IMPROVING ROD PUMPING OPERATIONS IN A MATURE FIELD: A CASE STUDY

Gabor Takacs
University of Miskolc, Hungary

ABSTRACT

The profitability of rod pumping operations is a direct function of the energy requirements of pumping. For maximum profits the efficiency of the pumping system must be maximized, this can only be achieved by finding the optimum pumping mode for the required liquid production rate. These principles are used in the paper by presenting a case study on the possible ways of improving rod pumping operations.

The project reported was conducted in a mature onshore field with 70-plus rod pumped wells. An extensive measurement program involving more than 50% of the wells was set up and pumping parameters were measured with a portable computerized system. The detailed evaluation of measurement data facilitated the detection of general and specific problems in the design and operation of the pumping installations. With the aim of improving the field-wide profitability of pumping operations, an optimization of each well's pumping parameters was made. Calculation results showed that a field-wide power saving of about 17% can be anticipated if all wells operate at their most economic pumping modes.

INTRODUCTION

The basic objective of the project was to improve sucker-rod pumping operations in a mature field by analyzing and optimizing the production conditions. In order to reach this final goal, the project was divided into three different, but strongly interrelated tasks:

1. Assessment of the current operating conditions of producing wells and discovery of problem areas.
2. Determination of the optimum pumping modes for each well while keeping current equipment and liquid production rate restrictions.
3. For selected **Key Wells**, taking into account the information available on inflow performance, determination and verification of optimum pumping system designs ensuring the greatest liquid production increase by reaching pumped-off conditions.

To achieve the project's objectives, an extensive measurement program involving more than 50% of the 70-plus producing wells was set up. Pumping parameters were measured with a portable computerized system that provided measurement of all principal operational parameters of the pumping installations. The detailed evaluation of the data received from each well's field measurements facilitated the detection of general and specific production problems. Based on these findings, detailed recommendations for their avoidance were given, and suggestions on improving operational conditions were specified.

Optimization of the current operational conditions involved the determination of the optimum pumping modes for the wells included in the project with the following restrictions: (a) liquid rates were kept at current levels, and (b) the main parameters of the installation (pump setting depth, tubing size, etc.) were not changed. Results of these optimizations allow the operator to see the positive changes made possible by the selection of the optimum pumping modes for each well. The most important improvement is the reduction of power requirements of pumping operations which is determined for each well and the whole field alike for two versions: (1) when no tubing anchors are used (the current practice in the field), and (2) when the tubing is anchored.

The final objective of the project is to investigate the possibility and the effects of increased liquid production rates. For this reason, several **Key Wells** were selected for which installations ensuring the possible maximum pumping rates are designed. The surface systems (pumping units and gearboxes) of the optimized installations, in contrast to current well conditions, are properly loaded and achieve sufficiently high power efficiencies.

EVALUATION OF THE STATUS OF ROD PUMPED WELLS

Measurement Procedure

All measurements on the pumping wells were executed with the help of a portable computerized system including the required hardware and software components, and specifically developed for testing and analyzing sucker-rod pumped oil wells.

A complete analysis of a sucker-rod pumping installation using the portable equipment involves several phases and requires the adherence to specific procedures. Each phase can be conducted independently of the other but proper and complete well analysis usually consists of the following steps:

1. Without stopping the operation of the sucker-rod pumping unit, first an acoustic device is used to find the dynamic liquid level in the well’s annulus.
2. After the casing valve is closed, the pressure buildup vs. time is measured at the casinghead for the determination of the well’s gas production rate.
3. Next, a dynamometer survey is conducted to measure the polished rod loads and movements for several pumping cycles. It is important to record a representative, i.e. stabilized surface dynamometer card for further analysis.
4. The downhole pump’s valves are tested next; by conducting the Traveling Valve test (TV) and the Standing Valve test (SV).
5. Finally, electric power measurements are executed to establish the electrical parameters of the motor’s input power.

