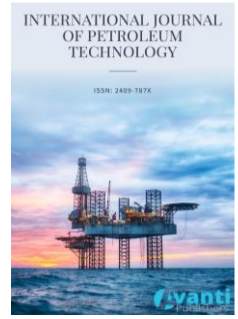
Published by Avanti Publishers

International Journal of Petroleum Technology

ISSN (online): 2409-787X



Selection and Application of Beam Pumping Unit for Heavy Oil Production

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ARTICLE INFO

Article Type: Research Article

Academic Editor: Adil Ozdemir

Keywords:
QRod3
API RP 11L
Sucker rod
Heavy oil production
Beam pumping system

Timeline:
Received: April 14, 2023
Accepted: September 04, 2023
Published: October 11, 2023

Citation: Bahuda RS, Abdallah EM, Mukhtar Y, Khan WA. Selection and application of beam pumping unit for heavy oil production. Int J Petrol Technol. 2023; 10: 81-95.

DOI: https://doi.org/10.15377/2409-787X.2023.10.7

ABSTRACT

Beam pumping units were among the first and are still among the most widely used artificial lift systems. This study investigates the components of beam pumping units and the manufacturing mechanism and design procedure recommended by Recommended Practice and the QRod simulator. The API provides API RP 11L Recommended Practice to obtain the values and operating characteristics for each component in dimensionless form. A trial-and-error method is used during the design procedures to determine the best surface and subsurface equipment for a given well's data. When completing a well, the artificial lift method must be considered to ensure that the well is able to be produced at a satisfactory rate. Besides, the procedures created nine cases to compare the requirements of different production rates and depths for a heavy oil well with 14 APIs. A depth of 5,000 ft with a rate of 300 bbl/day and a depth of 7,000 ft with a rate of 500 bbl/day is the specific production rate and depths at which the well will produce. For 300 BBL/Day the tubing size selected was 2-7/8" OD, for this size the suitable plunger size is 2", and the suitable stroke length was 74in. In cases 6, 8, and 9, all the simulated rod strings were unable to handle the stress imposed by the combination of high depth and high production rate. As a result, all designed systems will fail during production.

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1. Introduction

In the last two centuries, oil consumption has increased to keep up with the production of energy that humanity demands, causing an increase in the price of oil in the global market; since that high demand, oil has been named the black gold. According to the statistics and reports, most countries that discovered oil and mined it have improved from the economic aspects and raised from nothing.

To maximize and utilize the extraction and production of oil, most oil wells have adopted different technologies that are highly dependent on the extraction depth and the volume of the oil production. Currently, the number of beam pumping units came to around 21%. In the USA, 350,000 sucker-rod pumping installations were made that year. In 2014, there were around 160,000 sucker-rod pumping wells in China, and 80% of oil pumping units were located in oil fields. At the same time, the artificially lifted well is around 33.38% of the total power consumed [1].

An invention that has for a long time been used in artificial lift technology is the Beam pumping unit. Rod pumps are one of the world's oldest and most widely used forms of beam pumping unit technology [2]. A beam pumping unit is a special pumping unit that reciprocates rod string, thereby providing a positive displacement pump inserted inside the tubing string and adjusted below the fluid operating level inside the well. Its surface pumping level supplies enough power required in the reciprocation of the rod string [3].

1.1. Working Principle of a Beam Pumping System

The Beam pumping unit's surface pumping level is designed with two essential primary components, i.e., A walking beam that is connected to the pivotal post and a prime mover or motor. The walking beam is typically mounted on top of a pivotal post, which is a vertical support structure that allows the walking beam to move up and down. The walking beam acts like a seesaw, with one end attached to the rod string and the other end attached to a counterweight [2]. On each of the rod string's upward strokes, a significant volume of the liquid mixture is pumped to the surface of the well through the tubing string. Its capacity to pump the volume of liquid is highly dependent on the size of the down-hole pump, the rod string stork length, and the rod string reciprocation speed [4]. Suppose the beam pumping unit exceeds the wellbore fluid entry-level capacity. In that case, the surface pumping unit could be adjusted to operate intermittently by shutting down the pumping unit for the given set of periods. Currently, the latest Beam pumping technology is estimated to pump up to a maximum depth of about 15, 000 ft. This system is, however, able to pump a higher volume of liquids in wells with shallow depths [5].

1.2. Methods of Designing a Beam Pumping System

Since the use of the beam pumping system, design improvement has occurred through the years. Three methods of designing the beam pumping system have been used in the design procedure; each method has its assumptions that must be considered. Since the API was created API RP 11L, it has become the most popular method used in production. The following methods will provide a comparison between them.

1.2.1. The Mill's Method

In this method, the design procedure in the industry is by calculation sheet. Simplifying assumptions are being used, such as the harmonic motion of the unit, neglecting the inertia of fluids pumping and inertia, and finally, the mass of the rod must be concentrated.

The user will be able to calculate the minimum polished rod load (MPRL), and the peak polished rod load (PPRL) for two types of pumping units conventional unit (class I) and steel rod [6]. The equations used in this method assume that the system passes through accelerations that have harmonic motion, and at the same time, the friction is neglected [7].

