A Progress Report on "Fluid Slippage in Down-Hole Rod-Drawn Oil Well Pumps"

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Abstract and Scope

Fluid slippage is defined as the fluid that leaks past a metal plunger during the upstroke of a down-hole, rod-drawn, positive displacement pump. American Petroleum Specification 11AX covers this type of pump which is used in approximately 90% of artificially lifted wells.

This paper will present the first part of the results of a continuing research project covering the theoretical analysis and laboratory testing of pump slippage. The goal of this project is to present a mathematical model which will accurately represent the actual down-hole slippage for this class of pump. The current results should be useful to operators for selection of clearances between metal plungers and barrels.

In the review of literature many of the clearances and differential pressures were lower than what is normally experienced in light oil operations. Tested clearances that were reported in the literature were 0.007" or lower. This investigation will evaluate some new ground looking at larger clearances and higher differential pressures.

Summary of Results

Historical slippage equations based on static pressure leakage have overstated the slippage experienced by down-hole, rod-drawn positive displacement pumps with metal plungers. The historical equations predict about twice the observed slippage for clearances equal to or less than .006" (six thousandths of an inch) depending on the historical equation. For clearances larger than .006" these historical equations can overestimate the slippage by a factor greater than three.

It should be obvious, from the equations, that leakage can be reduced with a longer plunger. This paper has concentrated on the leakage using a fixed plunger length.

History

Oil well owners and operators have always been sensitive to the amount of fluid slippage past a metal plunger during operation of a rod-drawn, down-hole pump. This slippage fluid contributes slightly to a lower pumping efficiency by leaking high pressure fluid past the plunger back to the pump compression chamber. The amount of slippage fluid is recommended to be about two percent of the produced fluid. A pump is considered to be worn out when the plunger and/or barrel wears to a point that the slippage area becomes large enough to dramatically affect daily fluid production.

Slippage past a metal plunger is necessary for two reasons. The obvious reason is that the metal plunger needs a film of fluid between it and the metal barrel to prevent galling of the two materials. Galling causes transfer of metallic material between the two sliding surfaces and quickly causes the pump to hang up and become ineffective. The other reason is to allow enough clearance between the pump plunger and barrel to allow particulates to pass between the two without causing the plunger to become stuck in the barrel due to these particulates.

A tight fitting plunger will also increase the drag on the downstroke as compared to a "loose" fitting plunger. Opening up or using larger clearances will reduce rod compression on the downstroke. There is a limit to the clearance that can be used while maintaining reasonable pump slippage.

Historical equations have taken the general form of the equation listed below with slight differences in the leading constant (K) and/or exponents on the variables in the equation. *It should be noted that all of the following discussions on the various leakage equations are based upon a constant differential pressure being applied across the plunger. In an oil well installation, the differential pressure is only applied during half of the cycle; therefore, the leakage equations should be divided by two. The authors will point out when the equations, being divided by 2, reflect downhole conditions.*

$$\text{Slippage in BPD} = K \frac{D^a P C^b}{L V}$$

where: K = constant

- D = plunger diameter in inches, with exponent a which varies from 0.7 to 1.0
- C = clearance between plunger and barrel in inches, with an exponent b which varies from 3.0 to 3.3
- L = plunger length in inches
- V = viscosity in centipoise
- P = differential pressure across the plunger in psi

There have been several efforts to measure the pump leakage and develop a constant to correct the theoretical equation to match the measured data. Two papers have been the historical reference for future investigators who have studied pump slippage. Tao and Donavan (1) evaluated flow through concentric and eccentric annuli with small clearances and developed the following theoretical equation:

$$\text{Slippage in BPD} = 2 \times 10^6 \frac{D P C^3}{L V} (1 + 1.5e^2) \qquad \text{Tao, Donavan, Coberly}$$

The eccentric factor is "e". If the plunger is concentric with the barrel, e = 0 and the multiplier is 1; but if the plunger is totally eccentric, e = 1 and the multiplier is 2.5. Depending on the position of the plunger, the constant K will range from 2×10^6 (concentric) to 5×10^6 (eccentric). This equation was also used by Coberly(2) in the Kobe hydraulic design manual.

Davis[3] is the other paper quoted as the theoretical basis for slippage. The Davis equation was used by Stearns[4] to develop the constant based on test data and was later corrected by Reekstin[5] and presented the following equation:

$$\text{Slippage in BPD} = 2.8 \times 10^{7} \frac{D^{0.9} P C^{3.1}}{L V} \qquad \text{Davis, Stearns, Reekstin}$$

The slippage data obtained by Stearns used a pumping unit and a 2.25" liner barrel pump to collect slippage data under controlled conditions. Test data was obtained at various pressures between 190 psi and 1026 psi, at temperatures ranging between 35 and 195 degrees F., with two plunger lengths (48" and 60") and two different clearances (0.002" and 0.003"). Oil was used as the fluid and was heated or cooled to change the viscosity (0.47 cp at 188 F and 1.4 cp at 35 F).