Evaluation of Measured Data

Most of the measured data were processed on-line by the portable analyzer system at the wellsite and appropriate parameters and diagrams were stored in computer files. In addition to the factors calculated by the software, further operational parameters were evaluated for each well. In the following, short descriptions of those parameters not readily available or otherwise requiring explanations are presented.

Well Inflow calculations are based on the knowledge of the dynamic fluid level. After the FBHP (Flowing Bottomhole Pressure) is calculated, two options are available to find the well’s inflow performance: (1) the use of the constant PI (Productivity Index) principle, or (2) the use of the **Vogel** IPR curve. For the majority of cases in this study, the PI principle could be used because no free gas entered the wells from the perforations

Surface System Loadings are expressed as percentages of equipment ratings. Beam loading is calculated as the ratio of the measured PPRL (Peak Polished Rod Load) to the pumping unit’s structural load rating, gearbox loading means the ratio of the measured Peak Net Torque and the torque capacity of the gearbox. Motor load is expressed by the ratio of the RMS current taken by the electric motor to the motor’s full-load current rating.

The analysis program calculates the degree of counterbalancing of the gearbox and gives recommendations for achieving optimum conditions. This may involve moving or replacing counterweights on the unit’s cranks.

Downhole Pump Conditions are evaluated from the results of valve tests as well as from the shape and other parameters of the calculated pump cards. In some cases (usually for wells with older production tests) the calculated pump displacement very significantly diverged from the latest measured liquid rate. In such cases, in order to verify the accuracy of the measurements, the pumping rate was calculated by using the **API RP 11L** [1] model. If the liquid rate thus received agreed with the output of the analysis program, production test data were not used and a new test was recommended.

Rod Loading of the individual tapers is expressed as the percentage of the maximum allowed rod stress. The allowed stresses are calculated from the modified **Goodman** diagram, used for evaluating the fatigue loading of sucker-rod strings.

Power Efficiencies of sucker-rod pumped installations are defined and calculated in different ways in different publications [2 – 4], this is why a more detailed description of the method followed in this study is required.

Power efficiency, in general, is defined as the ratio of the useful and the total input powers to a system. The useful power exercised by the sucker-rod pumping system is found from the amount of liquid lifted and the lifting depth; while the total electrical energy input to the system is actually measured by the portable analyzer. Thus, total System Efficiency is calculated as given in the following:

$$\eta_{system} = 100 \frac{P_{hydr}}{P_e} \qquad (1)$$

where: P_{hydr} = useful hydraulic power, HP, and

P_e = electrical power input to the system, HP.

The system's total efficiency is composed of the efficiencies of the downhole system and the surface drive train. The latter is made up of the pumping unit, the gearbox, the V-belt drive, and the electric motor. If efficiencies to those two components are assigned then **System Efficiency** may be expressed as:

$$\eta_{system} = \eta_{lift}\,\eta_{surf} \qquad (2)$$

where: η_{lift} = lifting efficiency, %, and
η_{surf} = surface efficiency, %.

Lifting Efficiency, as defined in the following, represents the efficiency of energy utilization and the amount of losses in the downhole system: the pump, and the rod string. Its value depends on the proper selection by the production engineer of the pumping mode; i.e. the pump size, the polished rod stroke length, and the pumping speed. It is easily calculated from the measured value of the Polished Rod Power (PRHP):

$$\eta_{lift} = 100\,\frac{P_{hydr}}{PRHP} \qquad (3)$$

where: PRHP = polished rod power, HP.

The **Surface Efficiency** covers all the energy losses occurring in the drive train: the pumping unit, the gearbox, the V-belt drive, and the electric motor. It is easily found as given here:

$$\eta_{surf} = 100\,\frac{PRHP}{P_e} \qquad (4)$$

Comparison of the efficiency values discussed previously facilitates the detection of problem areas in a given rod-pumped installation.

Conclusions

The main results of well evaluations led to the following conclusions.

Counterbalancing of gear reducers for the wells investigated is illustrated in the following table.

