil) are very similar. A higher viscosity liquid (39 cp oil) makes a substantial difference with a much lower plunger velocity. For comparison Table 9 shows crude oil viscosity versus API gravity for selected crude oils.

Figure 6 shows a similar plunger velocity trend with viscosity for the larger clearance plunger. Comparing Figures 5 and 6, the larger clearance produces essentially the same velocity as the smaller clearance in the low viscosity fluid.

In the larger viscosity fluid the larger clearance produces a higher plunger velocity. This is clearly shown in Figures 7 and 8.

Plunger Free Fall and Rod Buckling: The plunger free fall velocity is the intercept of Figures 5 through 8. This velocity corresponds to the weight of the plunger and the pull rod which are shown in Table 2.

Any plunger velocity that exceeds free fall is a forced velocity achieved by pushing with the added weight shown in the figures. The added weight is over and above the weight of the plunger and the pull rod. In practice the added weight is supplied by the rods just above the pull rod. For ¾" rods an additional weight above 23 pounds will likely cause the rods to buckle, see Table 1.

Figure 5 for the 0.002" clearance plunger shows that buckling of a ¾" sucker rod is likely to occur when the plunger velocity reaches 2 ft/sec for the 39 cp oil and 7 ft/sec for the 3.7 cp oil. Figure 6 for the 0.008" clearance plunger shows that buckling of a ¾" sucker rod would likely occur when the plunger velocity reached 3.5 ft/sec for the 39 cp oil and 7 ft/sec for the 3.7 cp oil. So, rod buckling is likely to occur at slower plunger velocities in fluids with larger viscosity.

Using the example data set shown in Table 8 a series of calculations were made for the maximum down stroke velocity of the 1.5 inch pump using a plunger with the 0.008" clearance for a variety of pumping speeds. The well depth was chosen to reflect a depth where a three foot long plunger might be used in order to match the length of plunger in our experiments. Table 5 shows the results using oil with a viscosity of 3.7 cp. Table 6 shows the results using oil with a viscosity of 39 cp.

The compression force was calculated using curve fits to the measured velocity data. The curve fits are shown as equations (2) and (3). The curve fits for all pumps tested are shown in Table 14.

Curve fit for the 0.008" clearance plunger in 3.7 cp oil.

$$v_{\max} = 0.0617 w_{add} + 5.8155 \qquad (2)$$

Curve fit for the 0.008" clearance plunger in 39 cp oil.

$$v_{\max} = 0.0373 w_{add} + 2.4981 \qquad (3)$$

$$v_{\max} = \text{ maximum down stroke plunger velocity } (\text{ft/sec})$$

$$w_{add} = \text{ weight added to produce velocity } (\text{lb}_\text{f})$$

Sinker Bars: It is common practice to use sinker bars above the pull rod to provide enough weight and rod stiffness to avoid buckling in the lowest section of sucker rods and in the sinker bars. Taking the data shown in Tables 5 and 6 at face value shows that only one 1.5", 25 foot long sinker bar would be required to provide the additional pushing force and prevent buckling in the situations where it is likely to occur in these tests. From a purely pump friction view point the use of more sinker bars would serve no useful purpose for the pumps tested here.

However, as the larger diameter sinker bar is added to the rod string an increase in viscous friction around the larger rod occurs. The increase in viscous friction also adds to the compressive force that will be felt by the smaller rods above the sinker bar section. There are many models for this, but perhaps the simplest is shown as equation (4) for flow through an annulus (Bird, Stewart, and Lightfoot, 1960).

$$F_v = \pi r^2 \left(1 - k^2\right) \Delta p \qquad (4)$$

$F_v =$ viscous force $\left(\mathrm{lb_f}\right)$

$r =$ internal radius of tubing (in)

$k =$ ratio of sinker bar OD to tubing ID

$\Delta p =$ pressure drop in annulus (psi)

The pressure drop necessary for the flow through the annular space created between the sinker bars and the inside of the tubing can be calculated using the mechanical energy balance in any available pipe flow calculator or developed from flow texts.

The length of sinker bars needed to offset the plunger friction and the viscous friction around the sinker bars can be determined through a trial and error process because the pressure drop around the sinker bars is a function of sinker bar length.

As an example consider the result from Table 6 where 110 Lbf of compression force is needed to produce 243 Bbl/day when pumping at 10 spm. The length of 1.5 inch sinker bars required assuming the ¾" rods will buckle with a compressive load of 23 Lbf is calculated using equation (5).

$$L_{SB} = \left[F_p + F_v - F_{cr}\right] / w_{rf} \qquad (5)$$

$L_{SB} =$ sinker bar length (ft)

$F_p =$ plunger friction $\left(\mathrm{lb_f}\right)$

$F_v =$ viscous friction $\left(\mathrm{lb_f}\right)$

$F_{cr} =$ critical buckling force $\left(\mathrm{lb_f}\right)$

$w_{rf} =$ buoyed unit sinker bar weight $\left(\mathrm{lb_f/ft}\right)$

For the first iteration the viscous friction is calculated assuming one 1.5" sinker bar will suffice. Using equation (4) with a calculated pressure drop of 14 psi for flow through the sinker bar – tubing annulus provides an additional viscous friction force of 41 Lbf.

Using equation (5) the sinker bar length required is:

$$L_{SB} = [110 + 41 - 23] / 5.6 = 22.9 \text{ ft}$$

So, for this example one 1.5" sinker bar is long enough. If the calculated length exceeded the length assumed for equation (4), another iteration using the new length would be made and the process continued until a solution is reached.

Effect of Pumping Unit: The pumping unit is the driver for the speed of the rods and plunger. Table 7 shows the effect of pumping unit geometry on the pumping speed that creates a plunger velocity that equals the free fall velocity for the example data set in 3.7 cp oil. The plunger velocities were predicted using QROD.

The faster down stroke units have a smaller pumping speed if plunger free fall velocity is not to be exceeded.

Other Pumps Tested:

We have tested a 2" pump with 4 foot plungers having 0.002" and 0.007" clearances and a 1.25" pump with 4 foot plungers having 0.002" and 0.006" clearances. The results of these tests are shown in Figures 9 through 12 and

Tables 10 and 11. The dimensions of the pumps are shown in Tables 12 and 13. The conclusions drawn from examination of the 1.5” pump hold for these pumps as well. A sinker bar example using the 2” pump is shown at the end of the paper.