Reekstin also evaluated data presented by Robinson[6] who did a test in a well at 4000' with out a standing valve. Static pressure was determined by two sub-surface pressure surveys. The tubing was filled with oil from the surface and the pump was operated using the existing pumping unit at a constant speed. Leakage past the plunger was determined by gauging the amount of oil (33.5 API) necessary to keep the tubing full. A 1.5" plunger 72" long was used in the test. Reekstin used the graph presented by Robertson and developed the following equation:

$$\text{Slippage in BPD} = 5.6 \times 10^{6} \frac{D^{0.7} P C^{3.3}}{L V} \qquad \text{Robinson, Reekstin}$$

Juch and Watson investigated slippage while working on heavy oil applications in Venezuela. They tested a variety of plunger sizes, lengths and fits with fluids ranging in viscosity from 180 to 470 cp and used a maximum differential pressure of 500 psi. They also referenced the work by Coberly and provided the following equation assuming the plunger is completely eccentric:

$$\text{Slippage in BPD} = 1.57 \times 10^{7} \frac{D P C^{3}}{L V} \qquad \text{Juch and Watson}$$

Additional testing using various plunger clearances and using refined oil has resulted in equations with different constants and exponents. Well Oilfield Specialties measured leakage with a 2.25" x 36" plungers using ISO-VG-46 oil. Viscosity at the testing temperature of 68 to 70 degrees F was between of 500 to 550 SSU. Based on their tests with -0.003", -0.005" and -0.007" plungers at 1000 psi differential pressure, they reported the following equation:

$$\text{Slippage in BPD} = 2.47 \times 10^{7} \frac{D^{0.8} P C^{3.2}}{L V} \qquad \text{Wells Oilfield Specialties}$$

References for known, published sources of historical slippage information are listed at the back of this paper.

Laboratory Setup for Testing

The testing was performed at EVI Oil Tools, Trico Industries, Inc. location, at San Marcos, Texas in the Hydraulic Test Lab.

Plungers were obtained in three foot lengths and all of the various minus sizes needed for testing. The sizes are listed in the chart below. The "minus size" refers to the actual outside diameter of the plunger less than the nominal diameter. For example: a 1-3/4" by -.002" (minus two thousandths of an inch) plunger measures 1.748". These plungers were cut off to provide an exact 36" (thirty six inches) of seal length and were dedicated to the test program so that they will always be available for future testing. The nominal plunger diameter used for these tests was 1-3/4" (one and three quarters inch.) The barrel used for these tests measured 1.751" on the inside diameter. The test barrel length was five feet long as determined by the length of the plungers and the necessary hydraulic attachments.

Actual Plunger Size, inches	Minus Size of Plunger, inches	Barrel Size, inches	Plus Size of Barrel, inches	Total Clearance Between Plunger and Barrel, inches
1.749	-.001	1.751	+.001	+.002
1.748	-.002	1.751	+.001	+.003
1.747	-.003	1.751	+.001	+.004
1.746	-.004	1.751	+.001	+.005
1.745	-.005	1.751	+.001	+.006
1.744	-.006	1.751	+.001	+.007
1.743	-.007	1.751	+.001	+.008
1.741	-.009	1.751	+.001	+.010
1.736	-.014	1.751	+.001	+.015
1.731	-.019	1.751	+.001	+.020

Testing was started in the Fall of 1997 and the initial data was collected and analyzed. This initial data showed that the historical slippage rate was overstated as suspected. However, when the initial tests were repeated to check the setup for repeatability the initial results could not be duplicated. It was determined that this was due to the plunger laying against one wall of the barrel tube at varying degrees off center during different tests. The test setup was modified such that each plunger was provided with a machined centering device that allowed for full fluid flow while centering the plunger in the barrel. This setup provided repeatability for slippage testing. Figure 1 shows the data for the 1.75" barrel with the plunger centralized with the test fixture and the eccentric data was obtained with the barrel horizontal. A maximum clearance of 0.007" was due to the limitation of the pneumatic pump being used.