Counterbalancing Condition	**No. of Wells**	**Percentage**
Perfectly balanced	3	8.8%
Not perfectly balanced, but correctable	13	38.2%
Impossible to balance	18	53.0%
Total	**34**	**100.0%**

The conclusion is that more than half of the investigated wells cannot be properly balanced. The reason for this very specific behavior lies in the fact that, due to the very light pumping loads, the units are weight heavy even with no counterweights on the unit's cranks.

Stuffing Boxes require regular checking for leaks and tightness. Too loose boxes result in fluid leaks, whereas over-tightening of stuffing boxes increases well loads and may cause downhole problems as well. Our experiences on the wells surveyed are summarized here:

Stuffing box condition	**No. of Wells**
Slightly over-tightened	4
Excessively over-tightened	6

Downhole Pump Conditions are heavily influenced by the operation of the standing and traveling valves. They should be frequently checked for proper operation and the amount of their wear. Valve conditions, based on field measurements, are presented in the following.

SV Condition	No. of Wells	Percentage
Holds perfectly	32	97.0%
Leaking	1	3.0%
Total	**33**	**100.0%**

TV & Barrel Conditions	No. of Wells	Percentage
Perfect	13	40.6%
Leaking less than 5 bpd	11	34.4%
Leaking more than 5 bpd	8	25.0%
Total	**32**	**100.0%**

Lifting Efficiency, as defined in **Eq. 3**, represents the amount of downhole losses in a sucker-rod pumped well. For any well producing a specific liquid rate, it can be changed in a broad range by modifying the pumping mode while the well's rate is unchanged. For properly designed pumping installations, lifting efficiencies range between 70% and 85% [5]. The values found in this survey are grouped according to their numerical values in the following table.

Lifting Efficiency Ranges	No. of Wells	Percentage
Less than 25%	1	4.0%
25 – 50%	7	28.0%
50 – 75%	6	24.0%
More than 75%	11	44.0%
Total	**25**	**100.0%**

As seen from the table, lifting efficiencies in more than half of the investigated wells are below 75%, meaning that current pumping modes (plunger sizes, stroke lengths, and pumping speeds) are not at their possible optimum.

Rod Strings, as concluded from our measurements, are strong enough, their fatigue loading is sufficiently uniform, but they are excessively over-designed and are therefore too heavy. The following table shows the average fatigue loadings of rod strings in the investigated wells, grouped according to their numerical values.

Avg. Rod String Loading	No. of Wells	Percentage
Acceptable (more than 60%)	3	9.0%
Light (between 60% and 40%)	21	63.6%
Very light (less than 40%)	9	27.4%
Total	**33**	**100%**

Surface Efficiency of sucker-rod pumping system components, if they are properly loaded, is usually very high. Average efficiencies are the following [5, 6]: pumping unit = 90%; gearbox = 80%. The efficiency of the total surface system, therefore, lies between 60% and 75%, provided the pumping unit and the gearbox are properly loaded.

Efficiencies calculated from measured data, shown in the following table verify that, in line with previous findings, practically all pumping units are extremely oversized for the job.

Calculated Surface Efficiency	No. of Wells	Percentage
Optimum (more than 70%)	0	0.0%
High (between 60% and 70%)	0	0.0%
Low (between 40% and 60%)	20	77.0%
Very Low (less than 40%)	6	23.0%
Total	**26**	**100.0%**

CALCULATION OF OPTIMUM PUMPING PARAMETERS

Introduction

The aim of any artificial lift design is to ensure the **most economic** means of liquid production within the constraints imposed by the given well and the reservoir. For sucker rod pumping, this means selecting the right size of pumping unit and gear reducer, as well as determining the pumping mode to be used: i.e. the combination of the plunger size, stroke length, pumping speed, and rod string design. The size of the pumping unit and gear reducer can only be selected if the operating conditions (loads, torques, etc.) are known, which vary with the different pumping modes. Therefore, the basic task of a proper design lies in the optimal determination of the pumping mode.