Conclusions:

If a plunger must be forced into the barrel at a velocity exceeding free fall in order to match the pumping speed, the extra force will be a compressive force against the sucker rods just above the plunger. The compressive force can be enough to cause the lower portion of ¾ inch diameter sucker rods to buckle as shown in Table 1. Rod buckling accelerates rod and tubing wear and early rod failure due to fatigue. The compressive force can be offset and rod buckling prevented by placing a larger diameter rod on top of the plunger. As shown in Table 1 the larger diameter rods do not buckle as readily as the smaller diameter sucker rods. The large diameter rods should be long enough to provide the weight necessary to balance the compressive force. The use of more large diameter rods than needed leads to higher cost, larger loads that must be carried by the rest of the beam pump equipment, larger power demand, and increased viscous friction around the larger diameter rod section.

Ancillary conclusions include:
In low viscosity fluids the plunger clearance has very little influence on plunger velocity for the pumps tested. In high viscosity fluids, the plunger clearance has the effect of reducing plunger free fall velocity.

The choice of pumping unit affects plunger velocity with faster down stroke units requiring more added weight than long stroke and conventional units for the same pumping speed.

Using the design software QROD from the Echometer Company we have prepared examples of the added weight needed to achieve production rates for the example data set and a variety of pumping speeds. While not making operational recommendations these examples show the limits of pump rate beyond which the plunger must be forced into the barrel for the pumps we tested.

Example Using the 2” Pump: For this example the 2” pump with the 4 foot plunger and the 0.007” clearance is used. The well data is the same as shown in Table 8. The fluid is the 3.7 cp oil. The measured plunger free fall is 4.47 ft/sec from Table 10. Using QROD the maximum down stroke plunger velocity is simulated to be 6.64 ft/sec when pumping at a speed of 10 strokes/minute. The pump displacement at this speed is 235 barrels/day. The extra pushing force necessary to achieve this plunger velocity is calculated to be 43 lbs using the curve fit in Table 14. Using the buoyed weight of a 1.5” sinker bar as 5.6 lb/foot, only one 25 foot long sinker bar will be required. Using equation (4), an extra 26 lbs of viscous friction is added due to the presence of the sinker bar. This increases the compressive force to 69 lbs, but one 25 foot long 1.5” sinker bar will still more than offset this compressive load.

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Table 1 Buckling forces for various 25 ft long sucker rods.

Rod Diameter	Rod Air Weight	Buckling Force (-Lbf)			
(inch)	(Lbf/ft)	Euler	Lea (in air)	Lea (in water)	Measured in air
1.500	6.262	204.4	251.6	229.7	
1.375	5.44	144.3	204	186.2	641
1.000	2.904	40.4	87.8	80.2	
0.875	2.224	23.7	61.5	56.1	162
0.750	1.634	12.8	40.8	37.2	23

Table 2 Test Pump Description for 1.5" Pump

API 25-150-RHAC-10-3				
Nominal Barrel Outer Diameter	2.5"	Clearance	0.002"	0.008"
Barrel Inner Diameter	1.5"	Plunger Wt (lb)	14.75	14.35
Barrel Length	10'	TV Wt (lb)	1.74	1.74
Plunger Length	3.2'	Pull Rod Assbly Wt (lb)	18.51	18.51
Plunger Clearances	0.002" and 0.008"	Total Plunger Assbly (lb)	35.00	34.60
Plunger Inner Diameter	0.705"			
Pull Rod Outer Diameter	0.875"			
Pull Rod Length	7'			
Standing Valve Seat	1.547"OD x 1.00" ID			
Standing Valve Ball	1.375"			
Traveling Valve Seat ID	0.656"			
Traveling Valve Ball	0.938"			

Table 3 Test Liquids

Test Liquid	Specific Gravity	Viscosity at room temperature
		(cp)
Fresh Water	1	1
Exxon Spectrasyn 2C Mineral Oil	0.8	3.7
Crystal Tech 200 FG Mineral Oil	0.856	39

Table 4 Maximum Velocity Data for the 1.5” Pump

Plunger Clearance 0.002 inch				
Fluid	Added	Max Vel	Fall Time	Avg Vel
	Weight (lb)	(ft/sec)	(sec)	(ft/sec)
Air	0.00	10.15	1.35	5.19
Water	0.00	6.03	1.85	3.78
Water	2.38	6.10	1.53	4.58
Water	15.60	6.86	1.27	5.53
Water	78.00	11.17	0.68	10.29
Oil 1 (3.7 cp)	2.38	5.94	1.47	4.78
Oil 1 (3.7 cp)	15.60	6.68	1.11	6.31
Oil 1 (3.7 cp)	75.00	10.52	0.91	7.73
Oil 2 (39 cp)	2.38	1.49	4.96	1.41
Oil 2 (39 cp)	15.60	1.76	4.10	1.71
Oil 2 (39 cp)	75.00	3.99	1.90	3.68
Plunger Clearance 0.008 inch				
Fluid	Added	Max Vel	Fall Time	Avg Vel
	Weight (lb)	(ft/sec)	(sec)	(ft/sec)
Oil 1 (2.7 cp)	2.38	6.06	1.32	5.30
Oil 1 (2.7 cp)	15.58	6.66	1.28	5.47
Oil 1 (2.7 cp)	75.00	10.47	0.87	8.05
Oil 2 (39 cp)	2.38	2.60	4.10	1.71
Oil 2 (39 cp)	15.58	3.06	3.18	2.20
Oil 2 (39 cp)	75.00	5.30	1.53	4.58

Table 5 Compression Force versus Pumping Speed and Pump Displacement in 3.7 cp oil.

Pumping Speed (spm)	Pump Displacement (BPD)	Max Velocity (ft/sec)	Compression Force (Lbf)
Free Fall 9.1	204	5.95	0.0
9.5	216	6.25	7.0
10	232	6.53	11.6
11	268	6.6	12.7
12	304	7.7	30.5

Table 6 Compression Force versus Pumping Speed and Pump Displacement in 39 cp oil.

