# Rod Pumping System Design

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## INTRODUCTION

The sucker rod pumping system is of extreme importance to the oil industry. More than 75% of all wells on artificial lift are being produced by rod pumps. The basic system has taken on few changes since its conception. There have been numerous refinements, but these were a result of an increased understanding of old principles rather than the development of new ones. The transition from the first systems to our present systems has been one of gradual change, with new ideas and designs occurring and reoccurring throughout the cycle of development.

In spite of the many years of association with the rod pumping system, our understanding of the complete system is still limited. We can take any specific part of the system and define it fairly well, but all too often we fail to predict how a complete system will function over a wide range of conditions.

In the future, more and more attention will be focused on rod pumping system design. The continued use of the computer will make it possible to analyze and evaluate, in detail once considered uneconomical, the many designs possible. The ever-present demand for maximum design at minimum cost, plus an increased knowledge of the system itself, should bring about significant changes in design in the years to come.

## GENERAL

For the purpose of discussion, the design of a rod pumping system will be divided into 3 separate and distinct phases:

(1) PRELIMINARY PHASE
(2) SPECIFIC PHASE
(3) SELECTION PHASE

The initial phase will be referred to as the PRELIMINARY PHASE. This phase does not concern itself with the mechanical aspects of the rod pumping system. Its purpose, however, is to consider all the factors that will or could have an effect on the overall design of the system. These factors are as follows:

(a) Reservoir Producing Characteristics
(b) Legislative Control
(c) Economics
(d) Operating Costs
(e) Future Requirements
(f) Surplus Equipment

The second phase in the design of the rod pumping system will be referred to as the SPECIFIC PHASE. This phase is specific in that it deals directly with the physical installation. Its purpose is to compare and analyze the many systems possible. To do this, the Specific Phase is described in terms of the evaluation of 3 sets of variables. These are:

(a) Controlling Variables
(b) Fixed Variables
(c) Dependent Variables

The third and final phase in the design of a rod pumping system is the SELECTION PHASE. This phase coordinates the information from the Preliminary and Specific Phases and, based on the existing conditions, selects that complete system or systems which will best suit the needs of the specific well in question.

## PRELIMINARY PHASE

Before a system can be designed properly, its purpose must be fully understood. The purpose of the rod pumping system, as discussed in this paper, will be to adequately produce the well on which it is installed, at a minimum cost. "To adequately produce" will be defined as being able to produce in excess of the optimum rate, as established by the existing physical, economic and legal limitations.

The purpose of the rod pumping system, therefore, is to serve the well on which it is installed. This being the case, the designer must first investigate the conditions under which the rod pumping system will be required to work. To do this, the designer must examine the well itself or, more specifically, the producing formation.

### Reservoir Producing Characteristics

To define the producing characteristics of the well, the following information should be prepared in graphic form:

1. Maximum oil producing rate versus cumulative oil recovered.
2. Water producing rate versus cumulative oil recovered.
3. Gas-oil ratio versus cumulative oil recovered.
4. Formation pressure versus cumulative oil recovered.

To prepare this information, the reservoir engineer will have to analyze all available data. This data will include well logs, core analyses, PVT studies, and well tests pertaining to the formation. In some instances, he will not have sufficient data and history to determine all the variables, and will have to make assumptions based on his past experience and the experience of others with similar reservoirs. Fortunately, in wildcat areas where little if any information is available, the well will generally flow long enough to permit the determination of some of the variables in question.

In analyzing the reservoir, the engineer is often faced with the possibility of secondary recovery in the immediate future. In this case, the curves will have to reflect, to the best of his ability, the fluid volumes that the formation can be expected to produce during this period. This, in turn, will be based on the flood pattern selected and the water volumes to be injected.

The time involved in preparing this information will be substantial but, for reasons other than rod pumping design, will be well justified.

Legislative Control

Once the well's producing capabilities have been defined, it will be necessary to modify these rates based on the proration laws of the given state. All possible increases or decreases of allowable days or allowable factors should be considered. A secondary recovery operation will normally have a higher allowable assigned to its producing wells than it had during primary operations. This will result from transferring allowables from injection wells and being granted bonus allowables for the secondary effort.

Frequently, a well will be capable of producing in excess of its top allowable but, because of a high gas-oil ratio, will be restricted to a lower allowable. The effects of all anticipated allowable increases or decreases should be indicated on the graphs of producing rates versus cumulative production.