Optimum pumping mode is defined [6, 7] as the combination of pump size, polished rod stroke length, pumping speed, and rod string design resulting in the maximum value of the **Lifting Efficiency** (see **Eq. 3).** This coincides with the case of setting the polished rod power (PRHP) to a minimum. This is because lifting a given liquid volume from a given pump setting depth (i.e. for a given hydraulic power), lifting efficiency and PRHP are inversely proportional.

The pumping mode determined with the previously described principle needs the least amount of prime mover power, because the system's total energy requirement is a direct function of PRHP. Application of this optimization concept, therefore, gives the **most energy-efficient** and thus most economic pumping mode for the production of the required liquid rate from the given pump setting depth. As shown by **Gault** [8] also, a pumping system design utilizing this principle results in minimum operational costs and in a maximum of system efficiency.

In rod pumping, the power costs of driving the prime mover constitute a significant part of the operating costs. Thus the importance of the proper selection of the pumping mode that achieves minimum energy requirements cannot be overestimated. The optimization procedure just detailed provides the least amount of power requirement at the polished rod. Since total energy usage of the pumping system is directly related to polished rod horsepower (PRHP), the optimization model automatically finds the most energy-efficient pumping system.

Optimization Strategy

Application of the optimization principle detailed previously was accomplished for the wells included in this study with the following restrictions:

- Liquid production rates were kept at the values reported in the latest production tests, if reliable,
- The use of the present surface equipment (pumping unit and prime mover) was assumed,
- The current rod string composition (API Rod Code) was used,
- Pump setting depths were not changed,
- Dynamic fluid levels were assumed according to our measurements, and
- The water cut was set as given in the latest production test.

Two cases were studied, one with and one without tubing anchor. The results of the optimization process include not only the parameters of the optimum pumping mode but the required design of the rod string as well.

Calculation results, conclusions

Table 1 contains the results of pumping mode optimization for some of the wells investigated. Details of the optimum pumping modes along with the required rod string designs are given. Additionally, the table includes for each well the following parameters related to the power efficiency of the pumping system:

- Increase of Lifting Efficiencies, related to the current value, and
- Decrease of energy requirements (energy savings), related to the current energy consumption.

The average energy savings per well for the 30 valid cases in this study are 16.4% for unanchored, and 18.3% for anchored tubing strings. In conclusion, a field-wide power saving of about 17% can be anticipated if all wells are converted to their most economic pumping modes.

OPTIMIZATION OF KEY WELLS

Introduction

Investigation of increasing the liquid production rates was accomplished for several Key Wells where intensification of liquid removal from the reservoirs was expected to have a limited affect on the well’s water cut.

Optimization of the Key Wells’ future performance involves the determination of the maximum possible liquid rates as well as the selection of the optimum pumping modes ensuring those rates. All predictions were performed by using the following assumptions: (a) since wells are completed with the maximum possible tubing size for their casing sizes, tubing size is not used as an optimization factor, (b) the pumping units existing on the wells are used for optimization purposes.

Calculation Procedure

In sucker-rod pumped wells, maximum liquid production is attained when the subsurface pump operates near to a pumped-off condition. Practically, this means that the dynamic liquid level should fall down to the pump's setting depth. It follows from this rule that the rod pumping system's maximum liquid production capacity is reached when the pump is set at a depth just above the well's perforations. Recommended pump setting depths for the Key Wells, therefore, are specified a few hundred feet above the perforations.

The first step in the optimization of the Key Wells is the determination of the maximum possible liquid rate from the well. This liquid rate, q_{lmax}, is found from the productivity index and the calculated flowing bottomhole pressure.

Assuming the existing pumping unit with its capacity restrictions, the maximum liquid production capacity, q^*_{max}, of the pumping installation is calculated next. When determining this rate, the following parameters are considered:

- The pump sizes compatible with the well's tubing size,
- The available polished rod stroke lengths and pumping speeds on the given pumping unit, and
- Pumped-off well conditions.

During the optimization process all possible combinations of these parameters are evaluated and rod strings are designed for each and every individual case. Of the results, only cases meeting the next criteria are kept:

- The rod string is not overloaded, considering the fatigue endurance limits of Grade D rods,
- The gearbox is not loaded above the torque rating of the given pumping unit, and
- The peak polished rod load (PPRL) is less than the pumping unit's polished rod capacity.