Pumping Speed (spm)	Pump Displacement (BPD)	Max Velocity (ft/sec)	Compression Force (Lbf)
Free Fall 4.35	100	2.52	0.0
5	115	2.93	11.6
6	138	3.6	29.5
7	165	4.16	44.6
8	192	4.55	55.0
9	212	6.02	94.4
10	243	6.62	110.5
11	280	6.64	111.0
12	316	7.67	138.7

Table 7 Effect of Pumping Unit Geometry on the Maximum Pumping Speed that Does Not Require Additional Compressive Force

Pumping Unit Type	3.7 cp max spm
Conventional CW	9.1
Conventional CCW	11.8
Air Balanced	8.9
Mark II	8
240" Long Stroke	5

Table 8 Example Data Set for a vertical well.

Pump Depth	5,000 ft	Tubing Pressure	50 psig
Barrel OD	1.5 in	Pump Intake Pressure	50 psig
Plunger Clearance	0.008 in	Rod Design	API 76
Plunger Length	36 in	Rod Class	D
Surface Stroke	100 in	Damping Factor	0.1
Tubing OD	2.875" (6.4 ppf)	Unit Efficiency	95%
Tubing Anchored	Yes	Liquid Specific Gravity	0.86

Table 9 Comparison of Various Crude Oil Viscosities

Crude Oil	API Gravity	Viscosity	Temp
	(deg API)	(cp)	(deg F)
Boscan	10.1	11206.0	100
Tia Juana Heavy	12.3	87.0	100
Leona	25.3	20.0	100
Mesa 28	28	11.8	100
Tia Juana Light	31.9	7.6	100
Iranian Light	32	6.0	100
Arabian Light	34.2	9.1	68
Bonny Light	35.6	2.5	122
Brent	38	2.4	122
West TX Intermediate	39	4.1	68
Anaco Wax	43.3	1.6	100
Kutubu	44	1.7	68

Table 10 Maximum Fall Velocity Data for the 2" Pump

2" Pump with Plunger Clearance 0.002"				
Fluid	Added	Avg. Max Vel	Avg. Fall Time	Avg. Vel
	Weight (lb)	(ft/sec)	(sec)	(ft/sec)
Oil 1 (3.7 cp)	2.38	5.30	1.35	4.87
Oil 1 (3.7 cp)	15.58	6.32	1.25	5.27
Oil 1 (3.7 cp)	75.00	9.10	0.95	6.93
Oil 2 (39 cp)	2.38	2.00	3.58	1.84
Oil 2 (39 cp)	15.58	2.44	2.94	2.24
Oil 2 (39 cp)	75.00	3.76	1.78	3.70
2" Pump with Plunger Clearance 0.007"				
Fluid	Added	Avg. Max Vel	Avg. Fall Time	Avg. Vel
	Weight (lb)	(ft/sec)	(sec)	(ft/sec)
Oil 1 (3.7 cp)	0.00	4.47	1.80	3.66
Oil 1 (3.7 cp)	2.38	4.91	1.49	4.42
Oil 1 (3.7 cp)	15.58	5.61	1.31	5.03
Oil 1 (3.7 cp)	75.00	8.05	0.97	6.77
Oil 2 (39 cp)	0.00	2.04	4.27	1.54
Oil 2 (39 cp)	2.38	1.90	4.22	1.56
Oil 2 (39 cp)	15.58	2.33	3.37	1.96
Oil 2 (39 cp)	75.00	3.75	2.02	3.26

Table 11 Test Pump Description for 2.0" Pump

API 25-200-RWAC-12-4	
Nominal Barrel Outer Diameter	3.25"
Barrel Inner Diameter	2"
Barrel Length	12'
Plunger Length	4.2'
Plunger Clearances	0.002" and 0.007"
Plunger Inner Diameter	1.2"
Pull Rod Outer Diameter	0.98"
Pull Rod Length	8'
Standing Valve Seat	2.01" OD x 1.312" ID
Standing Valve Ball	1.688"
Traveling Valve Seat ID	0.94"
Traveling Valve Ball	1.25"

Clearance	0.002"	0.007"
Plunger Wt (lb)	31.5	30.9
TV Wt (lb)	21.1	3
Pull Rod Assembly (lb)	3	21.1
Total Plunger Assembly	55.6	55

Table 12 Maximum Fall Velocity Data for the 1.25" Pump

1.25" Pump with Plunger Clearance 0.002"				
Fluid	Added Weight (lb)	Avg. Max Vel (ft/sec)	Avg. Fall Time (sec)	Avg Vel (ft/sec)
Oil 1 (3.7 cp)	0.00	3.17	2.57	2.56
Oil 1 (3.7 cp)	2.38	3.28	2.23	2.95
Oil 1 (3.7 cp)	15.58	4.06	1.68	3.92
Oil 1 (3.7 cp)	75.00	7.28	0.95	6.93
Oil 2 (39 cp)	0.00	1.34	6.08	1.08
Oil 2 (39 cp)	2.38	1.43	5.64	1.17
Oil 2 (39 cp)	15.58	1.88	3.92	1.68
Oil 2 (39 cp)	75.00	4.41	1.61	4.09
1.25" Pump with Plunger Clearance 0.006"				
Fluid	Added Weight (lb)	Avg. Max Vel (ft/sec)	Avg. Fall Time (sec)	Avg Vel (ft/sec)
Oil 1 (3.7 cp)	0.00	3.53	2.04	3.22
Oil 1 (3.7 cp)	2.38	3.79	1.90	3.46
Oil 1 (3.7 cp)	15.58	4.70	1.56	4.22
Oil 1 (3.7 cp)	75.00	7.81	0.96	6.89
Oil 2 (39 cp)	0.00	1.69	4.17	1.58
Oil 2 (39 cp)	2.38	1.76	4.04	1.63
Oil 2 (39 cp)	15.58	2.22	3.04	2.17
Oil 2 (39 cp)	75.00	5.01	1.36	4.83

Table 13 Test Pump Description for 1.25” Pump

API 20-125-RHAC-10-4-1-1	
Nominal Barrel Outer Diameter	1.63"
Barrel Inner Diameter	1.25"
Barrel Length	10'
Plunger Length	4.2'
Plunger Clearances	0.002" and 0.006"
Plunger Inner Diameter	0.565"
Pull Rod Outer Diameter	0.71"
Pull Rod Length	6'
Standing Valve Seat	1.388" OD x 0.844" ID
Standing Valve Ball	1.125"
Traveling Valve Seat ID	0.578"
Traveling Valve Ball	0.75"

