APPLICATION OF SYSTEMS ANALYSIS TO SUCKER ROD PUMPED WELLS

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ABSTRACT

In the last decade, systems analysis methods were widely used to describe the performance of flowing and gas lifted oil wells, several applications dealt also with gas wells. The present author's aim is to apply these procedures to sucker rod pumping and to develop calculations for modeling the operation of rod pumped wells.

A discussion of systems analysis methodology is given first. Then, a sucker rod pumped well is analyzed and considerations are given on the application of these methods to describe the performance of a pumping system. For simplicity, wells pumping liquid only are investigated in this preliminary study. The pumping system is described by constructing System Performance Curve sheets. These sheets show pumping rates versus pump setting depth for different pumping modes. Conventional pumping units are considered and RP 11L procedures are used. After superimposing the IPR curve of the given well on the System Performance Curves, the production rates attainable with different pumping modes are easily found.

INTRODUCTION

Petroleum fluids found in an underground reservoir must be moved through a complex system to reach their destinations on the surface. This system is called the production system and comprises the following main components: the reservoir, the producing well, the surface flowline, and the separator. Some of these can further be divided into smaller elements, e.g. the well, besides the tubing string, may contain safety and/or gas lift valves, etc. The production system is thus a system of interconnected and interacting elements which all have their own specific performance relationships but each, in turn, also depends upon and influences the other elements. In order to produce fluids from the well all components of the system must work together. Thus the solution of any fluid production problem requires that the production system be treated as a complete entity.

The outlines of the above principle were first given by Gilbert [1], the father of production engineering, in the 50's. He described the interaction of the reservoir, the well, and the wellhead choke and proposed a system-oriented solution for determining the production rate of a flowing well. The practical use of Gilbert's ideas was limited, mainly due to the limitations of the methods available in his time for modeling the performance of the system's elements. During the last decades, however, research into the behavior of the individual hydraulic elements of oil and gas wells has been very intensive. As a result of this progress, there exist today several different theories, calculation, and design procedures that reliably model the performance of the elements of a production system. Good examples for this are the numerous correlations available for calculating pressure traverses in vertical and horizontal pipes, etc.

The wide selection of available calculation models and the advent of computers that eased the burden of the necessary calculations, lead to the reappearance of Gilbert's ideas in the early 80's [2,3]. The new contributions aim at the numerical simulation of the production system's hydraulic behavior, but also enable the optimization of the system to most economically produce the desired flow rate. Although most of the investigators study the production system only, the basic concepts are already laid by Szilas [4] for the integration of these achievements into the description of a whole field's behavior.

The systems analysis methods and procedures mentioned above were named "Nodal Analysis" by K.E.Brown which term has generally been accepted since then. A full treatment of nodal analysis principles is given in [5,6]. The application of this theory to flowing and gas lifted wells can have immediate practical and economical advantages [7,8].

DESCRIPTION OF THE PRODUCTION SYSTEM

Consider a simple flowing oil well the schematic drawing of which is shown in **Fig. 1.** Fluids in the formation flow to the well from as far as the boundary of the drainage area, **1.** After entering the well through the sandface, vertical flow in the tubing starts at the well bottom, **2.** The tubing string may contain a safety valve and/or a downhole regulator, represented by **3.** Downstream of the restriction, vertical tubing flow takes place up to the wellhead, **4.** A surface choke bean is installed at **5**, which is also the intake point to the flowline. Horizontal or inclined flow in the flowline leads into the separator, **6.**

The points in the flowing well's production system designated by numbers in **Fig. 1** constitute the nodes of the nodal analysis theory. They separate the different components of the system: the formation, the tubing string, the flowline, etc. In order to define the system's behavior all components must first be evaluated separately, these evaluations forming the base of the total system's description.

