EFFICIENCY OF ARTIFICIAL LIFT SYSTEMS

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ABSTRACT

Efficiency of an artificial lift installation is the useful power transmitted to the produced fluid, divided by the power of the electrical energy being supplied to the prime mover. This definition applies where the prime mover is an electric motor. However, the output can be taken at the pump output, as it frequently is by electrical submersible manufacturers, or the output can be taken at the surface after power is lost due to friction in the tubing. Both definitions are presented and compared and are nearly the same when losses from the pump to the surface are low. However, when comparing different types of lift by efficiency comparisons, it is good practice to be sure the values were calculated by the same efficiency formula.

Following the discussion of the possible definitions of artificial lift efficiencies, data is presented comparing the efficiency of beam units vs. ESP efficiency for some West Texas wells. It is suggested that all artificial lift installations be maintained by frequently collecting the few pieces of data necessary to calculate the efficiency of the artificial lift installation. The efficiency number might be used to trouble shoot the well, to compare the efficiency to other wells using difference types of lift, or to compare to wells using similar types of lift to see what efficiencies are possible and what might be done to tune wells to near the peak possible efficiency.

SYSTEM EFFICIENCY FROM REFERENCES

Many excellent papers in the literature make reference to system efficiency of an artificial lift installation. However, as will be seen, there are many definitions, each differing somewhat in the actual definition or in the simplifications that were used to arrive at the final form of the expression.

To begin, several definitions of efficiency from measured data of an artificial lift installation are found in the literature and discussed here. Some of the differences are discussed. Then a preferred definition is presented taken at the pump discharge and/or at the surface.

Efficiency from measured data is the ratio of useful system output, Ho divided by the input to the motor times 100. The input horsepower to the motor will be taken as the input Kilowatts (KW) divided by .746, or KW/.746. The differences in expressions for efficiency will then depend on what is selected as the definition of the useful system output of the artificial lift installation.

$$\text{Efficiency} = \text{Ho}/(\text{KW}/.746) \times 100 \qquad [1]$$

From Moncrief[1] the following definition of system output to the fluid is:

$$\text{Output Horsepower, Ho} = .000017 \times Q \times \text{Delta P} \times \text{Depth} \qquad [2]$$

(Equation [2] is a misprint from Ref. 1 -- Depth should be removed.)

Where: Q = Flow rate, BPD. Note: This should be the volumetric flow rate through the pump although most references use the production, or the production times a formation volume factor.

Ho is referred to as hydraulic HP, HHP.

Delta P = The pressure increase across the pump, psi.

Equation [2] is incorrect due to a misprint and should read:

$$Ho = .000017 \times Q \times \text{Delta P} \quad \text{or} = Q \times \text{Delta P}/58823 \qquad [3]$$

or in terms of lift:

$$Ho = .00000736 \times Q \times \text{Lift} \qquad [4]$$

Where: Lift = Net lift, ft. This is sometimes approximated by depth.

So Equation [2] is a misprint. Equation [3] is what was intended for Equation [2]. If in Equation [4], lift does not include a height to account for friction, then Ho would be at the surface and not at the pump discharge.

Reference 2 presents the following for the output of the system where Ho is called HHP.

$$Ho = \frac{SG \times Q \times \text{Delta P}}{135{,}800 \times FG} \qquad [5]$$

SG = specific gravity of fluid
FG = fluid gradient, psi/ft (flowing or static?)

Equation [5] is approximately correct, but has unnecessary terms in it. Ho at pump discharge is just Q x Delta P times a constant to obtain the appropriate units. The Delta P across the pump is determined by the type of fluids flowing and no additional specific gravities or gradients need be in the formula. Essentially Equation [5] should reduce to Equation [3].

Gault[3] uses the following expression for Ho referred to as HHP.

$$Ho = .00000736 \times Q \times \text{NET LIFT} \qquad [6]$$

Where: NET LIFT = depth as used by Gault which becomes Equation [4], ft.