1.2.2. The Gibbs Method

In this method, the design procedure will be done using partial differential equations using a numerical simulator. It has the fewest assumptions made compared to other methods. Gibbs' method is capable of solving the whole system, but the design procedure will be much easier using the other methods. Gibbs' method will provide results for the motions of the fluids, the rods, and the surface unit with a slipping prime mover [7].

1.2.3. API Method

In 1954, a group of engineers researched the complex problems associated with lifting fluids from the wells. Specifically on the beam pumping system. The research was done voluntarily, so there was no profit gained from the researchers. Even though there was no profit to the engineers, they got help from the Midwest Research Institute in the condition to achieve the objectives of the organization. Engineers have done the calculations using well-testing data from fields and then transformed it to the American Petroleum Institute for publication. The calculations and data were converted into charts that can be used in designing beam pumping systems based on field data (charts and correlations). The created correlations have been proposed to the American Petroleum Institute under the name of the analog electrical study of the sucker rod pumping system. From that point, API has developed API RP 11L to design a beam pumping system based on the non-dimensional parameters from over 1100 dynamometer cards [8].

The API Method will provide a completed and accurate solution for the rod motion compared to the Mills' method but with quite limited assumptions like simple polished rod motion and the pump must be filled with fluids. The API method will provide dimensionless parameters and variables. The API method seems to match results obtained in the field better than the other two methods [9].

1.3. Problem Statement and Objectives

This research is aimed at determining an efficient beam pumping unit that would enhance the pumping of higher volumes of heavy oil at a relatively lower cost. Designing an efficient beam pumping unit is a complex process that involves careful consideration and evaluations of each of the major and minor components for three different types of beam pumping units based on the analysis of the given well data. To design appropriate surface and down-hole equipment for an efficient Beam pumping unit. To achieve this aim, this research study will focus on studying the following questions.

i. Examine the production process and stages of the Beam pumping system during the oil production process.

ii. Investigate various components of beam pumping units.

Since Sucker Rod pumping unit has been the most efficient form of beam pump available in the market, this study will focus on designing a beam pumping unit incorporating Sucker Rod pumping unit`s components to be applied in x oil field.

2. Methodology

To design the beam pumping system, for the given data of a well, it is necessary to go through a sequence of calculation steps to determine the right components from the surface to the subsurface; each component has a variety of types and grades that has different limitations and ability. The API Recommended Practice has provided API RP 11L to get the valuables and operating characteristics for each component in dimensionless form. During the design procedure trial and error method must be done to obtain the right combination of surface and subsurface equipment for the given data of a well, even though the artificial lift method needs to be considered during the completion of any well to design the casing that is suitable with the beam pumping system for having a sufficient design with minimum cost. In the following calculation, a freeware program named QRod3 developed by sucker rod pump expert company Echometer will be used as the program acts as a simplified calculator according to API-RP 11L [10, 11].

2.1. QRod3.1 Software

QRod is the world's most widely used software for designing sucker rod pumping systems. QRod uses the wave equation to accurately plot the surface and loads of the pump dynamometer of a stroke as well as the unbalanced gearbox torque and velocity of the plunger. QRod immediately shows the effect of changing parameters with just a click of a button for any pump depth and desired flow rate, such as tubing anchor, stroke length, stroke rate, and pump diameter (Fig. **1**). QRod outputs include pump displacement, rod string load, surface unit, and motor sizing requirement. User inputs include a selection of surface unit geometry such as conventional unit, Mark II, or air-balanced units; the motion of a unit surface is approximated as a boundary condition of the surface [12].