Economics

To further define the rate at which a well should be produced, the economic aspects of producing it at various rates must be carefully considered. Producing some reservoirs at high rates during early life will result in low ultimate recoveries. The production of all wells in reservoirs of this type should be limited to the maximum economic rate. Competition among operators sometimes makes this impossible.

In the case of either a waterflood project or a water drive reservoir, there will exist a maximum water-oil ratio above which it will be uneconomical to continue production. The fact that the well will not be required to produce beyond this point should be indicated in the graphs of production rate versus cumulative production.

For a well with rapidly declining oil productivity, it might be more economical to defer the production of a part of the reserves for a year or two than to initially equip the well to produce at maximum rate. In such a case, the present worth of the deferred oil would have to be compared with the difference in the net cost of the alternate pumping systems.

After investigating the effects of Reservoir Characteristics, Legislative Control, and Economics, it will be possible to establish the rate at which the well will, can, and should be produced. This rate will correspond to the design rate of the rod pumping system or systems. The depth from which the fluid will have to be lifted is obtained from the formation pressure versus cumulative oil curve, allowing for a wellbore drawdown as indicated by the productivity index of the well. Thus, the conditions under which the rod pumping system or systems will have to work, not only initially but throughout the entire producing life of the given well, can be defined.

As described earlier, the purpose of the rod pumping system is two-fold: (1) to adequately produce the well, and (2) to do so at a minimum cost. The cost referred to is not only the initial cost of the system but also the operating cost which includes all the labor, maintenance and replacement costs that the system will require. With this in mind, the need of additional information becomes obvious.

Operating Costs

The operating cost of a rod pumping system, on a yearly basis, will normally be in the range of 5 to 15% of the total initial cost of the system. There will, of course, be exceptions to this. Some extreme exceptions will be encountered. In general, however, the operating cost of a rod pumping system over its entire life will approach or exceed the initial cost of the system itself. Thus, in the design of a rod pumping system, the operating cost of the system becomes an important of the overall design. The system which is the lowest in initial cost will not necessarily be the lowest in overall cost. The lack of adequate operating cost data, however, will leave no other alternative but to design on the basis of minimum initial cost.

In considering the operating cost of a system, there are 2 basic sources from which information can be obtained: (1) calculation methods, and (2) past experience.

The operating cost of a rod pumping system is equal to the sum of the operating costs of the individual but related components. With respect to the individual components, there are some operating costs that cannot be accurately predicted by calculation methods but which can be easily defined by past experience. Likewise, there are some components whose operating costs cannot be predicted from past experience but can be estimated by calculation methods.

To take full advantage of past experience, it is necessary to have complete records which are centrally kept and compiled. Proper communication between office personnel and field personnel is necessary. To properly apply the information obtained from past experience, the field people must be called upon to aid in interpretation and to help pass judgement.

The shortcoming of a rigid standardization program is that it does not take full advantage of the accumulated past experience that is available in an area to help predict and solve the unforeseen problems.

Future Requirements of The Well

Many times, while in the process of changing out a rod pumping system, it becomes obvious that a little more insight at the time of initial installation could have saved considerable expense. To prevent costly changes in equipment, the future requirements of the well should be clearly defined and considered before making the final selection of the system. For example, an edge well in a water drive field might require, in a few years, a fluid handling capacity of twice what is initially required. The question then arises as to whether it would be better economics to install the smaller system and change out later or install the larger system initially. Should it be decided to install the smaller system initially, the use of a universal type foundation, which could serve both systems, would be worth consideration.

Future Requirements of the Company

The future equipment requirements of a company should have a direct bearing on its design policies. To ignore the future could result in policies which could cost a company considerable money. To illustrate this point, a simplified example is given below.

An operator has a 10 well lease. Most of the wells are equipped with rod pumping systems. These systems will be referred to as 114 systems. Within 2 years, he plans to start a waterflood operation on the lease. A 228 system will be required for each of the 5 remaining producing wells. Within the area, a well has ceased to flow. A 114 system will be required for production purposes. The obvious solution would be to buy the 114 system for the well. An alternate solution would be to purchase a new 228 system and move it to the lease to be waterflooded. A 114 system could then be salvaged and moved to the well which has ceased to flow.