Clearance	0.002"	0.006"
Plunger Wt (lb)	14	13.6
TV Wt (lb)	0.9	0.9
Pull Rod Assembly (lb)	13.4	13.4
Total Plunger Assembly	28.3	27.9

Table 14 Curve Fits to Plunger Velocity versus Added Weight Plots

Fluid	Pump and Plunger
	1.25" barrel x 4' x 0.002" clearance plunger
3.7 cp oil	$v_{\max} = 0.0548 w_{add} + 3.1738$
39 cp oil	$v_{\max} = 0.0411 w_{add} + 1.3105$
	1.25" barrel x 4' x 0.006" clearance plunger
3.7 cp oil	$v_{\max} = 0.0545 w_{add} + 3.7487$
39 cp oil	$v_{\max} = 0.0454 w_{add} + 1.5894$
	1.5" barrel x 3' x 0.002" clearance plunger
3.7 cp oil	$v_{\max} = 0.0636 w_{add} + 5.7435$
39 cp oil	$v_{\max} = 0.0354 w_{add} + 1.3166$
	1.5" barrel x 3' x 0.008" clearance plunger
3.7 cp oil	$v_{\max} = 0.0617 w_{add} + 5.8155$
39 cp oil	$v_{\max} = 0.0373 w_{add} + 2.4981$
	2.00" barrel x 4' x 0.002" clearance plunger
3.7 cp oil	$v_{\max} = 0.0495 w_{add} + 5.3306$
39 cp oil	$v_{\max} = 0.0231 w_{add} + 2.0505$
	2.00" barrel x 4' x 0.007" clearance plunger
3.7 cp oil	$v_{\max} = 0.0451 w_{add} + 4.7108$
39 cp oil	$v_{\max} = 0.0241 w_{add} + 1.9428$
$v_{\max}$ = maximum plunger velocity (ft/sec)	
w_{add} = weight added (lb_f)	

