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REVIEW PAPER-PRODUCTION ENGINEERING

A comprehensive review of sucker rod pumps' components, diagnostics, mathematical models, and common failures and mitigations

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Abstract
In many oil reservoirs worldwide, the downhole pressure does not have the ability to lift the produced fluids to the surface. In order to produce these fluids, pumps are used to artificially lift the fluids; this method is referred to as artificial lift. More than seventy percent of all currently producing oil wells are being produced by artificial lift methods. One of the most applied artificial lift methods is sucker rod pump. Sucker rod pumps are considered a well-established technology in the oil and gas industry and thus are easy to apply, very common worldwide, and low in capital and operational costs. Many advancements in technology have been applied to improve sucker rod pumps performance, applicability range, and diagnostics. With these advancements, it is important to be able to constantly provide an updated review and guide to the utilization of the sucker rod pumps. This research provides an updated comprehensive review of sucker rod pumps components, diagnostics methods, mathematical models, and common failures experienced in the field and how to prevent and mitigate these failures. Based on the review conducted, a new classification of all the methods that can fall under the sucker rod pump technology based on newly introduced sucker rod pump methods in the industry has been introduced. Several field cases studies from wells worldwide are also discussed in this research to highlight some of the main features of sucker rod pumps. Finally, the advantages and limitations of sucker rod pumps are mentioned based on the updated review. The findings of this study can help increase the understanding of the different sucker rod pumps and provide a holistic view of the beam rod pump and its properties and modeling.
Sucker Rod Pumps · Comprehensive Review · Sucker Rod Failures and Mitigations · Suker Rod Diagnostics

Abbreviations

a^2	Velocity force propagation
v	Damping factor
$u(x, t)$	Displacement of the sucker rod at arbitrary depth and time
L	Length of the sucker rod string
PPRL	Peak polished rod load
MPRL	Minimum polished rod load
W_f	Weight of the fluid column
W_r	Weight of the rods in air
A	Area
C_D	Viscous damping coefficient
A_r	Cross-sectional area of the rod
A and B	Constants empirically derived
S_F	Represents environmental effects; Service Factor
S_a	Fatigue endurance limit
$S_{\min}$	Minimum rod stress
T	Minimum tensile strength of the rod material
A_i	Metal area of the rod in the ith taper
a_i–d_i	Are best fitting line parameters
L_i	Sucker rod length
P_{inflow}	Inflow pressure
P_{outflow}	Outflow pressure
P_{wh}	Wellhead pressure
E	Young's modulus
g	Gravitational constant
t	Time
u	Elongation
ρ	Density
N	Matrix that represents the wave equation
I	Unit matrix, also known as the filter matrix

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W Newly obtained set of data with the least global error
f_r Fluid velocity
F_{rf} Viscous force per unit length of rod
F_{cf} Viscous force per rod coupling per unit length of rod
F_{rt} Friction force between tubing and rod per unit length of rod
$F_{C,\mathrm{API}}$ Equals unity for a uniform rod taper
U, G, H Column vectors defined based on initial and boundary conditions

Introduction

Sucker rod pumps include a wide range of artificial lift methods (Diaz et al. 2009; Guo et al. 2003; Mo and Xu 2000; Spears 1989; Arambulo et al. 2020). With the advancement in technology, the types of artificial lift methods that fall under the sucker rod classification have increased (Gauchel 1985; Yi et al. 2019; Byrd and Hale 1970; Pino et al. 2020; Nickell 2020; Shakhmatov 2020). These methods are used to increase oil recovery from relatively low-rate wells that are producing moderate to heavy crude oils with a moderate level of gas and solid particles (McCaslin 1988; Jacobs 1986; Jackson et al. 2003). Sucker rod pumps are used widely in the industry due to their multiple advantages including relatively low cost, well established technology, availability, and wide applicability range (Martin 2012; Teodoriu and Pienknagura 2018; Takacs 1997; Takacs and Mihaly 2017; Takacs and Gajda 2014).