Many other factors would have to be brought into the analysis before a final decision could be made. These factors would include the company's present cash situation, the possibility of surplus units in the future, the distances involved, the possibility of a different starting date on the waterflood, federal taxes, etc.

For a complete analysis, the future requirements of a company should not be limited to a district or regional level, but should be watched and analyzed from an overall position. The future requirements of a company could very well dictate the design policy with best economics at any given time.

Surplus Equipment

To insure maximum usage of equipment, most companies maintain surplus or idle equipment lists. Quite frequently the design of a system can be modified to permit the use of a surplus piece of equipment, rather than having to purchase something new. Possibly some district or region within a company might have a surplus piece of equipment that will fit the exact requirements of the system being designed.

Many operators of partnership properties will periodically send surplus equipment lists to the partners. Review of these lists might lead to a purchase which could result in a considerable saving to a company.

Surplus equipment lists should be continually used and kept up to date. In so doing, the objective of minimum cost, for rod pumping design, will be all the more possible.

SPECIFIC PHASE

The specific phase in the design of a rod pumping system deals with the physical aspects of the system. It is concerned with the mechanical performance of the entire system in terms of stresses, strains, velocities, accelerations, displacements and efficiencies. The interrelation of the many variables in the rod pumping system makes the problem of design analysis a complex one. In an attempt to simplify this problem, the variables will be divided into 3 groups.

(1) Controlling Variables
(2) Fixed Variables
(3) Dependent Variables

Controlling Variables

The controlling variables are those variables which describe the physical characteristics of the rod pumping system. To change any one of these variables would be the same as introducing a new system. The controlling variables of the rod pumping system are:

(1) Surface Stroke Length
(2) Surface Geometry
(3) Surface Operating Speed
(4) Bottom Hole Pump Size and Type
(5) Rod String
(6) Tubing String

Fixed Variables

The second group of variables are referred to as fixed variables. These variables are characteristics of the individual well and its producing formation. The fixed variables of the rod pumping system are:

(1) Fluid Volume Required
(2) Lifting Depth
(3) Casing String
(4) Type Completion
(5) Producing Interval
(6) Bottom Hole Temperature
(7) Crookedness of Hole
(8) Gas-Oil Ratio
(9) Flowline Pressure
(10) Fluid Viscosities
(11) Fluid Gravities
(12) Paraffin Deposition
(13) Corrosion
(14) Sand and Gyp Tendencies

Dependent Variables

The third group of variables is referred to as dependent variables. These variables are determined by calculated methods based on the conditions specified by the controlling and fixed variables. The dependent variables of the rod pumping system are:

(1) Rod Load
(2) Fluid Load
(3) Acceleration Factor
(4) Maximum Upstroke Load
(5) Minimum Downstroke Load
(6) Rod Stress
(7) Accelerated Plunger Stroke Length
(8) Rod Stretch
(9) Tubing Stretch
(10) Net Plunger Stroke
(11) Net Production Rate
(12) Maximum - Minimum Load Torques
(13) Counterbalance Effect
(14) Reducer Torque
(15) Hydraulic Horsepower
(16) Friction Horsepower
(17) Required Horsepower

The specific design of a rod pumping system will be treated as consisting of 4 basic steps. These steps are:

1. Assume a system. This corresponds to the selec- of values for the controllable variables.
2. Define the conditions under which the system will operate. This corresponds to the determination of the fixed variables.
3. Calculate the mechanical characteristics of the assumed system. This corresponds to the determination of the dependent variables.
4. If the calculated values check out satisfactorily, then complete the specific design by selecting the surface pumping unit and prime mover based on the calculated values of torque, maximum load, and horsepower required.

This method is then repeated for different systems until a system which appears to be optimum is found.

As can be seen, this method is more or less a matter of trial and error. The disadvantage of the rigorous application of this method is that too much time is spent analyzing systems which will prove to be completely unsatisfactory. To successfully apply this method, a relationship must be established between the fixed and the controlling variables which will point in the direction of the optimum system. Based on the analysis of thousands of systems and the experience gained from operating these systems, many companies have established relationships between these variables and are currently using these relationships in their manuals describing rod pumping system design. Many authors have published technical articles describing these relationships and the industry, in general, is conscious of the fact that optimum conditions do exist. However, the problem remains as to what is an optimum system.