To maintain the desired rate and pressure at the larger clearances, the hydraulic test loop was utilized. Additional plungers were made to include clearances of 0.008", 0.010", 0.015" and 0.020". All testing was done with the plunger and barrel in an upright position and the plungers were centralized using the fixtures. They were suspended from the top so that slippage samples could be collected from the bottom of the test apparatus. The slippage sample was collected in a graduated container below the test apparatus. The temperature of the fluid as well as the viscosity was measured from this sample. The temperature of the fluid entering the top of the barrel was also measured and recorded. The fluid was a 10W (ten weight) hydraulic fluid with pressure and flow provided by an industrial triplex pump. The collected data is represented in chart form in Table 1 at the end of this paper.

Test Parameters and Procedures

Tests were conducted at 2,000 psi (two thousand pounds per square inch) and 4,000 psi, at the top of the plunger. The intent was to test two sizes of plungers, 1-3/4" and 2-1/4" but time constraints limited the testing for this paper to 1-3/4" diameter. Testing was started in the morning and finished in the afternoon in most cases. This led to using low fluid temperatures in the morning and higher fluid temperatures in the afternoon due to heating of the fluid during use and due to rising air temperatures around the hydraulic fluid tank. The data was normalized to 70 degrees F. to account for varying viscosity due to temperature effects.

Problems were encountered with recording accurate temperatures for the slippage fluid. The fluid inlet temperature and the collected sample temperature were recorded during testing. However, during testing with the larger clearances the fluid temperature increased during each test. This made it difficult to assign a temperature to the fluid so that the fluid gravity could be determined for viscosity conversions.

This problem was dealt with by conducting a separate test of the test fluid. This test consisted of the collection of a fluid sample at temperatures ranging from 57 degrees F. to 108 degrees F., and a measurement of the sample gravity and viscosity in seconds. From this data a curve was derived for viscosity in seconds as a function of temperature. A curve was also derived for gravity as a function of temperature.

Test Data		
Temp. F.	Viscosity seconds	Gravity
57	38.3	0.860
63	36.8	0.855
68	35.7	0.853
75	34.0	0.851
82	33.5	0.849
88	32.4	0.847
95	31.2	0.845
102	30.8	0.843
108	30.6	0.841

The original test viscosity in seconds was then used to calculate a representative temperature for each original test. This temperature was used to calculate a representative gravity for each original test. Then this gravity was used to calculate the viscosity in centipoise from the original viscosity in centistokes. This allowed us to bypass the original temperature measurement problem. This was accomplished by converting the original cup viscosity measurements in seconds to centipoise for use in the slippage formula. This approach seems to be valid but future tests will be conducted with a constant temperature fluid so that the viscosity will be eliminated as a test variable. Future testing will also include the 2-1/4" diameter plunger.

Results

The slippage of fluid past the plunger has been overstated in historical equations, leading to operators using plungers with a tighter fit than has been necessary for proper lubrication of the plunger and barrel. This conclusion has been suspected by some operators due to their use of larger clearances to allow for particulate production, but without the expected decline in production efficiency.

The shape of the slippage equation clearance variable has been assumed in the past to be a power function with an exponent of three, (a cubic function.) This assumption has been based on the theoretical derivation of the slippage equation. This study has initial results which show that the curve may have a cubic function shape up to about a clearance of .006" to 0.008" and then change to approximately a squared function. This indicates that the slippage will increase less than previously expected with increasing clearance between the plunger and barrel.

Figure 1 shows the impact of the plunger being concentric and then eccentric within the barrel. The eccentric data follows the theoretical eccentric curve (see the Tao, Donavan, Coberly equation with a constant of 5.0 x 10^6) through a clearance of 0.006". Additional eccentric data above 0.006" could not be obtained at that time due to pump limitations. Concentric data followed the theoretical eccentric curve through a 0.004" clearance and then began deviating toward the theoretical concentric curve (see the Tao, Donavan, Coberly equation with a constant of 2.0 x 10^6). It is not clear if the data shift is a result of the necessity of having larger clearances before the plunger is truly eccentric to the barrel or if there is a change in flow regime at this point causing a shift in the slippage. Due to the test equipment there were pressure and temperature fluctuations that were not properly accounted and the viscosity was only estimated based on the test temperature and correcting published properties of the oil being used. It became apparent that improvements in the determining the viscosity and temperatures had to be made to obtain a correlation.

In the next set of tests the inlet temperature to the barrel was monitored along with the temperature of the oil collected. A dynamic viscosity curve versus temperature was developed. As previously mentioned the slippage data was collected at various fluid temperatures and was normalized to a standard temperature in order to compare the slippage on one graph or even to each other. These were normalized to 70 degrees F. by using a ratio of the test temperatures. These are linear variables and are directly related such that this normalization ratio is relevant. Some of the pressures deviated slightly from the expected pressures of 2,000 and 4,000 psi. A pressure ratio was also used to normalize the slippage data with respect to pressure. Table 2 in the Appendix lists these ratios and results.