The NET LIFT used in Gault's paper does not include the tubing friction. In other words friction has been he has subtracted out before using the formula. Since the friction is not included before calculating Ho, Equation [6] is finding the Ho at the surface and not at the pump discharge. Again if the friction is low, this does not matter much. Also, although Gault used the depth as the NET LIFT for calculations, it is usually reduced by the fluid in the annulus but Gault did his calculations near pumped off conditions. Also the above formula is for fluid specific gravity, SG = 1.

Clegg[4] gives the following expression for Ho, referred to as HHP:

$$Ho = L \times Q \times SG/136{,}000 \qquad [7]$$

Where: L = Net lift (surface to fluid level), ft.

In Equation [7], the lift is modified by a specific gravity, so a water gradient is not implied. However, the fluid in the annulus usually has a different specific gravity than the tubing so there is some approximation by using only one SG. Also the formula by Clegg does not include friction, so this becomes a formula for the output taken at the surface and not at the pump discharge. However approximations in the formula are probably better than the usual quality of the data entered into the efficiency formula.

Butlin[5] gives the formula for Ho (called HHP) as follows:

$$Ho = .000007376 \times Q \times \text{Feet of Lift} \qquad [8]$$

Equation [8] is the same as Equation [3] presented by Gault so the comments are the same as above.

Kilgore and Tripp[6] give the following expression for Ho (HHP):

$$Ho = Q \times H \times SG/3960 \qquad [9]$$

Where:

H = Height of the fluid. In this paper it was taken at pump conditions so no height in the annulus was needed, ft.

Q = Flow through the pump accounted for by the authors, GPM.

Since the flow rate Q, is in GPM and not BPD, then this looks differently than above formulas but if Q is in BPD then it is the same as Equation [7].

Since Equation [9] is the same as Equation [7], then the discussion is the same. However, there is a question from reading Reference 6 because it says that the Ho was derived from gradients in the tubing implying that the gradient included friction. However, a SG and height H imply friction is not included in the final expression.

The above discussion shows that the efficiency (from measured data) of artificial lift takes many forms in the literature. Some of the forms were developed for specific situations, such as when the well is completely pumped off. Other forms differ only since they have quantities input in different units, or are in terms of different variables such as heights or pressures with/without a specific gravity, etc. Other differences occur in how the pressure in the annulus is treated.

PREFERRED FORMS OF EFFICIENCY

Reference 7, page 90, lists the pump power out as:

$$Po = Q \times \text{Delta } P/1714 \qquad [10]$$

Where:

Po = Pump power output, hp. Ho is used as Po in preceding discussion.
Q = flow rate through the pump, GPM.

If one uses Equation [10] as a starting point of the definition of the output of an artificial lift installation, then you would choose the pump discharge as the point of the efficiency definition where the Ho includes the horsepower necessary to overcome friction effects in tubing, etc. This has been expanded in oil field units in Figure 1 showing how to calculate the efficiency of a pumping unit starting with the same concept as in Equation [10].

However, suppose that two wells had artificial lift devices (ESP, Beam pump, Moyno, etc.) of equal efficiency. Then, suppose that one well has a correctly sized tubing for the flow rate such that the friction pressure drop is low and suppose that the other well has a tubing diameter that is too small and a large frictional drop is present. Both wells would have the same efficiency at the pump discharge because the ratio of power out to power in would be the same. However after reaching the surface, the well with the small tubing would have losses greater than the well with the correctly sized tubing. So the entire system including the tubing would have an efficiency lower if there are substantial tubing losses. This is essentially what you obtain when you calculate a discharge pressure with a height and a specific gravity instead of a flowing gradient.

The example of subtracting out the tubing friction is shown in Figure 2. For many cases in the oil industry, the efficiencies as calculated in Figure 1 and 2 are close together because the friction is low. However if friction is high in the tubing, then the method shown in Figure 2 will be noticeably lower. When comparing different methods of artificial lift one method is to use the method in Figure 1 and then examine the effects of friction separately to be sure there are no excess friction drops. Another method is to calculate both efficiencies and if they are close, then the friction is low. Regardless, when comparing artificial lift efficiencies, especially from one method of lift to another, it is wise to be sure you are using the same efficiency definition before the comparisons are made.