Any oil or gas well's production system can be divided into its components using appropriately placed nodes. A typical sucker rod pumped case is illustrated in **Fig. 2.** The unique features of a common rod pumped well are the absence of a packer in the well and the connection of the annulus at the casing head to the flowline, usually through a check valve. Due to the annular space being open both downhole and at the wellhead, two paths are available for the fluids to move up the hole. One of these is the tubing string where fluids are lifted to the surface by the downhole pump. The other path open to fluids is in the annulus where liquids rise to a stationary level, above which a gas column exists. Since the two flow paths are connected at the bottom (Node **2** in **Fig. 2**), it follows from the hydrostatic law of communicating vessels that the pressures exerted at Node **2** by each subsystem must be equal. The result of this requirement is that, in contrary to flowing wells, there are two ways to calculate bottomhole pressures in pumping wells: one through the tubing string and the other in the annulus. The dynamic liquid level, therefore, is an indicator of the well's actual bottomhole pressure. This observation is of great importance to the systems analysis of rod pumped wells, as will be seen later.

THE BASICS OF SYSTEMS ANALYSIS

One of the objectives of nodal systems analysis is the determination of the flow rate of a given production system. As discussed before, in connection with **Fig. 1**, an oil well can be considered a series-connected hydraulic system made up of its components which are bracketed by appropriately placed nodes. Evaluation of this system's performance permits the following conclusions to be made:

- Mass flow rate throughout the system is steady, although phase conditions change with changes in pressure and temperature.
- Pressure decreases in the direction of flow because of the energy losses occurring in the various system components.
- At node points, input pressure to the next component must equal the output pressure of the previous component.
- System parameters being constant for considerable periods of time are:
  - the endpoint pressures at the separator and in the reservoir,
  - wellbore and surface geometry data (pipe diameters, lengths, etc.), and
  - inflowing fluid composition.

Taking into account the above specific features of the production system a procedure can be devised to find the flow rate at which the system will produce. This starts with dividing the system into two subsystems at an appropriately selected node. The next step is to find pressure vs. rate curves for each subsystem. These functions are constructed starting from the known points in the system at the separator and at the well bottom. The common point of the two curves gives the cooperation of the subsystems and thus the desired rate.

SYSTEMS ANALYSIS OF PUMPING WELLS

The production system of a pumping well is shown in **Fig. 2**. As discussed earlier, two paths are available for describing the system's performance: one in the tubing and the other in the casing annulus. In the first case, system analysis methods developed for flowing or gas lifted wells can be applied. This approach, however, involves two-phase pressure drop calculations in the tubing - rod string annulus, with increased calculation requirements, and reduced accuracy. The work of Schmidt and Doty [9] followed this line of thought.

One of the few other publications on systems analysis of pumping systems is contained in Brown's book [5]. The methods presented in that book utilized formulae of limited validity and were only given, as the authors stated, "... to encourage others to continue the work ...".

The procedure proposed in this paper, in contrary to previous works, is based on modeling the phenomena occurring in the well's annulus. It is well-known that the depth of the dynamic liquid level is a direct indication of the well's flowing bottomhole pressure. This fact is utilized in the proposed procedure by the way well inflow performance is coupled with pumping system performance, in order to find the attainable production rate.

Basic Assumptions

This paper gives a solution for the analysis of rod pumping systems in some particular cases only and does not treat the problem in its total complexity. It is hoped, however, that further developments will lead to more general solutions. The most significant assumptions that were used to develop the procedures presented here are:

- Conventional pumping units are considered, allowing for RP 11L procedures to be used.
- Pumping of a single-phase liquid is assumed and the effects of any free gas in the annulus are disregarded.
- Pumped-off conditions are presumed with dynamic liquid levels being at pump setting depth.

Although the above restrictions can considerably affect the applicability of the analysis method developed, there are several conditions where these requirements are met, e.g. wells produced from a strong water-drive reservoir.

System Performance Curves

In order to describe the performance of a rod pumped system, the pumping rates attainable at different conditions have to be found. The conditions most significantly affecting the production rate are:

- The pumping mode used, i.e. the combination of pump size, polished rod stroke length and pumping speed.
- Pump setting depth, which is considered, in the cases studied here, to be equal to the dynamic liquid level in the annulus.

In the light of the above, system performance can very effectively be illustrated by plotting pumping rates versus pump setting depth for different pumping modes. These plots are defined here as **System**

Performance Curves and can be constructed using the calculation procedure of API RP 11L [10]. These curves represent the rates attainable with different pumping modes from different depths and show the performance of the pumping system alone.

Systems analysis principles have shown that production equipment and the formation are connected in series. This implies that the same liquid rate must flow through both components of the total system. Therefore, in order to find the production rate under the given conditions, a common solution of the performance of these two components must be sought. In the case of a rod pumped well, the System Performance Curves represent the pumping system and the IPR curve represents the formation inflow. Intersections of these curves give pumping rates attainable under different conditions.