The test data normalized to 70 degrees and 2000 psi and 4000 psi was compared to each of the correlations to determine if any of these equations would predict the slippage at these conditions. Figure 2 compares the data at 2000 psi and Figure 3 at 4000 psi. The normalized data for both the 2000 and 4000 psi cases were matched with the centralized theoretical equation (see the Tao, Donavan, Coberly equation with a constant of 2.0 x 10^6) through a clearance of 0.005". Past 0.005" the normalized data was less than this curve. The Robinson, Reekstin equation provided good agreement up to a clearance of 0.008" to 0.010", but at larger clearances the normalized leakage data was less than predicted.

It needs to be noted that the empirical curves developed for viscous crude oils (Juch, Watson and Wells Oilfield Specialties) have the largest disagreement with the normalized test data. The viscosity of the crude and its properties as a function of shear can significantly alter the insitu viscosity for the slippage calculations. Crude oil viscosity will increase as the pressure is increased. This effect will occur in hydrocarbon systems that operate the bubble point. However, if a gas phase is present the crude viscosity will decrease as the gas goes into solution. However, with the dead oil being used in the test, Beal's correlation suggests that a 6 cp oil would be 7 cp at 2000 psi and 8 cp at 4000 psi. Although relatively small, the viscosity ratio at pressure to the atmospheric is 1.17 at 2000 psi and 1.33 at 4000 psi.

Additional analysis of the normalized data is shown in Figures 4 and 5. Both of these show the slippage in barrels per day plotted on the y-axis and the plunger to barrel clearance on the x-axis. These graphs are of the normalized slippage data and show that the rate of slippage decreases with clearances above about .006". One of the graphs has conventional axis units and the other has a log-log axis configuration. Both of these have trend lines plotted of the data with the derived equation and error data printed close to the trend lines. The trend line equations show that the exponents on the clearance variable decrease for clearances greater than .006" resulting in less slippage than shown by historical equations using a factor of three (3). The log-log graph is interesting in that the change in the clearance exponent is easily seen visually since the slope of the line is the exponent of clearance.

The Robinson, Reekstin equation has been plotted against the normalized leakage data for 2000 and 4000 psi in Figures 6 and 7. This equation has good agreement with the normalized data through a clearance of 0.008". Since the normalized data was collected from a centralized plunger, another curve is shown for an eccentric plunger using the Robinson, Reekstin equation. Without any eccentric data, the eccentric factor of 2.5 used by Coberly was applied to the constant.

Recommendations

1. Several large operators have recently started using greater initial clearances for their rod-drawn, down-hole pump specifications. This decision has been based in part on the initial results of this study, and the need to provide plunger lubrication and greater clearances for particulates in the production fluid. Specific recommendations are for one to two more minus fits on plungers than were previously used.

   ARCO Permian has recently instituted lager pump clearances as follows:

   1.25" to 1.75" pumps 0.005" to 0.007"
   2.00" to 2.25" pumps 0.007" to 0.009"

2. Additional testing needs to be done using both the concentric and eccentric plungers. It has been shown by theoretical calculations and by lab testing that an eccentric plunger will have more leakage than if the plunger was concentric to the barrel. Observation of plunger wear during pump teardowns indicates that plungers operate more eccentrically than concentric.

3. For light oil operations, the Robinson, Reekstin equation matched a larger range of the normalized data. At this point the test data has been only concentric data by use of test fixtures to center the plunger in the barrel and low viscosity oil. The following equations can be used to estimate pump slippage up to a clearance of 0.008":

$$\text{Slippage in BPD} = 2.8 \times 10^6 \frac{D^{0.7} P C^{3.3}}{L V}$$

note: The constant has been divided by 2 to represent the pumping cycle for <u>concentric plungers.</u>

Until more work is done investigating and modeling eccentric plunger leakage, caution should be used with the concentric equation. Until that data is available, it appears warranted to use a multiplier to estimate eccentric leakage. For lack of a better estimate it is suggested that the 2.5 eccentric factor be used as shown below.

$$\text{Slippage in BPD} = 7.0 \times 10^6 \frac{D^{0.7} P C^{3.3}}{L V}$$

note: The constant has been divided by 2 to represent the pumping cycle for <u>eccentric plungers.</u>

4. The test apparatus will need improvement to keep a constant inlet temperature to the pump inlet and keep track of the sample temperature with time as it is collected. Additional tests will be conducted on the 1.75" pump plus similar tests on the 2.25" pump. Will also consider a rolling ball viscometer to obtain oil viscosity at pressure and temperature.