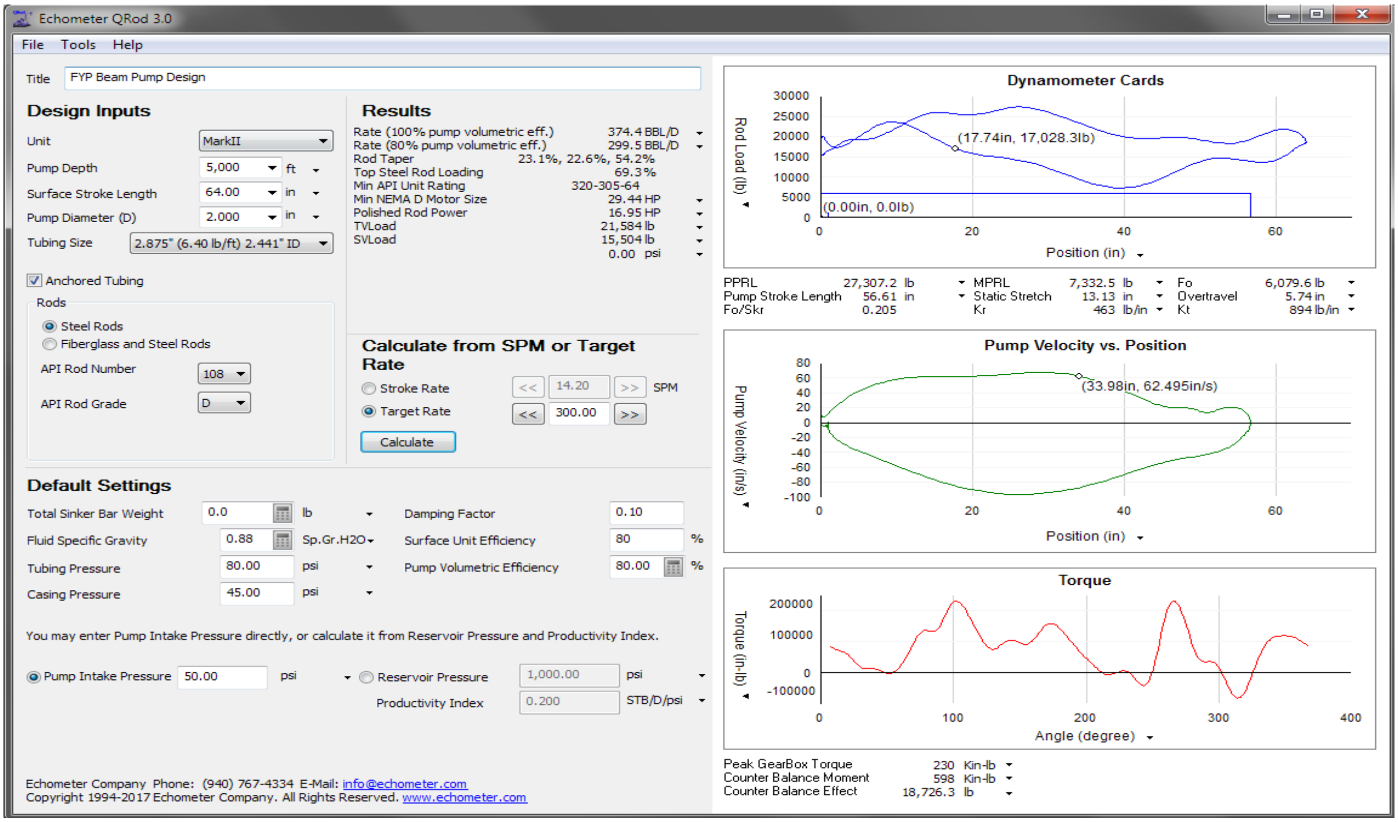

Figure 1: QRod3.1 example simulation run.

2.2. Design Assumption and Limitation

The following assumptions are made into API RP 11L to simplify the design process:

i. Equations and calculations only apply to conventional pumping unit motion; any other customized pumping motions should be considered separately.

ii. Each pumping unit is designed with a medium-slip prime mover.

iii. Steel rod string is used in the calculation; for fiberglass rods, special properties of the rod should be calculated separately.

iv. Insignificant friction at the stuffing box and within the pump.

v. No pump-off situation is considered, as the pump is always assumed to be completely liquid-filled (no gas interference or fluid pound).

vi. Anchored tubing, a correction formula should be used to approximate the effects if unanchored tubing is used.

vii. Pumping unit in balance.

viii. Net lift (L_N), working fluid level (D), and pump setting depth (L) are the same.

2.3. Minimum Information Needed for Designing the Pump

The following list of the minimum information should be known to initiate the design process:

i. Fluid production rate, q.

ii. Depth to pump, L.

iii. The working fluid level, if not known, is assumed to be equivalent to the pump setting depth.

iv. Volumetric efficiency of the pump (Usually 0.8 for design purposes), $E_{v.}$

v. The specific gravity of fluid, G, assumes as 1.0 if well-fluid properties are not known.

2.4. Design Factors

There are plenty of design factors varying from case to case, but generally, to start a rod pump design, the following primary factors are always to be considered first.

a. Primary Design Factors for Designing Sucker Rod Pump

i. Desired production rate, q, bbl/day

ii. Pump depth, ft.

b. After the Plunger Size is Determined, the Following Parameters can be Calculated

i. Rod sizes $A_{r.}$

ii. Lengths L.

iii. Stroke size S.

iv. Pumping speed N.

v. Torque rating of the unit T_p.

vi. The power rating of the prime mover H_b.

2.5. Design Input Data

The assumed cases are going to be designed in the variation of production rate and depth; the relevant data is shown in Table **1-2**.

2.6. Design Procedure

a. Pump Size

The pump size will be selected based on the tubing size already installed. The suitable pump size can be selected from Table **3**.

b. Stroke Length Pump Speed

Stroke length pump speed has to be determined using Eq. 1

$$SN = \frac{q}{(0.1166)D^2.E_p.E_s} \tag{1}$$

c. Operating characteristics based on API RP 11L

Table 1: Used data in artificial lift design of KUH-E-MOND, MD-6 well.

Field Name	Kuh-E-Mond
Reservoir Name	Sarvak
Well Name	MD-6
Location	Boushehr
Reservoir Depth (ft)	3651 (Top), 7514 (Bottom)
Maximum Reservoir Temperature (F)	160-170
Minimum Reservoir Temperature (F)	120
Maximum Reservoir Pressure (psig)	1535
Depth of Well (ft)	4578
Bottom Hole Temperature (F)	110
Bottom Hole Static Pressure (psig)	1408 @ 3671 ft
Static Oil Level (ft below surface)	1312
Dynamic Oil Level (ft below surface)	2297
Oil Specific Gravity (60F/60F)	0.9792
Water Specific Gravity (60F/60F)	1
API	13
Oil Viscosity (cp @F))	2680 @130 , 15763 @100F
OFVF (@psig) *	1.05 @ 915 psig , 1.03@1535
Bubble Point Pressure (psig)**	915
Bottom Hole Producing Pressure (psig)	1500 for 200 BFPD (calculated)
Present Production (BPD)	0
Required Production (BPD)	300-700
Required Well Head Pressure (psig)	100
Water Cut (%)	20
Sand Cut (%)	0
GOR (scf/STB)	100
Casing Properties	9 5/8 in., L80, 43.5 lb/ft
Liner Properties	7 in., C75, 29 lb/ft, Buttress
Tubing Properties (Present)	2 7/8 in., C75, 6.5 lb/ft, EUE

[Adapted from Taheri and Hooshmandkoochi, 2006) [13].