It can be shown that IPR curves plot as straight lines in the coordinate system production rate vs. dynamic liquid level, which is the coordinate system used for System Performance Curves. Systems analysis, therefore, can be accomplished by superimposing the IPR of the well on the System Performance Curve sheet valid for the given conditions. This procedure is illustrated in the following by presenting example problems.

EXAMPLE PROBLEMS

Several System Performance Curve sheets were constructed using the analysis methods developed in this paper. Common input parameters of the calculations were:

- An anchored tubing string was used.
- API taper percentages were used to increase calculation speed.
- 200 psig wellhead pressure.
- A liquid specific gravity of 1.
- 100% pump volumetric efficiency.
- All performance curves were based on the use of a conventional C-228D-213-100 pumping unit with stroke lengths of 73", 86", and 100".

To illustrate systems analysis methods for finding the pumping rate from a well, the following data were used to construct a straight-line IPR for an example well:

- 6,000 ft well depth,
- 3,000 ft static liquid level,
- 6,000 ft dynamic liquid level at 600 bpd production.

Figs. 3 and **4** show System Performance Curves for a pump diameter of 1.25" and API tapers of 76 and 86, respectively. Each sheet contains calculated pumping rates plotted against pump setting depth for the available stroke lengths and selected pumping speeds. Pump size, API taper number and rod material grade are held constant on every sheet. The different curves on such sheets, therefore, represent different pumping modes.

Every performance curve starts, at a pump setting depth of zero, from the pumping rate that can be calculated with a plunger stroke length equal to polished rod stroke length. As pump setting depth increases, a point is reached where maximum rod stress, due to the combined effects of fluid load, rod string weight, and dynamic forces, exceeds the allowable stress for the rod material. This depth gives the maximum pump setting depth that can be reached with the given rod material, which is Grade D for the examples.

Comparison of **Figs. 3** and **4** shows that use of a 86 taper string, instead of a 76 taper, allows pumping from greater depths. But this holds only if rod strength is considered as the sole limiting factor. The effects of the mechanical restrictions implied by the pumping unit are detailed below.

Figs. 5-6 contain the same System Performance Curves as the previous two figures. The only difference is that the individual curves end at depths lower than rod strength would allow. This is due to the fact that the mechanical limitations of the pumping unit (maximum structural load and maximum allowed gearbox torque) are reached before the rod string is overloaded. As can be seen, the use of the heavier 86 taper overloads the pumping unit at much less depths than the 76 taper. The result is that, in contrary to the conclusions drawn from **Figs. 3-4**, the lighter rod string can be used to greater pump setting depths.

The next two figures (**Figs. 7-8**) present System Performance Curves for two additional plunger sizes (1.5" and 2"), using a 76 taper rod string. An increase of the plunger size considerably increases the pumping rates, but the well depths that can be reached decrease gradually.

All figures presented here include the same IPR line for the example well. The intersections of this line with the performance curves indicate the rates attainable with the given pumping modes. Provided that System performance Curve sheets for different pumping units are available, one has only to select the right sheet and plot the actual IPR on it, in order to analyze the pumping system's performance.

The performance curves shown in the figures allow the determination of the maximum liquid production rates that can be reached from the example well. These are 260 bpd from 4,300 ft for a 2" plunger and a 76 taper string, and 210 bpd from 4,000 ft for an 1.25" plunger and an 86 taper string.

CONCLUSIONS

1. A calculation procedure is proposed for the systems analysis of rod pumped wells producing gasless liquids.
2. The concept of System Performance Curves is introduced to model the operation of a conventional rod pumping system.
3. System Performance Curve sheets, developed for different pumping units and operational conditions, provide an easy-to-use way to analyze the performance of the pumping system in any well.