Contributors

Several people were involved in the test parameter development and testing program for this paper. We want to express our appreciation to Trico Industries, Inc., Matthew Scott (Trico), Larry Rice (Trico), Jim Curfew (ARCO Permian) and Jim Lea (AMOCO.)

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Table 1
Slippage Test Data

Barrel Inside Diameter	Plunger Outside Diameter	Total Clearance	Test Pressure	Slippage volume in Milliliters	Slippage time in Minutes	Slippage in Barrels per Day	Temp. F. Inlet Fluid low	Temp. F. Inlet Fluid high	Temp. F. Ave. Inlet	Temp. F. Sample	Viscosity in Seconds	Viscosity in Centistokes
1.751	1.749	0.002	1950	60	5	0.11	68	68	68.0	68	35.8	7.48
1.751	1.749	0.002	2000	65	5	0.12	71	71	71.0	68	35.8	7.48
1.751	1.749	0.002	2050	69	5	0.13	69	69	69.0	68	35.8	7.48
1.751	1.748	0.003	2000	460	5	0.83	80	80	80.0	72	35.2	6.82
1.751	1.748	0.003	2000	490	5	0.89	84	84	84.0	74	35.0	6.6
1.751	1.747	0.004	2000	695	5	1.26	68	68	68.0	66	36.0	7.7
1.751	1.747	0.004	2000	760	5	1.38	73	73	73.0	70	35.8	7.48
1.751	1.746	0.005	2000	1945	5	3.52	90	96	93.0	76	34.8	6.38
1.751	1.746	0.005	2000	2580	5	4.67	84	92	88.0	84	33.5	4.95
1.751	1.745	0.006	2000	2310	5	4.18	70	70	70.0	70	35.8	7.48
1.751	1.745	0.006	2000	2490	5	4.51	74	80	77.0	74	35.0	6.6
1.751	1.744	0.007	2000	3455	5	6.26	82	94	88.0	60	34.2	5.72
1.751	1.744	0.007	2000	3082	5	5.58	68	70	69.0	70	36.0	7.7
1.751	1.744	0.007	2000	3805	5	6.89	74	86	80.0	80	34.2	5.72
1.751	1.743	0.008	2000	4955	5	8.98	64	64	64.0	70	35.8	7.48
1.751	1.743	0.008	2000	6320	5	11.45	70	75	72.5	75	34.7	6.27
1.751	1.741	0.010	2000	8550	4	19.36	70	77	73.5	78	35.0	6.6
1.751	1.741	0.010	2000	8050	3	24.31	74	84	79.0	85	33.2	4.62
1.751	1.736	0.015	2000	10700	1.5	64.62	78	88	83.0	92	32.4	3.74
1.751	1.736	0.015	2000	10920	2	49.46	68	68	68.0	73	35.2	6.82
1.751	1.731	0.020	2000	11230	1	101.72	73	73	73.0	85	33.4	4.84
1.751	1.731	0.020	2000	11195	1	101.41	72	80	76.0	85	33.4	4.84
1.751	1.749	0.002	4000	170	5	0.31	69	69	69.0	68	35.8	7.48
1.751	1.749	0.002	4000	175	5	0.32	70	70	70.0	68	35.8	7.48
1.751	1.748	0.003	4000	950	5	1.72	80	80	80.0	74	35.0	6.6
1.751	1.747	0.004	4000	1385	5	2.51	70	70	70.0	70	35.8	7.48
1.751	1.747	0.004	4000	1875	5	3.40	82	96	89.0	80	34.2	5.72
1.751	1.746	0.005	4000	2452	5	4.44	76	82	79.0	77	34.6	6.16
1.751	1.746	0.005	4000	3010	5	5.45	78	96	87.0	84	33.5	4.95
1.751	1.745	0.006	4000	3870	4	8.76	74	84	79.0	80	34.2	5.72
1.751	1.745	0.006	4000	4548	4	10.30	80	94	87.0	86	33.8	5.28
1.751	1.744	0.007	4000	3516	2.5	12.74	72	82	77.0	81	34.0	5.5
1.751	1.744	0.007	4000	4240	2.5	15.36	82	89	85.5	88	33.0	4.4
1.751	1.744	0.007	4100	4315	2	19.54	96	102	99.0	102	31.0	2.2
1.751	1.743	0.008	4000	9950	4	22.53	68	73	70.5	82	34.0	5.5
1.751	1.743	0.008	4000	9030	3	27.27	73	80	76.5	90	33.0	4.4
1.751	1.741	0.010	4000	10800	2	48.91	86	92	89.0	102	31.2	2.42
1.751	1.736	0.015	4000	12600	0.83	137.51	86	92	89.0	110	30.5	1.65
1.751	1.736	0.015	4000	10260	1	92.94	76	76	76.0	85	33.4	4.84
1.751	1.731	0.020	4000	12945	0.42	279.19	74	80	77.0	99	31.5	2.75
1.751	1.731	0.020	4000	13275	0.42	266.31	80	84	82.0	104	31.0	2.2