Table 2: Input data.

Design Input	Value			Unit
	Case 1	Case 2	Case 3	
Desired production rate	300	500	300	bbl/day
Pump Depth	5,000	5,000	7,000	Ft
Plunger Diameter	2	2.25	2.25	in
Tubing Size	2-7/8	2-7/8	2-7/8	OD in
Steel Rod Number/Grade	D75	D97	D86	
Fluid specific gravity	0.98	0.98	0.98	Sp.Gr.H2o
Surface Unit Efficiency	80	80	80	%
Pump Volumetric Efficiency	80	80	80	%

[Note: in surface stroke length, C refers to the conventional unit, M to Mark II, and A to the balanced air unit].

Table 3: Pump size.

Pump Type	Tubing Size (in)	Pump Diameter (in)
R.H. (Rod, Heavy Wall)	1.50	1.0625
	2.00	1.25
	2.50	1.25 – 1.75
	3.00	2.25
RW (Rod, Thin Wall)	1.25	0.875
	1.50	1.25
	2.00	1.50
	2.50	2.00
	3.00	2.50
TH (Tubing, Heavy Wall)	2.00	1.75
	3.00	2.25
	3.50	2.75

2.6.1. Dimensionless Variables

The dimensionless variables will help in the interpretation of charts that will give data for the calculation of operating characteristics. Dimensionless pump speed for non-tapered rod string (N/N_o), Dimensionless pump speed for tapered rod string (N/N'_o), dimensionless rod stretch (F_o/SK_r), and the spring constant for rod string (K_r) can be calculated using Eq. 2-5.

$$\mathrm{N/N_o} = \frac{NL}{245{,}000} \tag{2}$$

$$N/N'_o = \left(\frac{\mathrm{N}}{\mathrm{N_o}}\right)/\mathrm{F_c} \tag{3}$$

$$\mathrm{F_o/S\,k_r} = F_O \div SK_r \tag{4}$$

$$\mathrm{k_r} = \frac{1}{\mathrm{E_r L}} \tag{5}$$

Pump displacement can be calculated using Eq.6

$$PD = 0.1166 \times E_S \times SN \times D_P^2 \tag{6}$$

From the previous equations, the designer can now select the suitable rod string when the elastic constant is determined. Match the calculated elastic constant with the value from Table **4**.

Table 4: Rod and pump data.

Plunger Diameter, in	Rod Weight, lb/ft	Elastic Constant, in/lb-ft	Frequency Factor	Rod String, % of each size
D	Wr	Er x 106	Fc	½
1.06	.908	1.668	1.138	55.4
1.25	.929	1.633	1.140	50.5
1.50	0.957	1.584	1.137	43.6
1.75	0.990	1.525	1.122	35.4
2.00	1.027	1.460	1.095	26.3
2.25	1.067	1.391	1.061	16.6
2.50	1.108	1.318	1.023	6.5

2.6.2. Operating Characteristics

The operating characteristics of a polished rod pumping system, such as peak polished rod load (PPRL), minimum polished rod load (MPRL), peak torque (PT), polished rod horsepower (PRHP), and counterweight effect (CBE), are determined by using non-dimensional variables obtained from charts and variables obtained from equations 2-4. These variables are used to calculate the loads, power requirement, torque, and counterweight needed for the system to operate effectively. The operating characteristics can be calculated by Eq. 7-12.

$$\mathrm{PPRL} = \mathrm{W_{rf}} + \mathrm{F_1} = \mathrm{W_{rf}} + \frac{\mathrm{F_1}}{\mathrm{Sk_r}} \times \mathrm{Sk_r}. \tag{7}$$

$$\mathrm{MPRL} = \mathrm{W_{rf}} - \mathrm{F_2} = \mathrm{W_{rf}} - \left(\frac{\mathrm{F_2}}{\mathrm{Sk_r}} \times \mathrm{Sk_r}\right) \tag{8}$$

$$\mathrm{PT} = \left(\frac{2\mathrm{T}}{\mathrm{S^2k_r}}\right)(\mathrm{Sk_r})\left(\frac{\mathrm{S}}{2}\right)(\mathrm{T_a}) \tag{9}$$

$$\mathrm{T_a} = 1.0 + (\pm \mathrm{X})\left[\frac{\left(\frac{\mathrm{W_{rf}}}{\mathrm{Sk_r}}\right) - 0.3}{10}\right] \tag{10}$$

$$\mathrm{PRHP} = \left(\frac{\mathrm{F_3}}{\mathrm{Sk_r}}\right) \times \mathrm{Sk_r} \times \mathrm{SN} \times (2.53 \times 10^{-6}) \tag{11}$$

$$\mathrm{CBE} = (1.06)(\mathrm{W_{rf}} + 0.5\mathrm{F_O}) \tag{12}$$

2.6.3. Nameplate Horsepower

Nameplate horsepower, $\mathrm{HP_{np}}$ is the minimum rated horsepower for the pump unit motor. The nameplate can be calculated using Eq.11

$$\mathrm{HP_{np}} = \frac{(\mathrm{PRHP})(\mathrm{CLF})}{\mathrm{E_{surf}}} \tag{13}$$