REFERENCES

1 Gilbert, W.E.: "Flowing and Gas-lift Well Performance." API Drilling and Production Practice (1954) 126-57

2 Proano, E.A. - Mach, J.M. - Brown, K.E.: "Systems Analysis as Applied to Producing Wells." Congreso Panamericano de Ingeniera del Petroleo. March 1979 Mexico City

3 Mach, J.M. - Proano, E.A. - Brown, K.E.: "A Nodal Approach for Applying Systems Analysis to the Flowing and Artificial Oil and Gas Wells." SPE 8025

4 Szilas, A.P.: "Field-Integrated Production System Cuts Costs." OGJ June 13 (1983) 125-8

5 Brown, K.E.: "The Technology of Artificial Lift Methods." Vol.4 PennWell Publ. Co. (1984)

6 Brown, K.E. - Lea, J.F.: "Nodal Systems Analysis of Oil and Gas Wells." JPT Oct. 1985 1751-63

7 Mach, J.M.: "Apply Nodal Analysis to Production Systems." Well Servicing Vol. 21 No. 1 (1981)

8 Kanu, E.P.: "Systems Analysis Hikes Well Performance." PEI May 1981 96-119

9 Schmidt, Z. - Doty, D.R.: "System Analysis for Sucker Rod Pumping." Paper SPE 15426 presented at the 61st Annual Technical Conference and Exhibition of SPE, New Orleans October 5-8, 1986.

10 "Recommended Practice for Design Calculations for Sucker Rod Pumping Systems (Conventional Units)." **API RP 11L** 4th Ed. (1988)

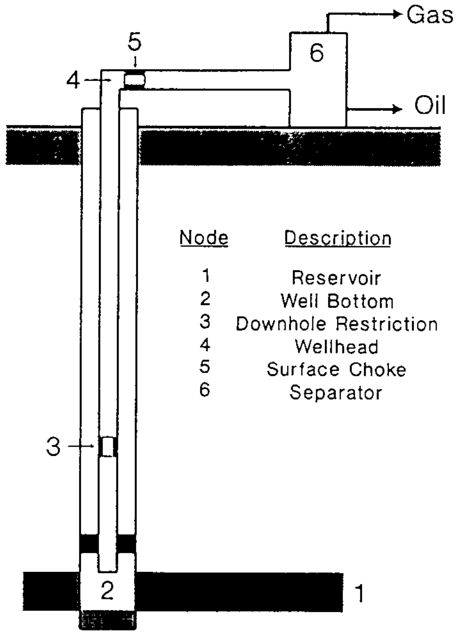

Figure 1 - Production system of a flowing well

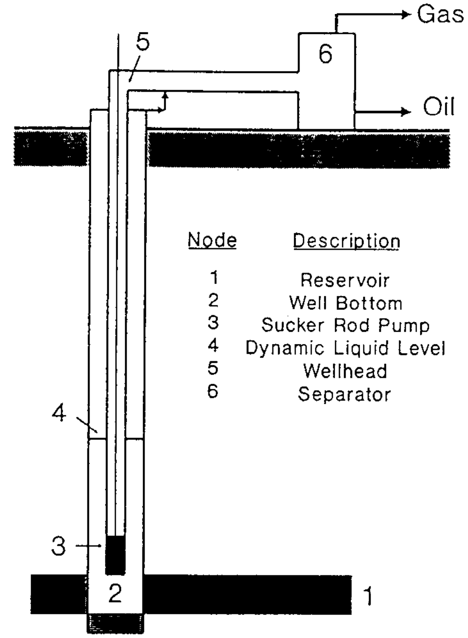

Figure 2 - Production system of a rod pumped well

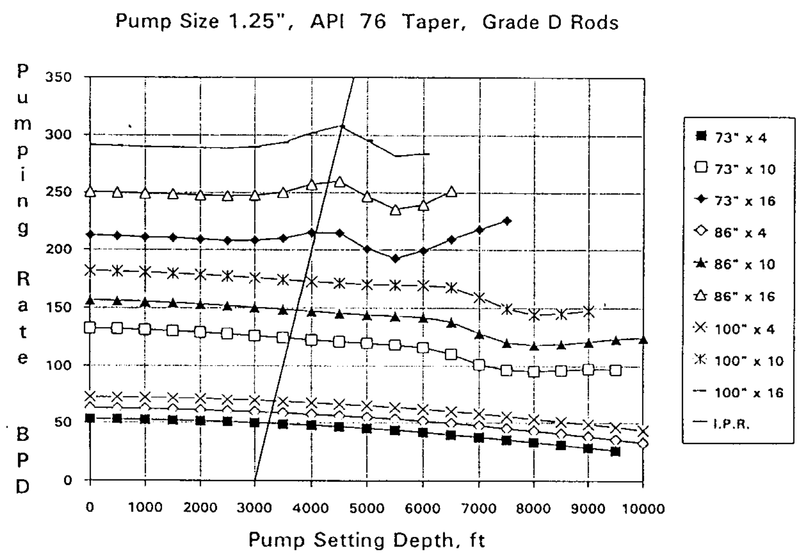

Figure 3 - System Performance Curve sheet for a 1.25" plunger, API 76 taper rod string, and Grade D rods