Table 2
Slippage Test Data

Clearance inches	Inlet Pressure psi	Slippage Uncorrected BPD	Viscosity centistokes	Viscosity centipoise	Ratio of Viscosities Std. = 6.38	Ratio of Inlet Pressure to 2,000 psi	Slippage Normalized to 2000 psi and 70 F BPD
0.002	1950	0.11	7.48	6.39	1.00	1.03	0.11
0.002	2000	0.12	7.48	6.39	1.00	1.00	0.12
0.002	2050	0.13	7.46	6.39	1.00	0.98	0.12
0.003	2000	0.83	6.82	5.81	0.91	1.00	0.76
0.003	2000	0.89	6.6	5.62	0.88	1.00	0.78
0.004	2000	1.26	7.7	6.58	1.03	1.00	1.30
0.004	2000	1.38	7.48	6.39	1.00	1.00	1.38
0.005	2000	3.52	6.38	5.43	0.85	1.00	3.00
0.005	2000	4.67	4.95	4.20	0.66	1.00	3.08
0.006	2000	4.18	7.48	6.39	1.00	1.00	4.19
0.006	2000	4.51	6.6	5.62	0.88	1.00	3.98
0.007	2000	6.26	5.72	4.86	0.76	1.00	4.77
0.007	2000	5.58	7.7	6.58	1.03	1.00	5.76
0.007	2000	6.89	5.72	4.86	0.76	1.00	5.26
0.008	2000	8.98	7.48	6.39	1.00	1.00	8.99
0.008	2000	11.45	6.27	5.34	0.84	1.00	9.58
0.010	2000	19.36	6.6	5.62	0.88	1.00	17.07
0.010	2000	24.31	4.62	3.92	0.61	1.00	14.93
0.015	2000	64.62	3.74	3.17	0.50	1.00	32.07
0.015	2000	49.46	6.82	5.81	0.91	1.00	45.07
0.020	2000	101.72	4.84	4.11	0.64	1.00	65.49
0.020	2000	101.41	4.84	4.11	0.64	1.00	65.29
0.002	4000	0.31	7.48	6.39	1.00	1.00	0.31
0.002	4000	0.32	7.48	6.39	1.00	1.00	0.32
0.003	4000	1.72	6.6	5.62	0.88	1.00	1.52
0.004	4000	2.51	7.48	6.39	1.00	1.00	2.51
0.004	4000	3.40	5.72	4.86	0.76	1.00	2.59
0.005	4000	4.44	6.16	5.24	0.82	1.00	3.65
0.005	4000	5.45	4.95	4.20	0.66	1.00	3.59
0.006	4000	8.76	5.72	4.86	0.76	1.00	6.68
0.006	4000	10.30	5.28	4.49	0.70	1.00	7.24
0.007	4000	12.74	5.5	4.67	0.73	1.00	9.33
0.007	4000	15.36	4.4	3.73	0.58	1.00	8.98
0.007	4100	19.54	2.2	1.86	0.29	0.98	5.55
0.008	4000	22.53	5.5	4.67	0.73	1.00	16.51
0.008	4000	27.27	4.4	3.73	0.58	1.00	15.94
0.010	4000	48.91	2.42	2.04	0.32	1.00	15.66
0.015	4000	137.51	1.65	1.39	0.22	1.00	29.96
0.015	4000	92.94	4.84	4.11	0.64	1.00	59.84
0.020	4000	279.19	2.75	2.32	0.36	1.00	101.64
0.020	4000	286.31	2.2	1.86	0.29	1.00	83.28