3. Results and Discussion

Through this paper, three cases have been designed to compare the requirements of different production rates and depths. The parameters that have been adjusted are the depth of 5,000 ft and 7,000 ft. Each depth has been matched with the following rates 300 bbl/day and 500 bbl/day. The variation in production rate and depth will lead to the complete reselection of all components of the system, including the plunger size, rod string, surface pumping unit, counterweight, and motor sizing. The change of the selected components will affect the operation and capital cost of the project, whereas the counterbalance effect can effectively reduce load fluctuation [14]. Moreover, through simulation, all standard parameters of a sucker rod pumping unit can be monitored [15] and controlled economically through cutting-edge technology and industry 4.0 principles [16].

3.1. Case 1: (300 bbl/day, 5000 ft)

The detailed results of case 1 are reported in Table **5**.

During the design of the beam pumping unit, various assumptions were made. Firstly, the plunger size had to be considered as it would determine the pump size and achieve the required production rate. If the plunger size is increased beyond what is necessary to achieve the desired production rate, it can lead to excess weight on the rod string [17]. This excess weight will cause a higher load on the rod string and the surface pumping unit, which can lead to increased wear and tear on these components and can also decrease the system's overall efficiency. However, if the designer adjusts the stroke length and pump speed, the desired production rate can still be achieved while avoiding the negative effects of an oversized plunger [18]. Hence, the selection of plunger size depends on the tubing size and production rate. For 300 BBL/Day, the tubing size selected was 2-7/8" OD; for this size, the suitable plunger size is 2".

Table 5: Detailed result can of case 1.

-	Conventional Unit	Mark II Unit (Selected)	Air Balanced Unit
Production rate (100% pump efficiency)	375 bbl/day	375 bbl/day	375 bbl/day
Production rate (80% pump efficiency)	300 bbl/day	300 bbl/day	300 bbl/day
Top steel rod loading	94.3 %	93.4%	92.7 %
Surface stroke length (S)	74 in	100 in	120 in
Peak polished rod load (PPRL)	18,369 lb	17,930.2 lb	18,342.7 lb
Minimum polished rod load (MPRL)	3885.2 lb	3406.5 lb	4442.9 lb
Peak torque (PT)	279 Kin-lb	295 Kin-lb	393 Kin-lb
Counterbalance effect (CBE)	11578.9 lb	11578.9 lb	11578.9 lb
Polished rod horsepower (PRHP)	16.95 HP	16.42 HP	16.39 HP
Pump stroke length (S_p)	54.20 in	82.42 in	95.09 in
Pump speed (N)	14.84 SPM	9.76 SPM	8.46 SPM
Minimum API unit required	320-200-74	320-200-100	456-200-120
Minimum motor sizing	NEMA D 35.31 HP	NEMA D 28.18 HP	NEMA D 28.85 HP

Pump displacement is mainly affected by the stroke length and pump speed; their increase will increase production. The optimal stroke length-pump speed (SN) calculation based on the required production rate had to be determined using Eq. (1).

According to the equations of optimal stroke length-pump speed and pump displacement, it was assumed that the pump efficiency is 80%, as it is not realistic to assume 100% due to:

i. The pump has fluid leakage around the plunger.

ii While lifting the reservoir fluid, pressure drops to bubble point pressure, resulting in gas production from the dissolved gas.

The calculation of pump displacement by using Eq. (6) of API RP 11L.

The chart used in the equation and also the missing variable of pump efficiency will result in pump displacement of 100% efficiency; as observed from the results, the production rate is 375 BBL/day, while the actual rate is 300 BBL/Day. The actual production rate is typically calculated by multiplying the calculated or predicted production rate by a factor, such as 80%, to account for any discrepancies or inefficiencies in the production process. This is known as a capacity factor or utilization factor. It can also change based on the specific production method or facility. To select the suitable Pump Speed (N) that will lift the desired production rate, a match between the surface stroke length and pump speed has to be done. The increase in stroke length will reduce the required pump speed to lift the desired production rate. At this step, the acceleration factor of the combination of surface stroke length and pump speed was considered. Transmitting linear forces like acceleration affects the dynamometer cards [19, 20]. Thus, the acceleration factor has been calculated by using Eq.14

$$C = \alpha = \frac{SN^2}{70{,}500} \tag{14}$$

The acceleration will affect the rod string's stability and fluid volume. A general rule of thumb is that the acceleration factor should be kept as low as possible to minimize the impact of ramp-up and ramp-down on production rates. Some experts recommend that the acceleration factor should be less than 0.3 to avoid significant effects on the production rate. However, this can vary depending on the specific production process and facility. Acceleration value can be reduced by increasing the stroke length, which will result in decreasing the pump speed.

The pump speed can be calculated based on the desired production rate and standard surface unit surface stroke length creating the following results as shown in Table **6**.

Table 6: Example of acceleration consideration.