As discussed in this paper, the optimum system is that system which will adequately produce the well with a minimum cost. In considering minimum cost, the operating cost of the system was described as being a substantial part of the total cost. Therefore, the optimum system will, to a large extent, depend upon the operating policies of the individual company.

A system which may be considered optimum by one company's standards might not be considered optimum by another company's standards based on the differences in operating policies and operating costs.

Assuming, however, that a general relationship between the fixed and controlling variables is available, the next step in the specific design is to proceed with the evaluation of the dependent variables.

No attempt will be made to give a detailed method of calculation for each of the dependent variables. However, the generally accepted method of calculation for each will be outlined, the main purpose of the discussion being merely to indicate the most important variables that should be evaluated.

The Rod Load is simply the weight of the rod string. It is sometimes considered as the rod weight in air and sometimes as the rod weight in fluid.

The Fluid Load is the force caused by fluid pressure acting on the area of the pump and rod string surfaces. Most companies define fluid load as the result of the pressure at the pump depth acting on the gross area of the plunger less the average cross sectional area of the rod string. Some companies define fluid load as the result of the pressure at the pump depth acting on the gross pump area. The difference is merely one of definition. Those companies that consider the net area of the plunger use the weight of the rods in air as the rod load, while those companies that consider the gross area of the plunger use the buoyant weight of the rods as the rod load. The pressure at the pump is equal to the fluid gradient pressure plus the flowline pressure.

The Acceleration Factor accounts for the force that is required to accelerate the system. The accelerated system is commonly taken as just the rod string. Some companies, however, make allowances for the acceleration of the fluid. The commonly used acceleration factor assumes the motion of the sucker rod string to be simple harmonic. In theory, the value of the acceleration factor will vary with the crank angle, reaching a maximum at both the top and bottom of the stroke and approaching zero at the middle of each stroke. For the standard geometrical system (Class I) the motion of the rod string is not simple harmonic, and the magnitude of the acceleration of the rods coming off the bottom of the downstroke is higher than the acceleration of the rods going over the top of the upstroke. The value of the acceleration factor is normally based on surface stroke length and speed. The more detailed method would consider surface geometry.

The Maximum Upstroke Load is the load at any position of the crank and is the summation of all the individual forces acting on the polished rod. The point at which the maximum load occurs is difficult to predict. The most common method of calculating the maximum upstroke load is to consider only the 2 main components of the load: the accelerated rod load and the fluid load. The other components which are present but difficult to evaluate are the pump, rod, and stuffing box friction forces.

The Minimum Downstroke Load is that particular downstroke load where the summation of all the forces on the polished rod is a minimum. This minimum load is generally described as the static rod load, less the buoyant rod force, less the accelerating force, less the frictional forces. The accelerating force on the downstroke, which tends to reduce the effective weight of the rods, is normally considered of equal magnitude to the accelerating force present on the upstroke.

The Rod Stress at any point in the rod string is the force at that point divided by the cross sectional area of the rod at that point. Since the maximum stresses of the system are the most important, the investigation of stress is normally limited to the top section of each rod size. In the design of tapered strings, most companies keep the stress in the top section of each rod size the same.

The Accelerated Plunger Stroke Length is the surface stroke length plus the overtravel of the pump plunger. Several different methods are commonly used to evaluate the overtravel. Overtravel is most commonly related to speed, surface stroke length and rod depth.

The Rod Stretch is the elongation of the rods due to the application of external forces. The amount of stretch is calculated from Hooke's Law. The force producing the stress is normally considered to be the force caused by the fluid pressure acting over the gross area of the plunger.

The Tubing Stretch is the elongation of the tubing due to the application of external forces. The amount of stretch is calculated from Hooke's Law. The force producing the stress is normally considered to be the force caused by the fluid pressure acting over the gross area of the plunger. In instances where tubing anchors are used, only the unsuspended portion of the tubing is subjected to this force.

The Net Plunger Stroke is the actual stroke of the bottom hole plunger. It is generally considered to be the accelerated plunger stroke length less the tubing stretch less the rod stretch.

The Net Production Rate is the volume of fluid that can be produced per unit of time. The net production rate is normally obtained by multiplying the net plunger stroke by the pumping speed by the total pump area by the volumetric efficiency. The volumetric efficiency is related to the conditions under which the pump will have to operate. No exact method is presently available which will permit the detailed calculation of the volumetric efficiency.