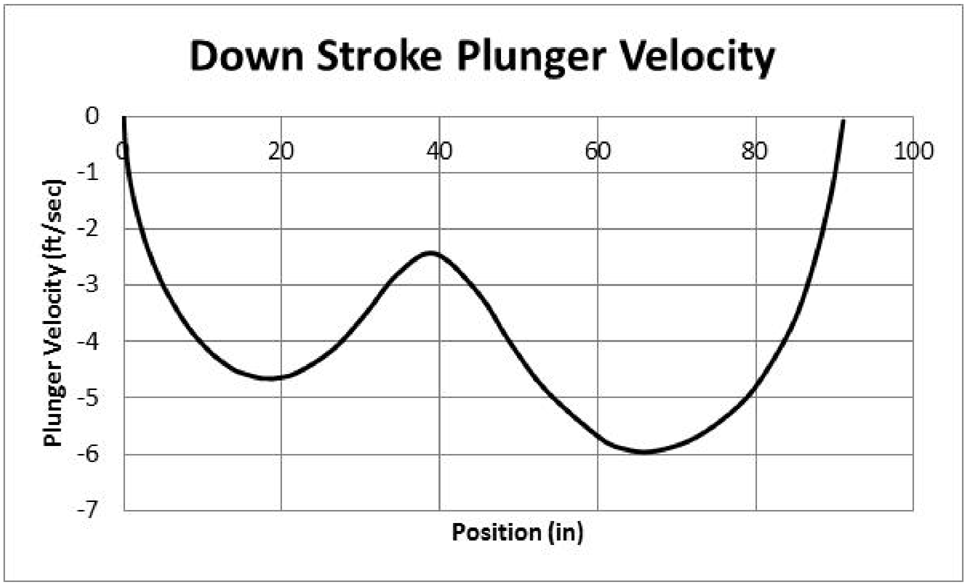

Figure (1) Example of Down Stroke Plunger Velocity

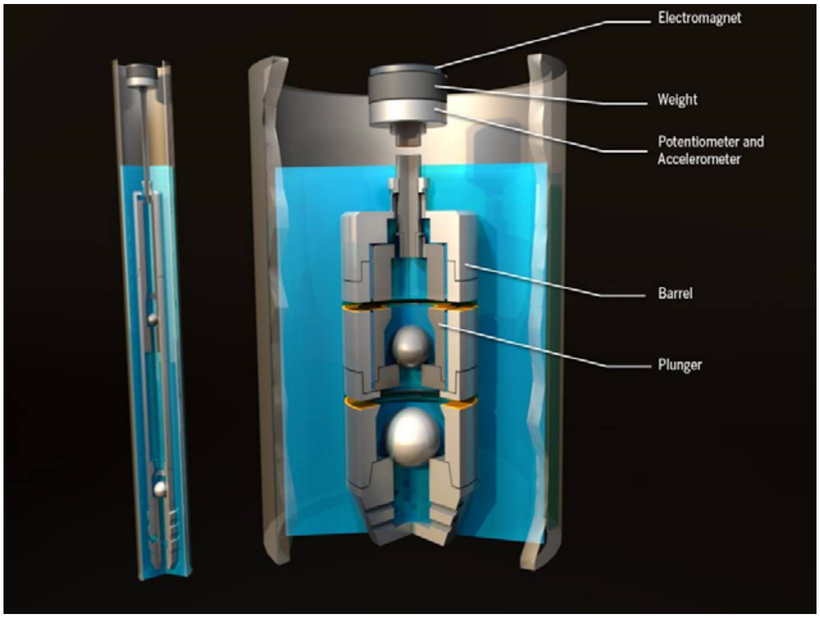

Figure 2 Test Cell Schematic

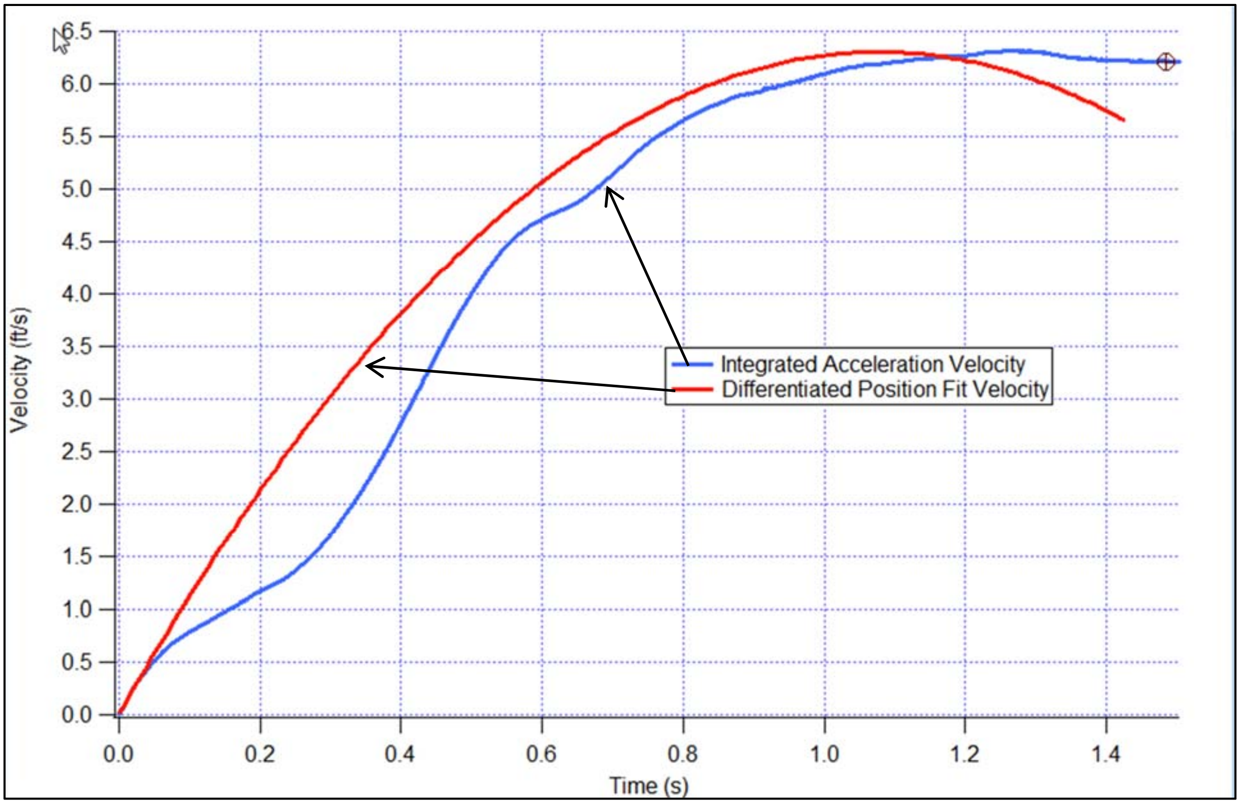

Figure 3: Plunger Velocity using both Differentiation and Integration Techniques

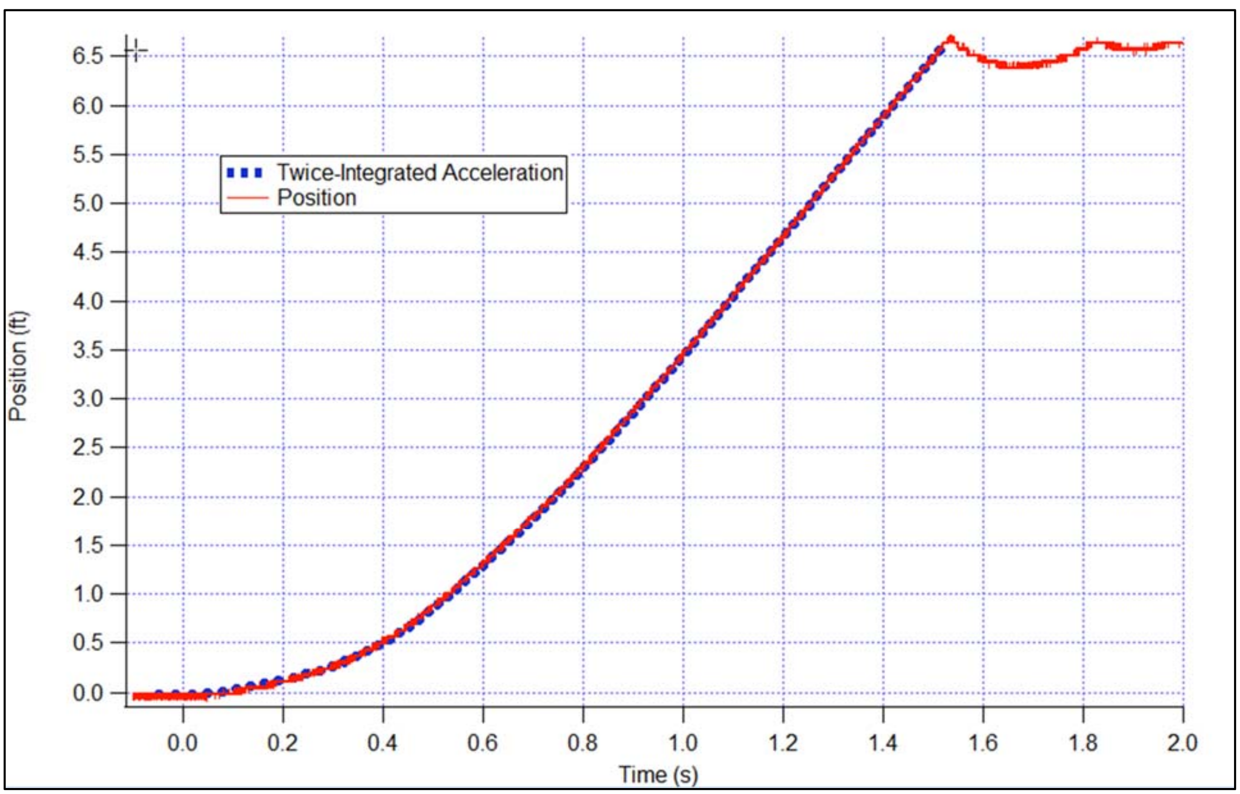

Figure 4: Comparison of Measured Position Data to Twice Integrated Acceleration Data