At this point the two liquid rates q_{lmax}, the well's capacity, and q^*_{max}, the pump installation's capacity are compared. Obviously, the smaller of the two is selected and all subsequent optimization calculations are performed using this rate.

The required liquid rate being selected, determination of the optimum pumping mode achieving this rate is accomplished next. This involves the selection of the pump size, polished rod stroke length, and pumping speed combination ensuring the maximum value of the **Lifting Efficiency**. As before, calculations assume a perfectly balanced pumping unit.

Results and conclusions

Table 2 contains, for some sample wells, the basic well data, the results of the inflow calculations, and the system capacity calculations. The parameters of the optimum pumping mode along with the detailed design of the sucker-rod string are listed also. Finally, the loadings of main system components are given.

Investigations of the results presented in the table allow the following conclusions to be drawn:

- Practically all of the optimum pumping modes determined have Lifting Efficiencies in the optimum range of 70% to 85%.
- The fatigue loading of the top tapers in the rod strings is sufficiently high ensuring a proper utilization of the rod's strength,
- All of the beam loads, compared to the unit's polished rod capacity, are greater than 60%, an indication of a proper design,
- Gearboxes are fully loaded ensuring a high torque efficiency of the pumping unit.

It must be emphasized that, in contrary to current operating conditions, the sucker-rod pumping installations designed for the Key Wells are properly loaded. Because of the proper loading of the gearbox and the pumping unit, surface system efficiencies in the optimum range between 60% and 75% can be expected. By comparison, all wells included in the field measurement phase of this project fell below the 60% efficiency range.

CONCLUSIONS

Field-wide analysis of sucker-rod pumping installations in a mature field containing more than 70 wells yielded the following conclusions.

- On more than 50% of the installations the pumping unit cannot be properly counterbalanced,
- Current pumping modes (the combination of plunger size, stroke length, and pumping speed) are not at their possible optimum, and
- Due to the very light loading of the surface equipment, overall energy utilization efficiencies are low.

Determination of optimum conditions for the current production scenario involved selection of the optimum pumping mode for each well included in the evaluation phase. Calculation results showed that a field-wide power saving of about 17% can be anticipated if all wells are converted to their most economic pumping modes.

Installation designs were prepared for selected Key Wells where maximizing of liquid production rates was desired. Investigation of the optimum installation designs resulted in the following conclusions:

- Lifting Efficiencies, characterizing the efficiency of the downhole pumping system, in the optimum range were achieved,
- The surface system (pumping unit, gearbox) is properly loaded, thus sufficiently high surface system efficiencies can be expected, and
- Energy efficiencies of the pumping systems attain levels much higher than current values.

REFERENCES

1. "Recommended Practice for Design Calculations for Sucker-Rod Pumping Systems (Conventional Units)." API RP 11L 4th Ed., American Petroleum Institute, Washington DC, 1988.
2. Lea, J. F. – Minissale, J. D.: "Beam Pumps Surpass ESP Efficiency." OGJ May 18, 1992. 72-5.
3. Lea, J. F. – Rowlan, L. – McCoy, J.: "Artificial Lift Power Efficiency." Proc. 46th Southwestern Petroleum Short Course. Lubbock, TX, 1999.
4. Takacs, G.: "Power Efficiency of Sucker-Rod Pumping Systems." Proc. 50th Southwestern Petroleum Short Course. Lubbock, TX, 2003.
5. Kilgore, J. J. – Tripp, H. A. – Hunt, C. L.: "Walking Beam Pumping Unit System Efficiency Measurements." SPE 22788 presented at the 66th Annual Technical Conference and Exhibition held in Dallas, TX. October 6-9, 1991.
6. Takacs, G.: SUCKER-ROD PUMPING MANUAL. PennWell Books, Tulsa, OK, 2002.
7. Takacs, G.: "Program Optimizes Sucker-Rod Pumping Mode." OGJ October 1, 1990, 84-90.
8. Gault, R. H.: "Designing a Sucker-Rod Pumping System for Maximum Efficiency." SPE Production Engineering. Nov. 1987, 284-90.