S (in)	N (SPM)	Acceleration (C)
42	23.9295	0.341136
48	20.9383	0.298493
54	18.6118	0.265327
64	15.7037	0.228869
74	13.5816	0.193617
86	11.6865	0.1666
100	10.05038	0.1432
120	8.3735	0.11939

The selection of an appropriate stroke length is critical to the performance of a polished rod pumping system. A shorter stroke length, such as 42 in, can cause the rod string to be lowered and pulled up too quickly, leading to instability of the rod string forces and decreasing the production rate. By selecting a stroke length that does not exceed 0.3 acceleration (48 in), the system can fill the pump barrel in an appropriate amount of time and maintain the stability of the rod string forces, which helps optimize the system's overall performance. This will result in a lower production rate or failure of the designed system. Moreover, the surface unit standard designation has to be considered too, where each unit has several surface stroke lengths that the manufacturer designs to handle the maximum torque, and the peak polished rod load.

After calculating the peak polished rod load and peak torque using 48in stroke length, the result will exceed the unit limits. So, the calculation with other stroke lengths had to be repeated or simulated using QRod3 software until the suitable stroke length, which is designed to handle produced peak torque and peak polished rod load, is achieved. In this case, the suitable stroke length was 74in for a conventional unit.

The selection of the rod string is typically made using a reverse method of calculation and correlation based on API RP 11L. This method uses the selected pump speed (N), surface stroke length, and assumed plunger stroke factor in equations 2 and 3 to obtain the dimensionless pump speed (N/No'). This information is then used to determine the appropriate rod string size and other design parameters. This method allows for the optimization of the polished rod pumping system by ensuring that the selected rod string is capable of handling the loads and power requirements of the system while also being within the recommended ranges for the specific surface unit being used. Using the dimensionless pump speed (N/No') and Sp/S, the suitable dimensionless rod stretches due to fluid load (Fo/SKr) can be obtained from API RP 11L charts plunger stroke factor. After that, by using Eq. (4) and (5), the value of the elastic constant of the tapered rod section (Er) can be obtained. After determining the elastic constant of the tapered rod section (Er) the rod string can be determined from Table **3**. In this case, the elastic constant of the tapered rod section (Er) was 0.6529E-6 in. per lb-ft, which is suitable with D75 tapered rod string.

After the selection of the rod string, the rod string has to be examined to ensure its ability to handle the stress on the top section of the tapered rod string and prevent the failure of the rod string.

The maximum allowable rod stress has been determined and ensured that it does not exceed the maximum limit of Grad D rod string. In all cases, QRod3.1 software has been used to simulate all rod strings to ensure the selection of the minimum top steel rod loading, which is, in this case (D75) equal to 93.4 % top steel rod loading.

The pump stroke length is typically shorter than the surface stroke length. This is because the rod string stretches when it is lifting the weight of the fluid from the well to the surface. This stretch causes the pump to lift a shorter distance than the surface unit, which is why the pump stroke length is shorter. The surface unit must compensate for this stretch by raising the rod string a greater distance to ensure that the fluid is lifted to the surface. The difference between the two stroke lengths is typically accounted for in the system's design and is known as "cushion stroke." So, theoretically and logically, the pump stroke length should be shorter than the surface stroke length. In case 1, the surface stroke length was 100 in for the Mark II unit, while the pump stroke length was 82.42 in, giving the difference of (17.58 in) caused by the load of the produced fluid and the weight of the rod string.

The peak polished rod load and the minimum polished rod load can both be affected by the length of the surface stroke. The increase of surface stroke length will result in the reduction of peak polished rod load and minimum polished rod load, which has been observed from the results. The surface geometry will also play an important role in the peak polished rod load, where Mark II resulted in less PPRL compared to conventional and air-balanced units; this is because Mark II has a longer and slower upstroke.

As observed from the results, the peak torque, which is the sum of torques in the gearbox required to move the polished rod and counterweight, kept increasing during the increase of the production rate and pump depth.

Operating characteristics (PPRL, MPRL, PT, PRHP, and CBE) for the conventional unit have been calculated using API RP 11L equations and correlations, while Mark II and Air Balanced units have been calculated using the modified equations of API RP 11L since the API RP 11L is designed only for a conventional unit.

As mentioned previously, the Mark II type can deliver the desired production rate of 300 bbl/day with much lower torque and power requirements than the conventional type. It is 20.2% lower in power requirement. Air Balance unit has the performance rating between the other two types. It also has a lighter and smaller size. Mark II has been selected based on the previous consideration discussed in this case study.

3.2. Case 2: (500 bbl/day, 5000 ft)

The detailed results of case 2 are reported in Table **7**.

Table 7: Case 2 detailed results.

-	Conventional Unit	Mark II Unit (Selected)	Air Balanced Unit
Production rate (100% pump efficiency)	625 bbl/day	625 bbl/day	625 bbl/day
Production rate (80%efficiency)	500 bbl/day	500 bbl/day	500 bbl/day
Top steel rod loading	84.4%	87.8%	86.3%
Surface stroke length (S)	144 in	120 in	120 in
Peak polished rod load (PPRL)	27,734 lb	27,211.7 lb	27,715.8 lb
Minimum polished rod load (MPRL)	7,622.6 lb	4270.3 lb	6,297.5 lb
Peak torque (PT)	847 Kin-lb	515 Kin-lb	575 Kin-lb
Counterbalance effect (CBE)	17,217.9 lb	17,217.9 lb	17,217.9 lb
Polished rod horsepower (PRHP)	28.87 HP	29.19 HP	28.93 HP
Pump stroke length (S_p)	126.62 in	106.15 in	106.30 in
Pump speed (N)	14.84 SPM	9.76 SPM	8.46 SPM
Minimum API unit required	912-305-144	640-305-120	640-305-120
Minimum motor sizing	NEMA D 55.7 HP	NEMA D 49.34 HP	NEMA D 49.63 HP

In case 2, the production rate has been increased to 500 BBL/day. The increase in production rate will change all the components selected earlier in case 1 since the weight and volume of fluid lifted is higher. In this case, the plunger size has to be higher than case 1, which is 2.25, to increase the pump volume.