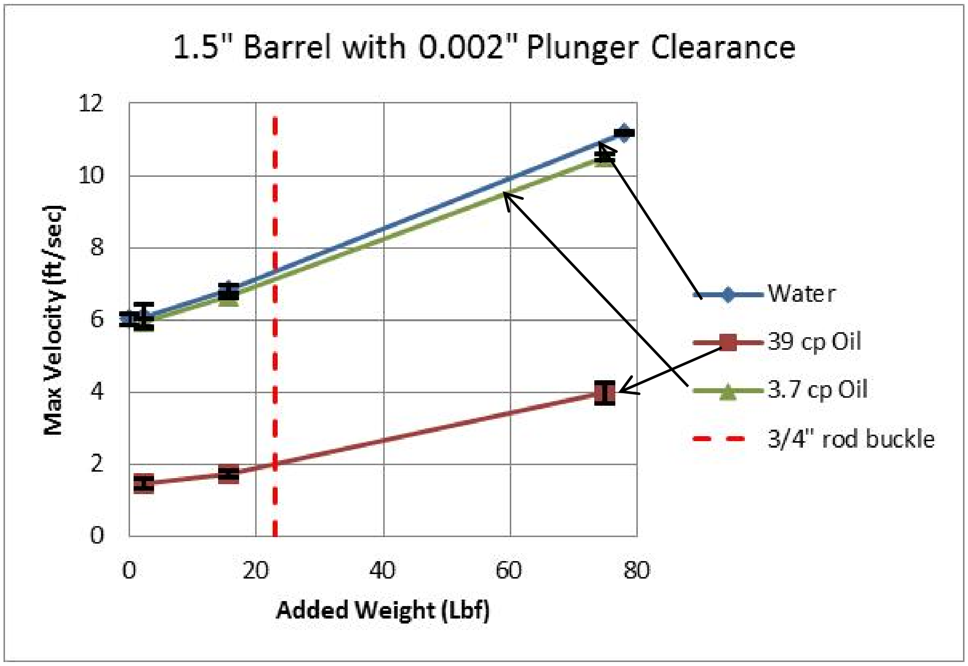

Figure 5 Maximum Plunger Velocities for the 1.5" pump with 0.002" plunger clearance

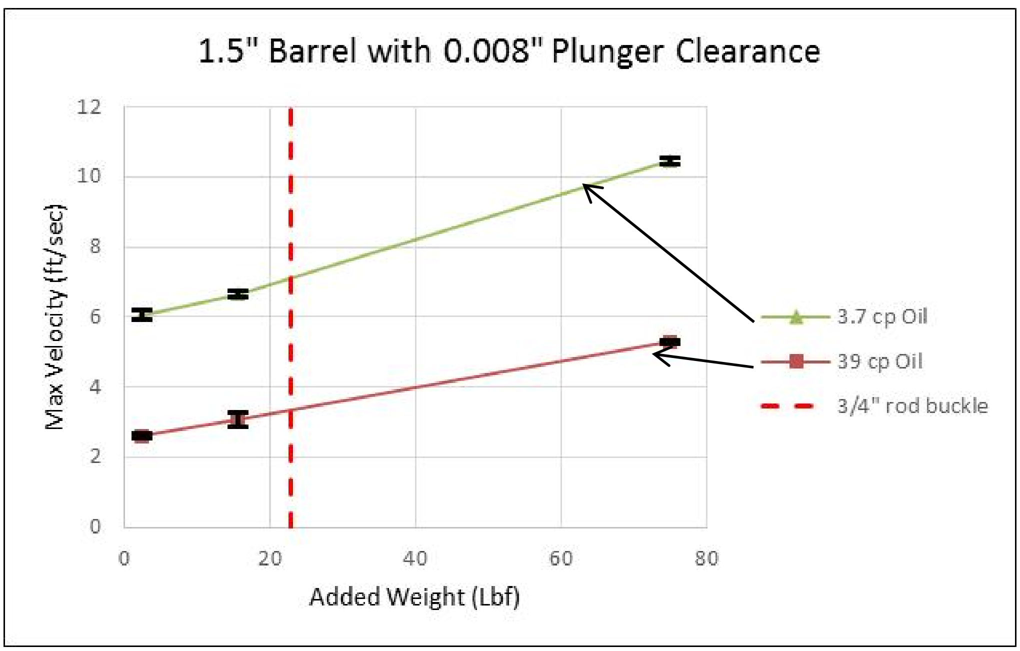

Figure 6 Maximum Plunger Velocities for the 1.5" pump with 0.008" plunger clearance.

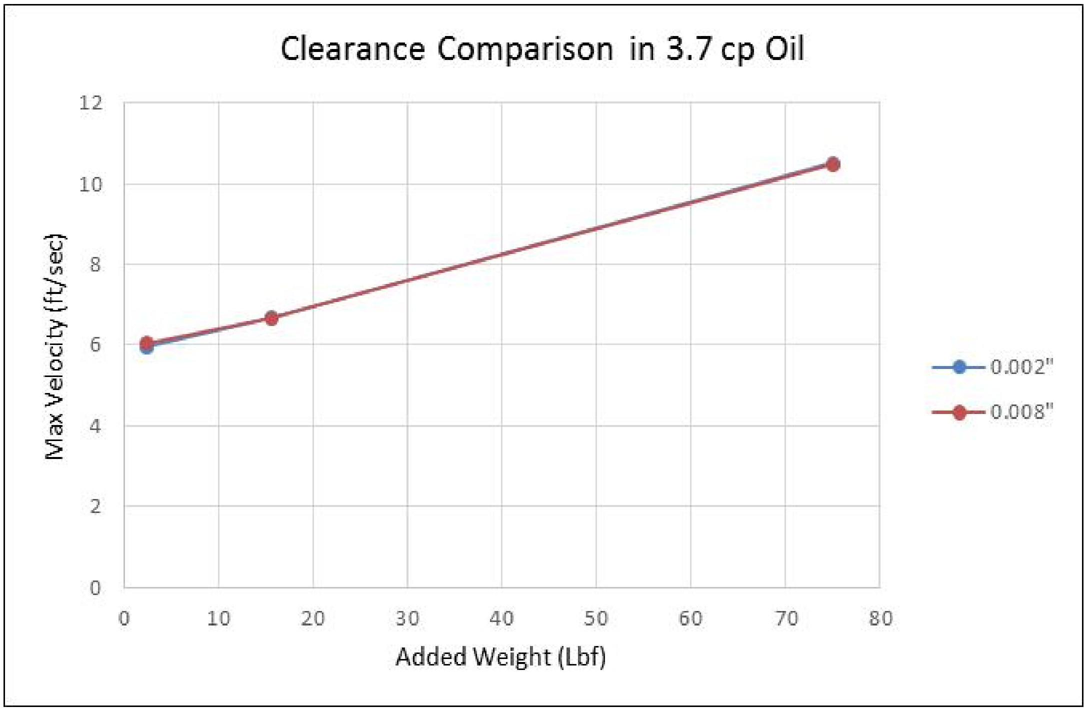

Figure 7 Comparison of plunger clearance in low viscosity oil for the 1.5” pump.