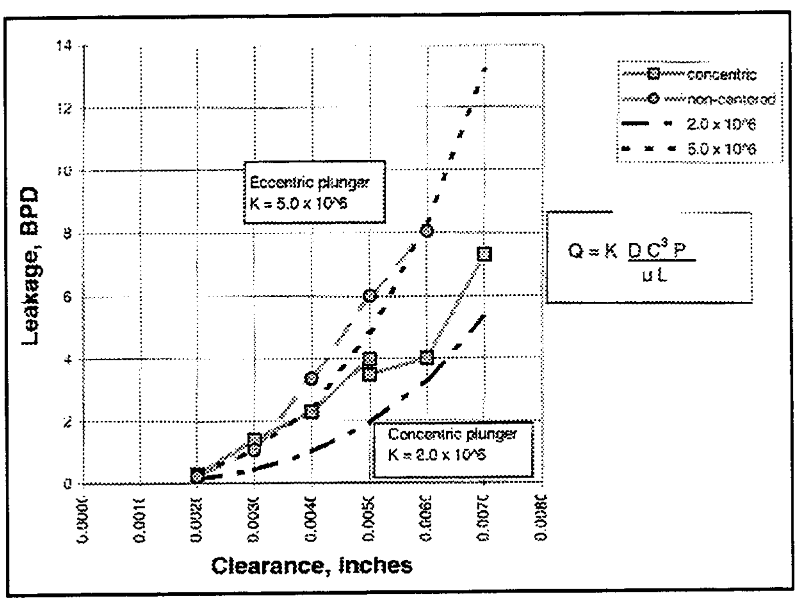

Figure 1 - Pump Leakage Data vs. Theoretical Leakage 2000 psi Differential Pressure with Oil

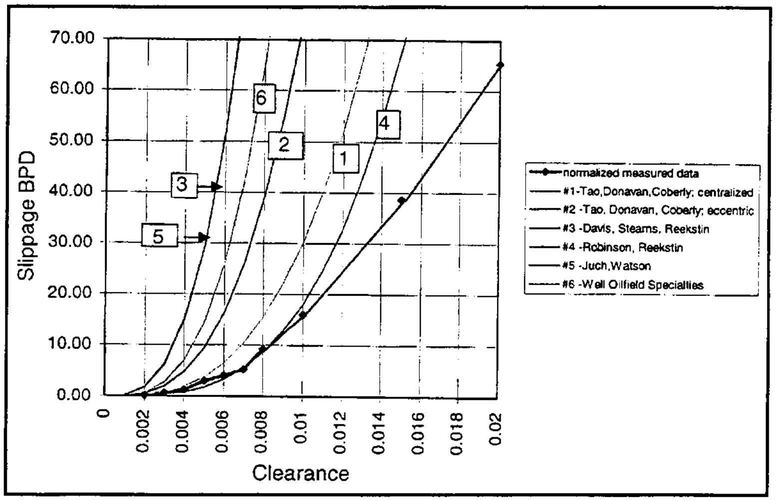

Figure 2 - 2000 psi Normalized Data Compared to Various Predictive Equations for 1.75" Pump, Oil Viscosity 6.38 cp, 36" Plunger Length

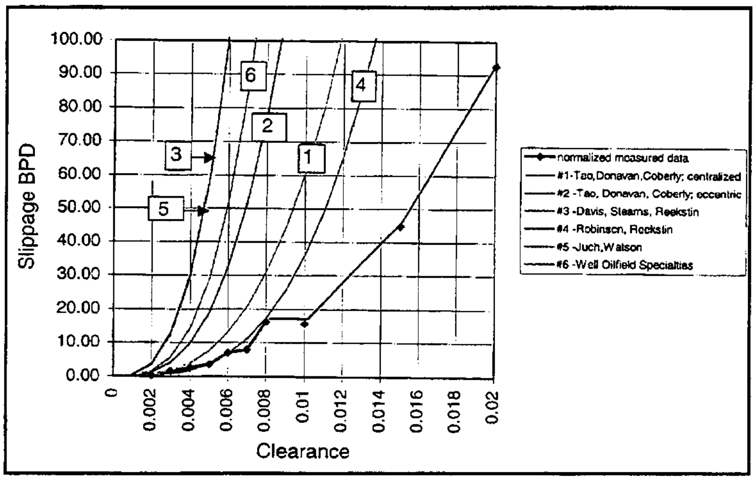

Figure 3 - 4000 psi Normalized Data Compared to Various Predictive Equations for 1.75" Pump, Oil Viscosity 6.38 cp, 36" Plunger Length