The increase of production rate to 500 BBL/Day required a larger rod size that can handle the stress by a higher cross-sectional area of the top rod string that will distribute pressure on a bigger area. For example, case 1 (300 bbl/day) required D75 rod string with a top rod string size 7/8". When the production rate increased to 500 bbl/day in case 2, the rod string had to be increased to D97 with a top rod size of 1-1/8".

During the comparison between case 1 (300 bbl/day) and case 2 (500 bbl/day), which have the same depth, a higher production rate results in higher operating characteristics of the pumping unit. When the rating of the pumping unit increases, it will increase the capital cost of the design, which is one of the main characteristics of the beam pumping unit.

Mark II unit has also been selected in this case due to the low peak torque and peak polished rod load, proving that the Mark II unit is the most efficient among other units.

3.3. Case 3: (300 bbl/day, 7000 ft)

The detailed results of case 3 are reported in Table **8**.

Table 8: Case 3 detailed result.

-	Conventional Unit	Mark II Unit (Selected)	Air Balanced Unit
Production rate (100% pump efficiency)	375 bbl/day	375 bbl/day	375 bbl/day
Production rate (80% pump efficiency)	300 bbl/day	300 bbl/day	300 bbl/day
Top steel rod loading	96.9 %	88.9 %	98.9%
Surface stroke length (S)	144 in	100 in	144 in
Peak polished rod load (PPRL)	25,207.2 lb	23,741.8 lb	25,879.6 lb
Minimum polished rod load (MPRL)	6,082.0 lb	7,332.9 lb	6,355.4 lb
Peak torque (PT)	812 Kin-lb	307 Kin-lb	676 Kin-lb
Counterbalance effect (CBE)	16,004.8 lb	16,004.8 lb	16,004.8 lb
Polished rod horsepower (PRHP)	26.90 HP	26.51HP	27.50 HP
Pump stroke length (S_p)	131.02 in	100.50 in	126.46 in
Pump speed (N)	10.92 SPM	14.23 SPM	11.31 SPM
Minimum API unit required	912-256-144	320-256-100	912-305-144
Minimum motor sizing	NEMA D 73.62 HP	NEMA D 43.78 HP	NEMA D 63.43 HP

In the case of changing the depth of the well, we can compare case 1 and case 3, that has the same production rate but with different depths. The result observed the change in component size and rating in production rate change was greater than the change in depth of wells. As the well depth increases, the rod string's weight and the fluid's static column also increase, which can cause more stress on the system. However, increasing the production rate by increasing the diameter of the pump barrel will displace a higher weight of the fluid, which can help offset the additional stress caused by the increased depth. This is one of the primary benefits of the beam rod pump system, as it allows for easy repair and replacement of components. Additionally, increasing the production rate will reduce the number of strokes the rod string needs to make, which can also help to reduce wear and tear on the system, making it more durable and efficient.

The selected pumping unit for this case is the Mark II unit, for the same reasons, discussed earlier in this paper.

3.4. Dynamometer Card

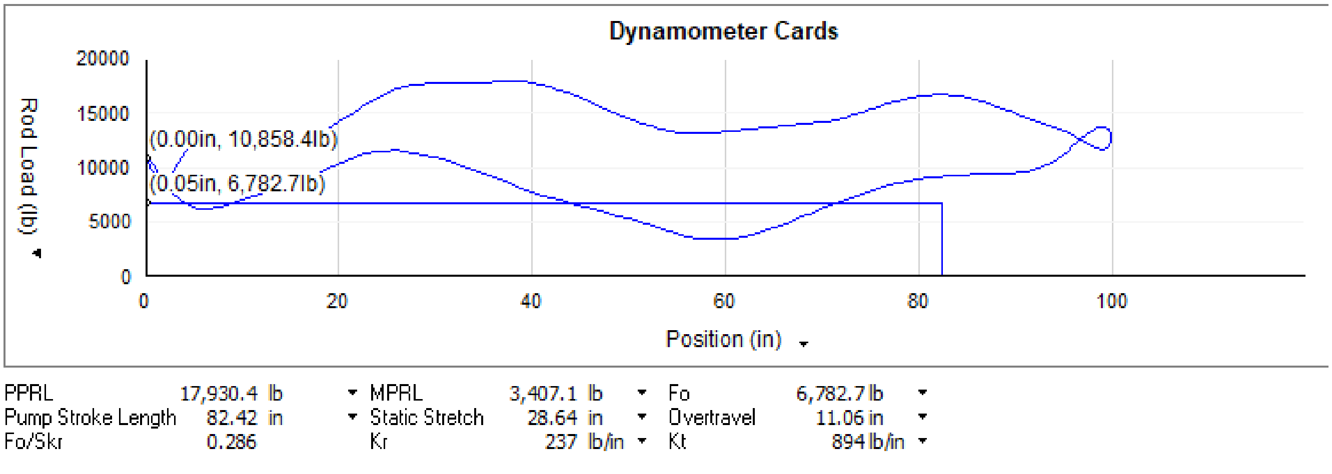

Figure 2: Mark II Dynamometer Card and Pump Card.