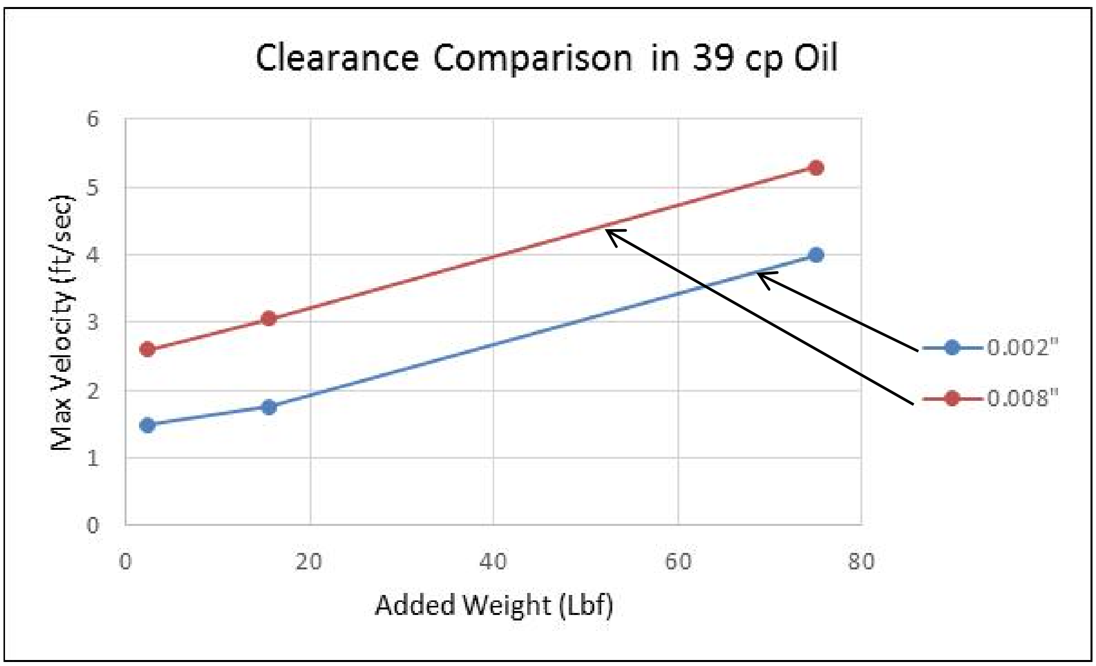

Figure 8 Comparison of plunger clearance in high viscosity oil for the 1.5” pump.

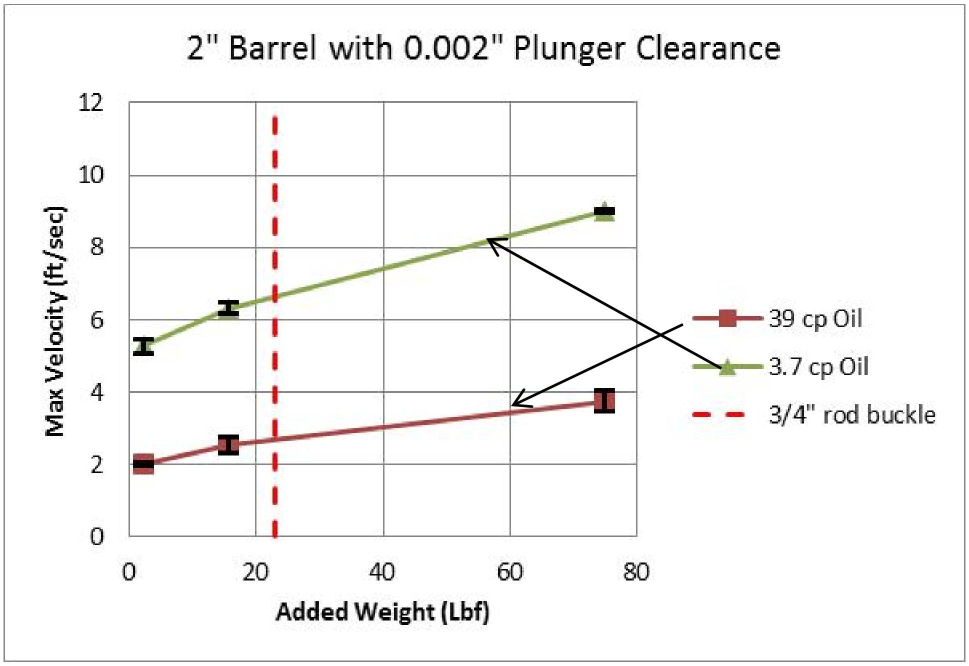

Figure 9 Maximum Plunger Velocities for the 2” pump with 0.002” plunger clearance.