The following section is a study of comparisons of the efficiencies of beam pump installations and electrical submersible pump installations. The details of the West Texas study follow, where the initial intent was to determine approximately, at what rate do the system efficiencies for ESP's become better than the efficiencies for beam pump installations, if in fact they do under the field conditions discussed below.

MEASURED EFFICIENCIES OF BEAM PUMPING AND ESP SYSTEMS

Beam pumping and ESP system efficiencies were calculated to determine the operating conditions where the installation of an ESP would be more economical than a beam pumping unit. Based on measured electrical power usage over the production ranges considered (500-900 BPD), a beam pumping system in this study always used less electric power per barrel of fluid produced than an ESP.

Electrical power usage for ESP's and beam pumping units were compared on a a per barrel of fluid produced basis. This comparison was made using measured electric power usage from 6 wells (3 ESP's and 3 beam pumping units) at 2 different properties (Property A and B) for a total of 12 wells. All of the beam pumped wells were equipped with pump-off controllers even though two of the wells ran 24 hours a day. Electric power measurements were collected for the six beam pumping units over a time period that ranged from three to seven days using KW-hr meters. ESP power usage was collected over a time period that ranged from 4 hours to one week. Electric power readings were converted to KW-hr/hr terms. Existing testing facilities were used to measure oil and water production rates. Gas production from the test wells is low, generally ranging from

5-30 MCFD, and was not recorded. Well fluid levels taken during the test period were averaged. From the pump set depth and average fluid level, the net producing depth was determined.

The average overall beam pumping unit efficiency was approximately 57%, while the average overall ESP efficiency was approximately 34%. Efficiencies were determined by dividing the power out of the system by the power into the system. The power out of the system is the HP over time calculated by the net depth, fluid specific gravity, and production rate. The power into the system is the electric power usage (measured KW-hrs) divided by time.

An effort was made to select test well locations where the lift equipment was properly applied. Details of the operating conditions of the wells in Property A and Property B are included as Tables 1 and 2. Based on pump volumetric efficiencies, the rod pumps appear to be in good condition. ESP pump test data available indicated that the ESP's were operating near the published performance specifications.

From the field measurements collected in this particular study, a beam pumping unit will use approximately 40% less electric power per barrel of fluid lifted than an ESP. Table 3 contains electrical operating expense projections for ESP's and beam pumping units based on these measurements. Using a cost for electric power of $0.03/KW-hr and a net pumping depth of 4500 ft, electrical power savings of approximately $5,000 per year can be achieved by using a beam pumping unit instead of an ESP at a 600 BPD producing rate.

Electric power measurements for beam pumping units and ESP's were also available from a previous field study for wells with producing depths of 5000 and 6700 ft (Properties C and D). Power consumption, in terms of KW-hrs per barrel of fluid produced, for each net producing depth (Properties A, B, C, and D) were plotted and the relationship between net depth and KW-hr per barrel of fluid produced was established. This relationship is shown in Figure 3. The relationship between output power (100% efficiency) and depth is also shown in Figure 3. As can be seen from this graph, beam pumping system power usage is considerably lower than ESP system power usage at all producing depths. The method of Figure 1 is used for the output power here. Also, based on the slope of the graphs, system efficiencies remain relatively constant with changes in producing depth.

SUMMARY

A review was made of some of the forms of equations appearing in the literature to which measured data are supplied to calculate the efficiency of artificial lift installations. It is shown that there are many types of formulas with varying degrees of sophistication or approximation. The user should be sure he is dealing with data from only one type definition efficiency before comparisons are made to assure good comparisons of artificial lift installations.