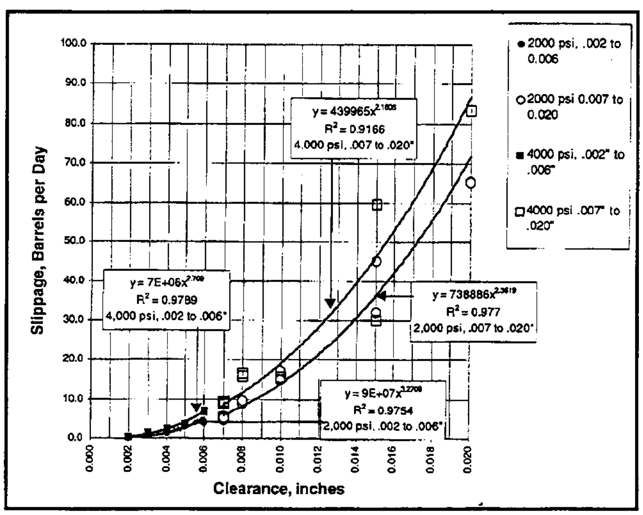

Figure 4 - Normalized Slippage vs. Clearance at 2000 psi and 4000 psi

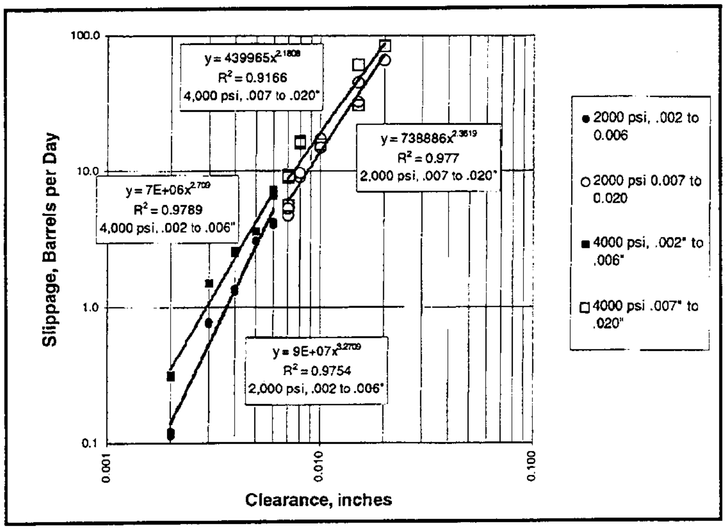

Figure 5 - Normalized Slippage vs. Clearance at 2000 psi and 4000 psi

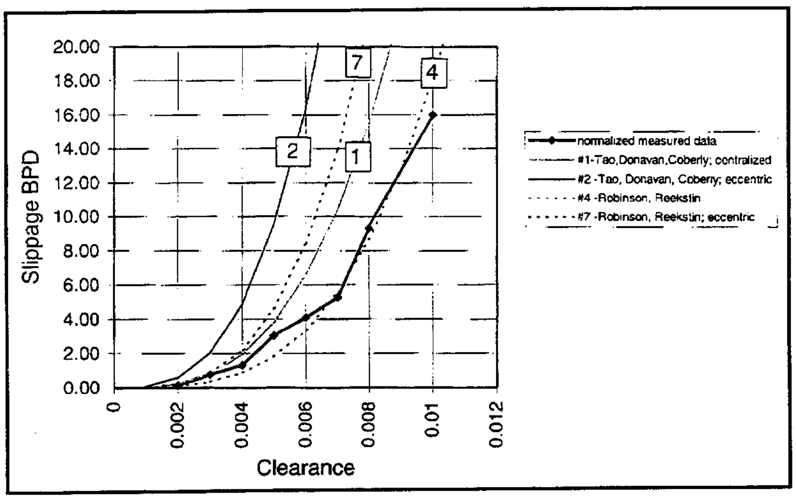

Figure 6 - 2000 psi Normalized Data Compared to Various Predictive Equations for 1.75" Pump, Oil Viscosity 6.38 cp, 36" Plunger Length

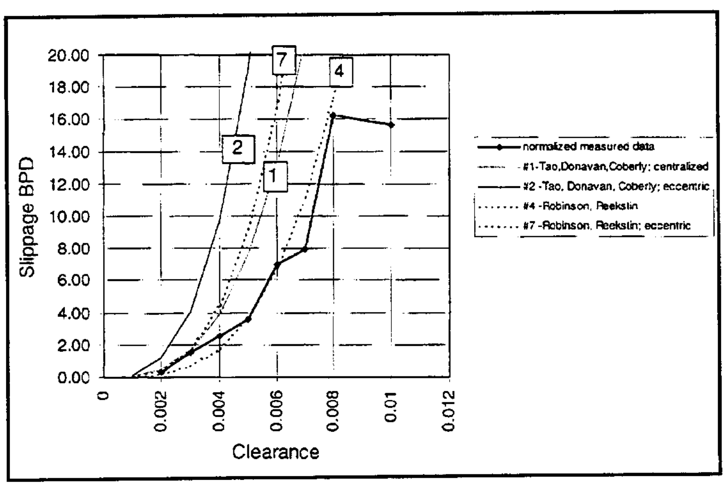

Figure 7 - 4000 psi Normalized Data Compared to Various Predictive Equations for 1.75" Pump, Oil Viscosity 6.38 cp, 36" Plunger Length