3.4.1. PPRL & MPRL

The peak polish rod load (PPRL), in pounds, is presented in this space. It is the maximum load calculated during the pumping cycle [6]. The Beam Rating of the Unit is determined from this value. The minimum polish rod load (MPRL) in pounds is presented in this space. It is the minimum load calculated during the pumping cycle [21] (Fig. **2**)

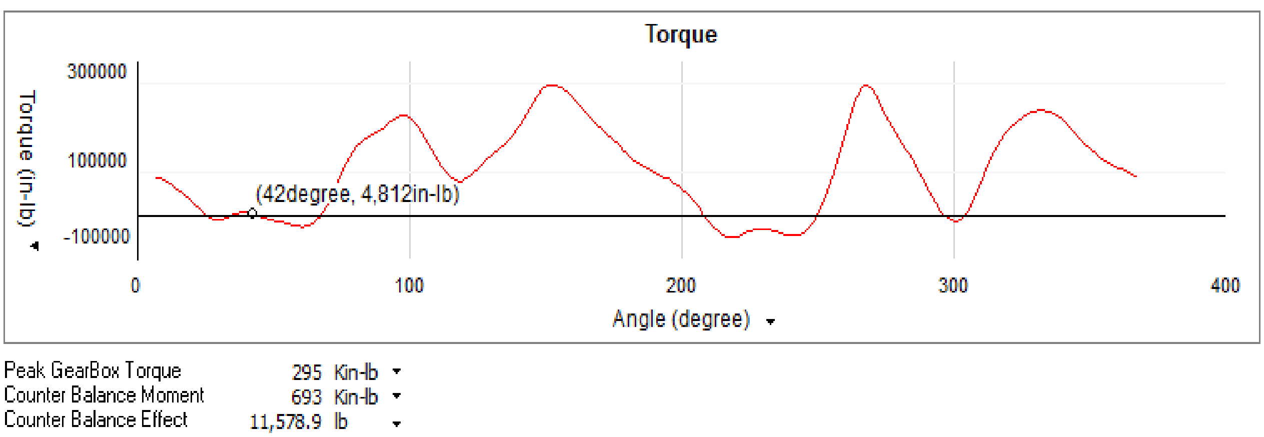

Figure 3: Mark II torque profile.

The Torque graph is the plot of the In-Balance Net Gearbox Torque on the gearbox versus crank angle. The crank angle is positive in the direction of rotation as shown in Fig. (**3**). For conventional units, the crank angle is measured from the 12 o'clock position; for the air-balance and Mark II units, it is measured from the 6 o'clock position [22].

3.4.2. Peak Gear Box Torque

The Peak Gear Box Torque is the maximum torque on the output crank of the gearbox expressed in inch-pounds. The counterweight effect describes the balancing of the torque on a rod string during the pumping process. It occurs either on the upstroke or the downstroke of the pumping system. On the upstroke, the torque is generated by the weight of the lifted fluid and the rods. On the downstroke, the torque is generated by the weight of the counterweights [23]. The program calculates the counterbalance moment and the corresponding counterweight effect required so that these two torque values are equal, thus achieving balance and reducing stress on the system. This helps ensure stability and minimize wear and tear on the system, leading to increased efficiency and longevity [24].

4. Conclusion

Beam pumping design entails a complex and time-consuming calculation procedure to determine the appropriate compensation of equipment and operation characteristics to prevent system failure at the lowest possible cost. The conclusion of this research can be outlined as follows:

- The beam pumping design procedure necessitates using the latest simulators and carefully considering and evaluating all major and minor components.
- A surface pumping unit was chosen after calculating peak torque and peak polished rod load with API RP 11L. According to API surface pumping designation and manufacturer information, each pumping unit has a maximum surface stroke length that can handle a maximum polished rod load and peak torque.
- The torque generated during the upstroke is caused by the weight of the fluid being lifted and the rods, while the weight of the counterweights causes the torque generated during the downstroke. The program uses the calculated counterbalance moment and the corresponding counterweight effect to equalize the two torque values, thus achieving balance and reducing stress on the system. This helps to ensure stability, minimize wear and tear on the system, and increase the efficiency and longevity of the system.
- Due to the increased production rate and depth of the well, a higher rating of the surface pumping unit was required. Because the number and size of the rod string selected have increased, as has the surface unit rating, the project cost will rise as well.
- When the production rate and well depth are both too high, the system fails to design because the stress exceeds the maximum allowable limit of all rod strings. Because the main principle of API Recommended Practice is to prevent system failure, those cases could not be included in the design.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

All praise and thanks go to God for giving us the strength, knowledge, and support we needed to finish this paper, which we believe would not have been possible without collaboration. We owe our gratitude to our researchers and friends for their valuable advice at various stages of this research project. The authors also thank the multiple institutions they belong to for their ongoing support.

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