Maximum - Minimum Load Torques: The load torque is the resultant moment about the crank caused by the well load. The load torque at any position can be found by multiplying well load at that position by the torque factor at that position. The torque factor is obtained from the unit geometry. The points at which the maximum and minimum values of load torque occur are difficult to determine. However the maximum well load is normally assumed to occur at the position of maximum torque factor and the product of these 2 is then considered the maximum load torque. Likewise, the minimum well load is assumed to occur at the position of minimum torque factor, and the product of these 2 is considered as the minimum load torque.

The Counterbalance Effect is the torque about the crank caused by the position and weight of the counterbalance. The required maximum counterbalance is frequently obtained by averaging the values of maximum and minimum load torques. It is also obtained by averaging the values of maximum and minimum load and then multiplying this value times half the stroke length.

The Reducer Torque is the algebraic summation of all the torques acting about the crank. It corresponds to the torque that the pumping unit gear reducer will be required to furnish. The maximum reducer torque is frequently obtained by taking half the difference between the maximum and minimum loads by half the stroke length. It can also be obtained by multiplying a peak torque factor times the stroke length times a specified well load. Of all the dependent variables, the maximum reducer torque is the most important and also the most difficult to predict.

The Hydraulic Horsepower is the theoretical horsepower necessary to produce at a given rate from a given depth. It is normally calculated in terms of net plunger stroke production at 100% volumetric efficiency.

The Friction Horsepower is the horsepower required to overcome the frictional losses of the subsurface equipment. Friction horsepower is normally considered a function of rod velocity and rod weight.

The Required Horsepower is the horsepower that the prime mover of the system must be capable of delivering. This horsepower is generally obtained by adding the hydraulic horsepower and the friction horsepower and multiplying this summation by a surface efficiency factor.

## SELECTION PHASE

The final phase in the design of a rod pumping system is to apply the information gathered from the first 2 phases of design and select a system which will satisfy the overall needs of the well. Sometimes the selection of the most desirable system is obvious, but frequently, it will take further analysis.

The rod pumping system, as finally selected, should be completely described in terms of:

1. Surface Pumping Unit
2. Surface Prime Mover
3. Rod String
4. Tubing String
5. Foundation
6. Bottom Hole Pump
7. Gas and Mud Anchors
8. Surface accessories, including polished rod, liner, pumping tee, stuffing box, packing, lubricator, chemical injection pump, clamps, etc.

In selecting the final system, the condition of being able to adequately produce the well must be satisfied. To adequately produce a well over its life might require several rod pumping systems. In these cases, the matter of timing becomes important. For instance, it might be to a company's advantage to modify the system that would seem optimum for the immediate needs to a compromise system that would also satisfy some future need.

In comparing systems for the purpose of making final selection, these are some of the most important questions that should be answered:

1. Will the proposed system adequately produce the well initially?
2. At what time in the life of the well will this system need to be changed?
3. At what value can the proposed system be salvaged at the time of changeout?
4. What will it cost to changeout the system at this time?
5. What is the initial cost of the proposed system?
6. What will the operating cost of the proposed system be during the time it remains on the well?
7. What is the total cost of the system in terms of present worth value?
8. Could a change in any of the assumed conditions greatly affect the overall design? If so, what is the probability of this change occurring?
9. Has acceptance of final design been obtained from operating personnel?
10. Have all other possible methods of lift been analyzed? Is the rod pumping system as selected the most economical method of artificial lift?

Having answered these questions and based on all the information that has been made available, the final selection can be made with the assurance that every possible alternative has been investigated and the selection is optimum for the application.

## SUMMARY

A general method of designing rod pumping systems has been described in terms of three equally important phases; (1) the Preliminary Phase (2) the Specific Phase (3) the Selection Phase.

The role of each phase in the overall design has been discussed in detail. The design of the rod pumping system has been shown to be more than the mechanical substitution of numbers into given formulas.

A basic method of design has been described that can be applied to the design of many systems commonly employed in the oil industry.

## CONCLUSIONS

To obtain optimum design of rod pumping systems, a company must have a definite method of approach, with objectives and responsibilities well defined.

The design of a rod pumping system can only be as accurate and complete as the data on which the design is based.

Operating policies have a direct effect on the mechanical design of rod pumping systems.

For this reason, there is no standard method of mechanical design that is generally accepted by all companies.