Table 1
Pumping Mode Optimization Results for Selected Wells.

Well ID	A	B	C	D	E
Present Pumping Mode					
Plunger Size, in	2.5	2.5	2	2.5	2.25
Stroke Length, in	124	88	106	124	88
Pumping Speed, SPM	9.5	9.5	9	9	10
Optimum Pumping Mode, without Tubing Anchor					
Plunger Size, in	2.75	2.75	2.75	2.75	2.75
Stroke Length, in	124	88	88	124	88
Pumping Speed, SPM	7.7	7.1	6.2	7	6.8
Rod String					
API Rod No.	87	86	86	87	86
Top Taper, %	28.8	26.4	25.3	29.7	25.7
Middle Taper, %	72.8	25.2	22.1	72.3	23.1
Bottom Taper, %		50.0	55.9		53.7
Optimum Pumping Mode, with Tubing Anchor					
Plunger Size, in	2.75	2.75	2.75	2.75	2.75
Stroke Length, in	124	88	88	106	88
Pumping Speed, SPM	7.6	7	6.1	8.2	6.7
Rod String					
API Rod No.	87	86	86	87	86
Top Taper, %	28.8	26.4	25.3	29.7	25.7
Middle Taper, %	71.2	27.1	26.3	70.3	26.1
Bottom Taper, %		46.5	48.4		48.2
Improvements					
Unanchored Tubing String					
Rel. Lifting Efficiency Increase, %	19.0	12.5	75.0	13.3	42.1
Rel. Energy Saving, %	16.0	11.1	42.9	11.7	29.6
Anchored Tubing String					
Rel. Lifting Efficiency Increase, %	20.2	14.9	80.0	16.8	42.1
Rel. Energy Saving, %	16.8	13.0	44.4	14.4	29.6

Table 2
Optimization Results for Selected Key Wells

Well ID	Key-1	Key-2	Key-3	Key-4	Key-5	Key-6	Key-7
Well Data							
Tubing Size, in	2.875	2.875	3.5	3.5	2.875	3.5	3.5
Pump Setting Depth, ft	4700	4600	4900	4200	4800	4800	4400
Inflow Data							
SBHP, psi	1749	1749	1820	1350	1749	1749	1350
PI, bpd/psi	0.47	0.65	0.96	5.80	0.91	0.67	3.70
q_{lmax}	755	1000	1620	6670	1457	1057	4536
System Capacity Calculations							
Plunger Size, in	2.25	2.25	2.25	2.5	2.25	2	2.5
Stroke, ft	144	144	124	106	124	144	106
Pumping Speed, SPM	12	12	12	12	12	12	12
q^*_{max}, bpd	910	922	770	783	767	741	777
Optimum Pumping Mode							
Plunger Size, in	2.25	2.25	2.25	2.5	2.25	2	2.5
Stroke Length, in	144	144	124	106	124	144	106
Pumping Speed, SPM	10	12	12	12	12	12	12
q_{opt}	755	922	770	783	767	741	777
PRHP, HP	34.2	40.5	33.6	28.9	34.1	37.4	28.9
Lifting Efficiency, %	72.1	75.4	77.0	78.1	76.0	65.5	79.7
Rod String							
API Rod No.	86	86	86	86	86	86	86
Top Taper, %	35.8	33.2	34.9	39.0	35.4	31.3	38.9
Middle Taper, %	34.2	32.6	33.6	37.4	34.0	30.8	37.4
Bottom Taper, %	30.0	34.2	31.6	23.6	30.6	37.9	23.6
Loadings							
Beam Loading, %	65.2	65.0	66.2	89.6	66.2	62.7	92.0
Gearbox Loading, %	85.0	88.7	75.9	88.2	76.5	83.5	89.3
Top Rod Loading, %	89.6	97.1	96.7	92.6	97.2	92.8	95.5