Data is presented from a West Texas field where it was desired to find a production rate above which EPSs are more energy efficient and below which beam pumps are more efficient. It was found that the beam pumps, for the range of depths and rates studied, were always more energy efficient. In fact the ESP's were lower in efficiency than expected and the beam pump installations were more efficient than expected. The ESP installations showed efficiencies in the mid 30s and the beam pump installations were in the high 50s. The beams were in the high end of ranges reported by Reference 6 although Reference 4 indicates a beam efficiency of 61% for a "typical good installation". However, Reference 4 (Clegg) reports a good installation for ESP's to be in the high 40s. Efficiencies in the mid 30s measured in this study were thought to be good applications but still showed relatively low efficiencies. These figures, along with failure rates, and other economic considerations, will determine the direction of artificial lift in this field and in other fields where these type of studies are made.

REFERENCES

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Table 1
Property A - Producing Depth Approximately 4700 Feet

ELECTRICAL SUBMERSIBLE PUMPS

Well #	Casing Press. psi	FLAP ft.	Pump Set Depth ft.	^ Head ft.	^ Press. psi	Tubing Size In.	Production Test Oil BPD	Water BPD
MFU-557	30	280	4750	4509	1998	2.875	33	800
MFU-168	16	368	4650	4334	1881	2.375	110	575
MFU-682	30	304	4785	4524	2002	2.875	25	500

Well #	Pump Manuf.	Pump Model #	# of Stages	Cable Size	Motor Size HP	Average Kw-hr/hr Reading	Hydraulic HP (calc.)	Kw-hr per Barrel	Pump Maximum Efficiency Eff. %	@ BPD	Pump Actual Operating Eff. %	Overall System Eff. %
MFU-557	Reda	DN-1000	190	#4	60	62.97	28.3	1.81	0.56	975	53	34
MFU-168	Reda	DN-800	191	#4	50	49.58	21.9	1.74	0.58	800	57	33
MFU-682	Reda	DN-800	172	#4	60	44.21	17.9	2.02	0.58	800	52	30
							AVERAGE	1.86			AVERAGE	32

BEAM PUMPING UNITS

Well #	Casing Press. psi	FLAP ft.	Pump Set Depth ft.	^ Head ft.	^ Press. psi	Tubing Size In.	Production Test Oil BPD	Water BPD
MFU-26	15	127	4760	4651	2062	2.875	21	570
MFU-687	28	670	4804	4228	1870	2.875	25	489
MFU-184	39	311	4708	4441	1971	2.875	20	650

Well #	Pump Manuf.	Pump Model #	Pump Diam. In.	Strokes per min.	Stroke Length In.	Average Kw-hr/hr Reading	Hydraulic HP (calc.)	Kw-hr per Barrel	BLAP Theoretical Prod. BPD	Volumetric Eff. %	Overall System Eff. %
MFU-26	Lufkin	C640-365-168	2.00	10.9	144	28.77	20.7	1.17	670	88	54
MFU-687	Lufkin	A640-305-168	2.00	8.5	168	22.04	16.4	1.03	547	94	55
MFU-184	Lufkin	A640-305-168	2.25	8.2	168	29.43	22.5	1.05	752	89	57
							AVERAGE	1.08		AVERAGE	55

Table 2
Property B - Producing Depth Approximately 6000 Feet

ELECTRICAL SUBMERSIBLE PUMPS

Well #	Casing Press. psi	FLAP ft.	Pump Set Depth ft.	^ Head ft.	^ Press. psi	Tubing Size In.	Production Test Oil BPD	Water BPD
AI-356	30	108	5920	5827	2572	2.875	30	441
AI-333	28	150	6050	5921	2638	2.875	3	548
AI-305	31	177	5850	5698	2510	2.875	47	578

Well #	Pump Manuf.	Pump Model #	# of Stages	Cable Size	Motor Size HP	Kw-hr/hr Reading	Hydraulic HP (calc.)	Kw-hr per Barrel	Pump Maximum Efficiency Eff. %	@ BPD	Pump Actual Operating Eff. %	Overall System Eff. %
AI-356	Cent..	FC-650	224	#5	60	50.06	20.6	2.55	0.58	660	56	31
AI-333	Reda	DN-600 Tan	247	#6	50	45.76	24.7	1.99	0.58	625	57	40
AI-305	Reda	D-950 Tan	248	#4	60	54.91	26.7	2.11	0.62	920	54	36
						AVERAGE		2.22			AVERAGE	36