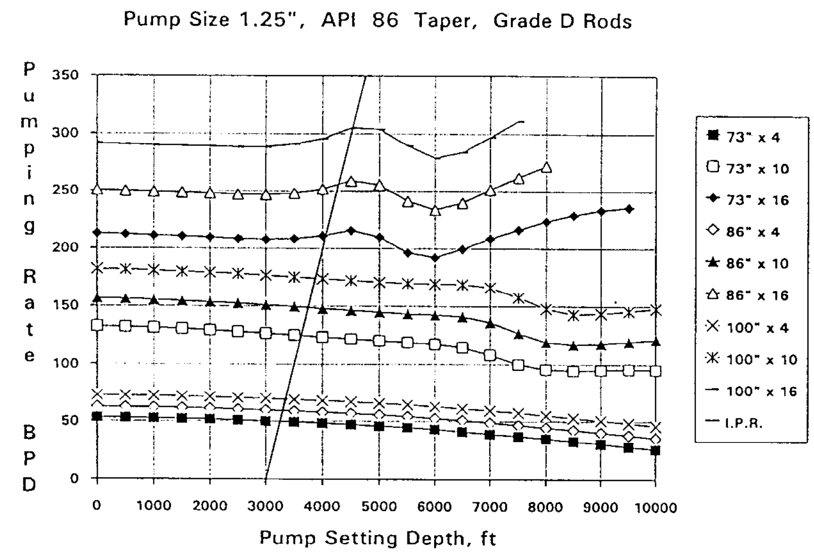

Figure 4 - System Performance Curve sheet for a 1.25" plunger, API 86 taper rod string, and Grade D rods

C-228D-213-100 Unit, Pump Size 1.25", API 76 Taper, Grade D Rods

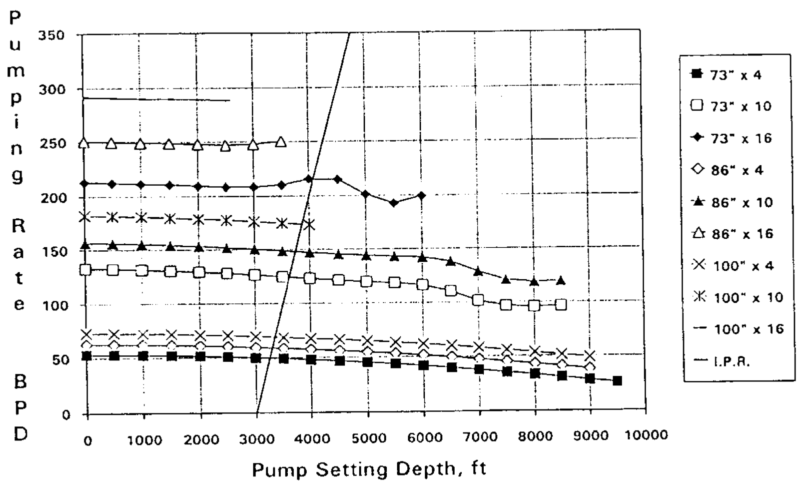

Figure 5 - System Performance Curve sheet for a C-228D-213-100 unit, 1.25" plunger, API 76 taper rod string, and Grade D rods