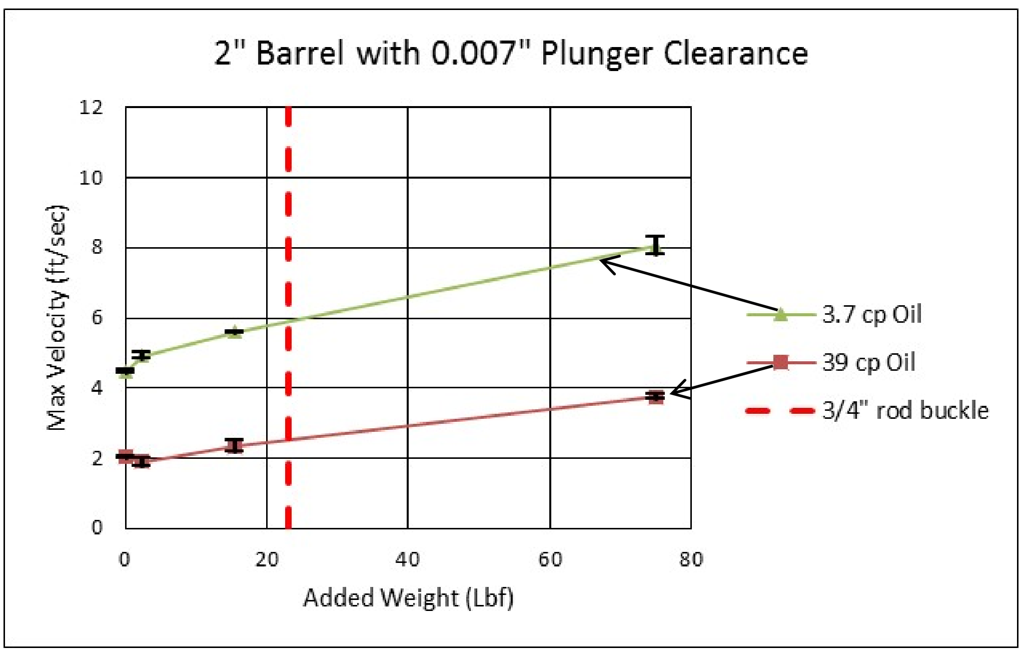

Figure 10 Maximum Plunger Velocities for the 2” pump with 0.007” plunger clearance.

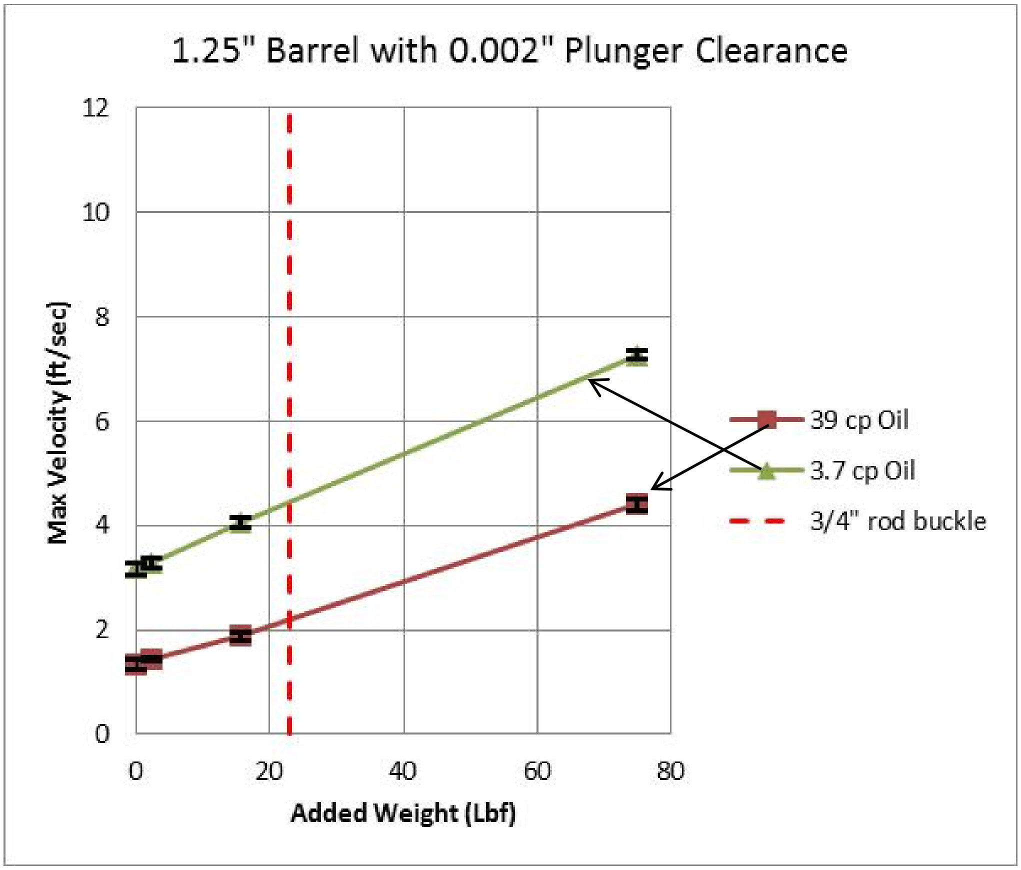

Figure 11 Maximum Plunger Velocities for the 1.25” pump with 0.002” plunger clearance.

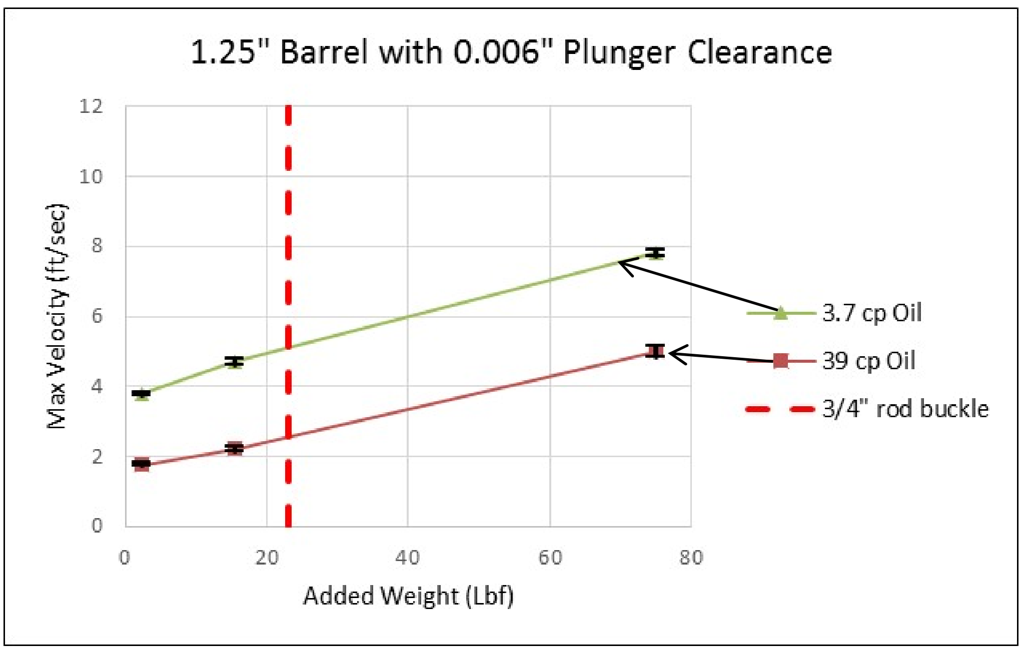

Figure 12 Maximum Plunger Velocities for the 1.25” pump with 0.006” plunger clearance.