BEAM PUMPING UNITS

Well #	Casing Press. psi	FLAP ft.	Pump Set Depth ft.	^ Head ft.	^ Press. psi	Tubing Size In.	Production Test Oil BPD	Water BPD
AI-470	30	125	6040	5933	2630	2.875	22	579
AI-173	39	63	6160	6106	2686	2.875	33	363
AI-324	35	510	6050	5611	2456	2.875	45	352

Well #	Pump Manuf.	Pump Model #	Pump Diam. In.	Strokes per min.	Stroke Length In.	Average Kw-hr/hr Reading	Hydraulic HP (calc.)	Kw-hr per Barrel	BLAP Theoretical Prod. BPD	Volumetric Eff. %	Overall System Eff. %
AI-470	Amer.	C640-365-144	2.00	10.3	144	35.8	26.9	1.43	677	89	56
AI-173	Amer.	C640-365-144	1.75	10.1	144	21.69	18.1	1.31	475	83	62
AI-324	Lufkin	C456-305-120	1.75	10.2	120	22.18	16.6	1.34	398	100	56
						AVERAGE		1.36		AVERAGE	58

Table 3
Electrical Operating Expense Beam Pumping Units and ESPs

PROPERTY A

PRODUCING DEPTH - APPROXIMATELY 4700 FT.
NET DEPTH - APPROXIMATELY 4500 FT.

Electric Power Expense

Rate BPD	Beam $/yr	ESP $/yr	Difference $/yr
400	4,744	8,147	3,403
500	5,929	10,184	4,254
600	7,115	12,220	5,105
700	8,301	14,257	5,956
800	9,487	16,294	6,807

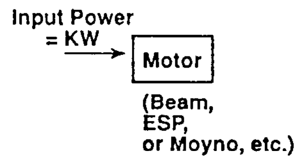
PROPERTY B

PRODUCING DEPTH - APPROXIMATELY 6000 FT.
NET DEPTH - APPROXIMATELY 5850 FT.

Electric Power Expense

Rate BPD	Beam $/yr	ESP $/yr	Difference $/yr
400	5,957	9,724	3,767
500	7,446	12,155	4,709
600	8,935	14,585	5,650
700	10,424	17,016	6,592
800	11,914	19,447	7,534

Yearly power costs were calculated based on an electric power cost of $0.03/kw-hr

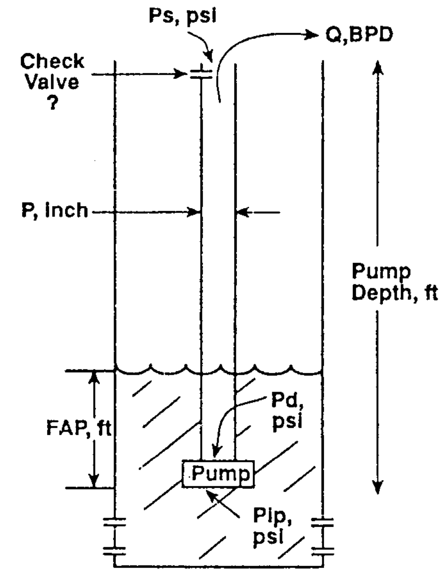


Efficiency (at pump discharge)

$$= \frac{Ho}{\text{Input HP}} \times 100, \%$$

Input HP = KW/0.746

Ho = (Q,BPD)(Pd-Pip)/58800



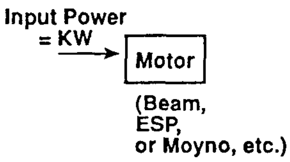
EXAMPLE:

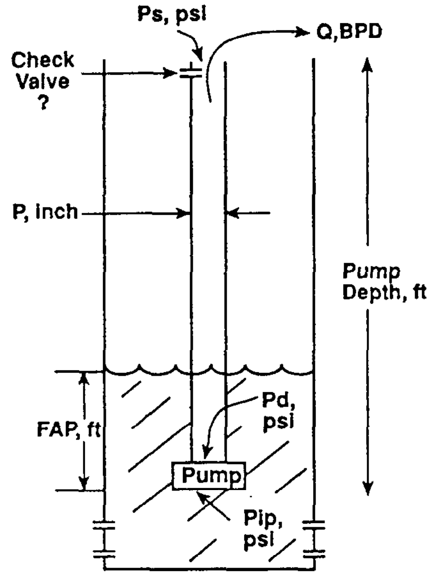
Input HP = 25 KW/.746 = 33.5 HP
Q = 500 BPD (assumed through pump)
Ps = 20 psi, Depth = 5000 ft, FAP = 200 ft
Gradt = tubing flowing gradient = .43 psi/ft
Pd = discharge pressure = Ps + Gradt (Depth)
= 20 + .43(5000 ft) = 2170 psi
Gradc = casing fluid gradient = .37 psi/ft
Pip = intake pressure = Ps + Gradc (FAP)
= 20 + (.37)(200) = 94 psi
(check assumed)

Ho = Q(Pd - Pip)/58800 = 500(2170 - 94)/58800
= 17.65 HP

$$\text{Efficiency} = \frac{\text{Ho} \times 100}{\text{Input HP}} = \frac{17.65(100)}{33.5} = 52.7\%$$

Figure 1 - Overall efficiency of artificial lift installation at pump discharge





Efficiency (at surface)

$$= \frac{Q\ (Pd - Pip - \Delta P_f)/58800}{\text{Input HP}}$$

Input HP = KW/.746

ΔP_f = delta pressure in tubing due to friction

EXAMPLE:
Same as on Figure 1 except:

Assume ΔP_f = 64.5 psi
ΔP_f Q/58800 = 64.5 (500 BPD)/58800 = .548
Q (Pd-Pip - ΔP_f)/58800 = 17.1 HP

$$\text{Efficiency (@ Surface)} = \frac{Q\ (Pd - Pip - \Delta P_f)/58800}{\text{Input HP}} \times 100$$

$$= \frac{(17.1)(100)}{33.5} = 51\%$$

(Note: with high friction efficiency at surface could be much lower)

Figure 2 - Overall efficiency of artificial lift installation at surface

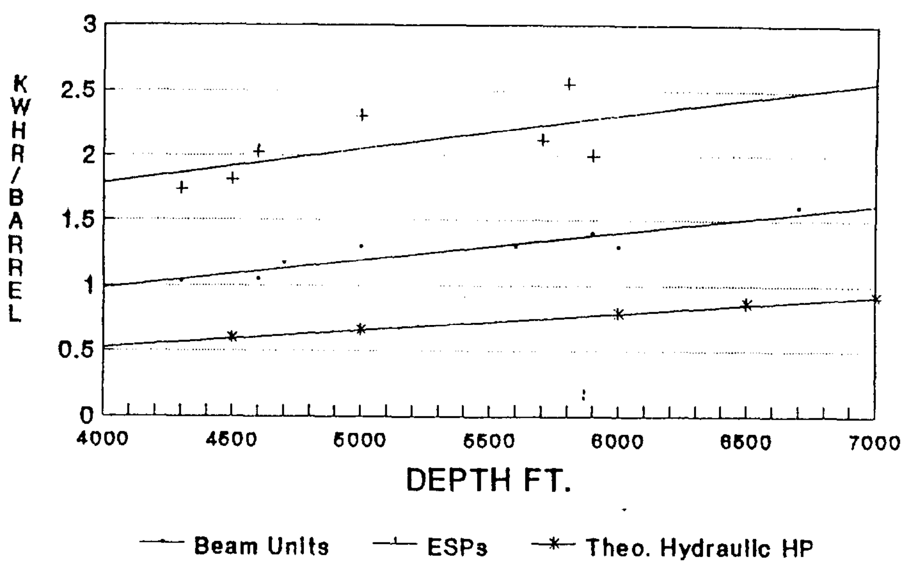


Figure 3 - Beam and ESP power consumption vs. producing depth