C-228D-213-100 Unit, Pump Size 1.25", API 86 Taper, Grade D Rods

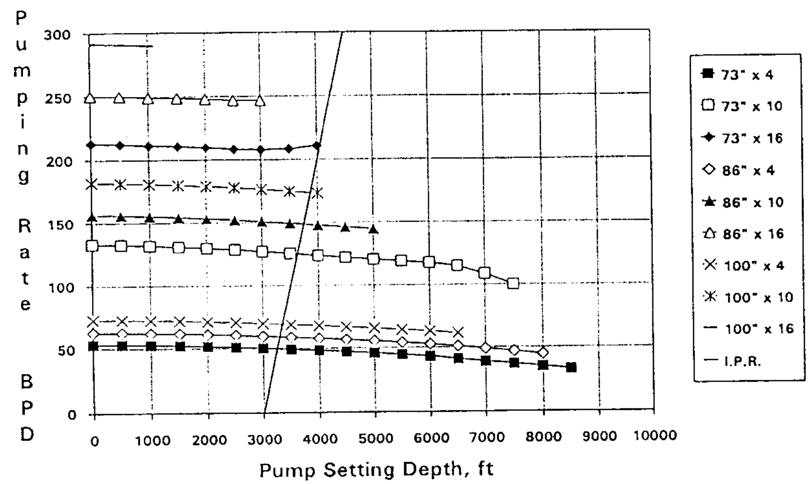

Figure 6 - System Performance Curve sheet for a C-228D-213-100 unit, 1.25" plunger, API 86 taper rod string, and Grade D rods

C-228D-213-100 Unit, Pump Size 1.5", API 76 Taper, Grade D Rods

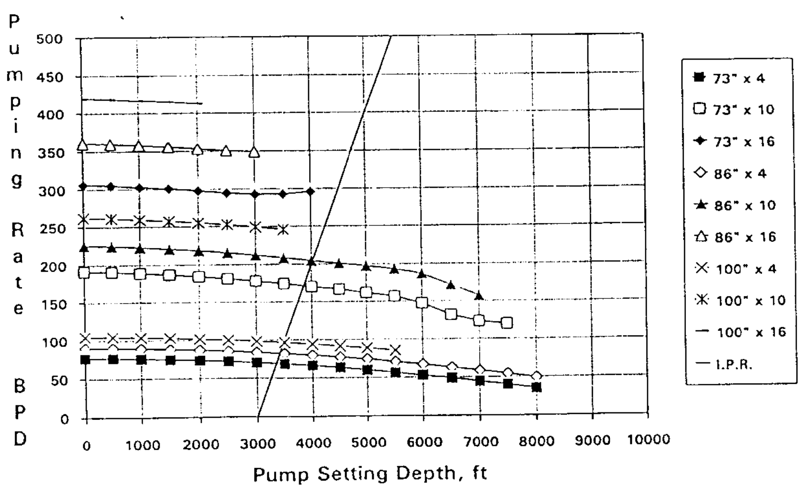

Figure 7 - System Performance Curve sheet for a C-228D-213-100 unit, 1.5" plunger, API 76 taper rod string, and Grade D rods

C-228D-213-100 Unit, Pump Size 2", API 76 Taper, Grade D Rods

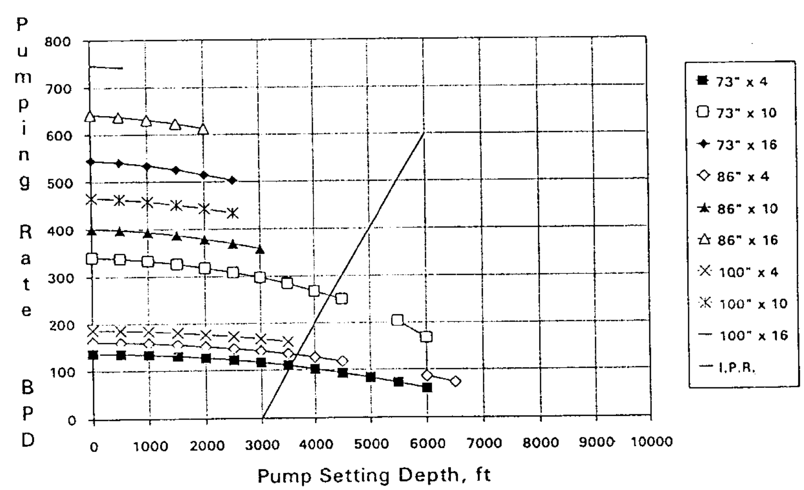

Figure 8 - System Performance Curve sheet for a C-228D-213-100 unit, 2" plunger, API 76 taper rod string, and Grade D rods