Several researchers have attempted to model the sucker rod pump using different methods. McCafferty (1993) illustrated the importance of calculating the maximum available compression ratio compared to the required compression ratio for sucker rod installation designs. Jennings (1989) showed some of the most important parameters that are needed for a proper design of the sucker rod pump. These parameters included reservoir rock and fluid properties, wellbore properties, and operational properties. Peng et al. (2019) used a deep autoencoder neural network to obtain features of the dynamometer card which can minimize information loss and improve data management. Langbauer and Antretter (2017) used finite element method for improvement of the sucker rod pump efficiency by increasing production and reducing cost and failure. Using finite element method managed to improve sucker rod performance by 30%. Ferrigno et al. (2018) compared the results of the dynamometer cards obtained from controllers and telemetry with other software that consider friction effects in deviated wells. Chen et al. (2018) used the Fourier series method to solve sucker rod prediction problems using the conventional surface dynamometer card. Caicedo and Carma (2009) introduced another sucker rod analysis method other than the conventional dynamometer card. This method introduces and algorithm to generate piston tubing rod performance curve. Chevelcha et al. (2013) performed tests on the sucker rod pump in an attempt to obtain a relation between the noise produced by a well during sucker rod operation and its relation to the sucker rod condition.

Experimental and field analysis of sucker rod pumps have also been conducted to evaluate the importance of some factors on sucker rod performance and failure. Podio et al. (2003) presented results for tests with a sucker rod pump model in the laboratory to provide information on dynamic and static pump friction measurement. They reasoned that one of the major costs during production is the lifting cost. It should be optimized by minimizing down time, and increasing the pump efficiency through loss reduction. Xu and Hu (1993) showed that using the assumption that the sucker rod for deviated wells can be performed using the conventional vertical wells models can lead to serious errors. Dave and Mustafa (2017) presented a comparison between the different sucker rod artificial lift systems based on the production area, depth, downhole failures, power saving, and safety concerns. Allison et al. (2018) studied the impact of gas on sucker rod pumps and found that they have the advantages of tolerating gas production without damage to the pump itself, however the overall volumetric efficiency of the pump is reduced significantly due to gas presence, up to 40%. Ali et al. (2015) performed a screening criterion for sucker rod pumps and compared their performance to that of electrical submersible pumps. Gauchel (1985) presented the results for a test design for fiber glass sucker rods to determine tensile, shear, and tensile/tensile fatigue performance as a function of temperature. Reynolds (1988) performed a review on the advantages of fiberglass sucker rods compared to steel sucker rods.

Many researchers have studied the sucker rod pump and attempted to improve its design and applicability. Very few have attempted to combine this knowledge together in order to provide a holistic review on the most current advancements in the sucker rod pump. Also, since new sucker rod designs are being added under the sucker rod classification, a new comprehensive classification of what types of artificial lift pumps can fall under the naming of the sucker rod pump is needed. This research addresses these gaps by performing a comprehensive review of the main type of sucker rod pumps, the beam rod pump, components, diagnostics methods, mathematical models, and common failures experienced in the field and how to prevent and mitigate these failures. The research also provides a new classification of all methods that can fall under the sucker rod pump technology based on newly introduced sucker rod pump methods in the industry. The main focus of this review is the beam rod pumping unit since it is the main type of sucker rod pumps and is also the most widely used worldwide.

The research begins by introducing a new classification of sucker rod pumps based on the novel pump designs that have been recently introduced in the industry. Following this, the main focus of the research is on the beam rod pump, which is the most widely used sucker rod pump. The components of the beam rod pump are explained in detail, along with the diagnostics methods used to evaluate the performance of the beam rod pump. The most widely applied mathematical models used with the beam rod pump are then mentioned and explained. This is followed by a detailed failure analysis of the beam rod pump based on field studies. For all the failure mechanisms, a mitigation recommendation is also provided based on the comprehensive literature review. Advancements in the beam rod system are then mentioned and the added value of each advancement is explained. Finally, beam rod pump case studies worldwide are mentioned along with their results and the beneficial information gained from each case study. Using all the data collected, the advantages and limitations of the beam rod pump are then mentioned. Figure 1 shows a flowchart for the research conducted and the problems studied.

Sucker rod pump classification

Sucker rod pumps include a wide range of methods used to increase oil recovery. Since classifications have varied significantly along the years mainly due to the development of new technologies, the first step in this research is to include a new classification of sucker rod pumps that includes all the new technological developments that fall under this category.

Beam rod pumping

The beam rod pumping unit is the most applied sucker rod method (Jalikop et al. 2020), shown in Fig. 2. This method will also be the main focus of this research. It is mainly composed of a surface unit and downhole pump and rods. The surface unit has multiple variations based on the size

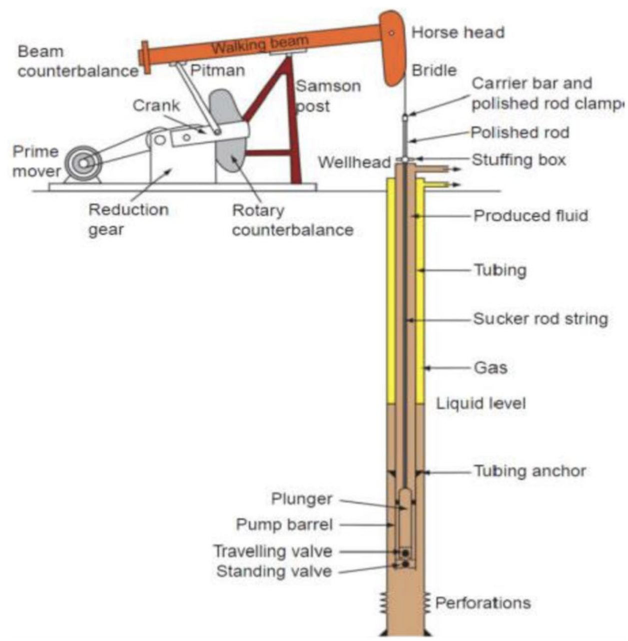
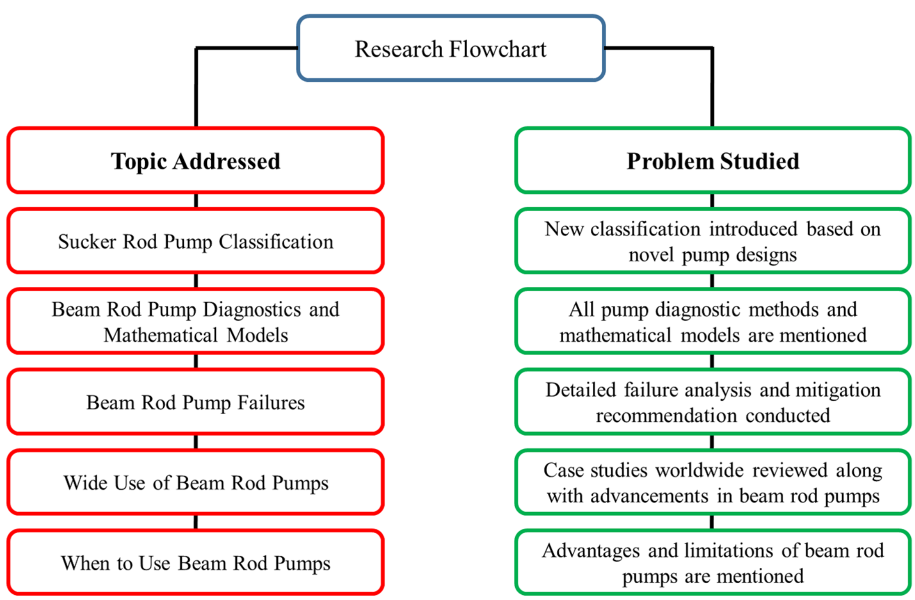


Fig. 2 Beam rod pump (Wang et al. 2018)

Fig. 1 Research flowchart



and application. The three main types are the Type *A*, *C*, and *M* beam rod. Type *A* (Air balanced) uses compressed air to counterbalance the load that comes from the rods. Type *A* has the benefit of reduced weight and lower installation and transportation cost. Type *M* (Mark II) lowers the torque and power requirements throughout the pumping cycle. Type *C* is the conventional beam rod pump; a detailed description of this type will be provided in this review (Teodoriu and Pienknagura 2018).

Coiled tubing sucker rod

The use of coiled tubing as sucker rods is mainly performed in small diameter holes. This technology was first applied in Argentina and was then used in the USA and Canada (Parekh and Desai 2013). It has the advantage of reducing cost since the coiled tubing acts as both the production string and the sucker rod. This method also reduces time during well intervention jobs and allows the conduction of various operations in live wells without the need of kill fluid. An example of coiled tubing sucker rod is presented in Fig. 3. Some of key design parameters in this type of sucker rod pump are the coiled tubing material, fatigue failure analysis, corrosion resistance, completion design, non-return valve (one way valve), gas separation, and surface facilities (Parekh and Desai 2013).

Hydraulically actuated sucker rods

Hydraulically actuated sucker rods have been present since the 1940s. They contain a hydraulic cylinder at the surface used to impart a reciprocating motion on the polished rod and the rod string, and the downhole assembly which is almost identical to the conventional beam unit (Phillips et al. 2013). Figure 4 presents an illustration of the surface components of the hydraulically actuated sucker rod pump.

The hydraulically actuated sucker rod pump has the following advantages (Phillips et al. 2013):

- Is not subject to damaging torque limitations.
- Has no structural loading concerns.
- Polished rod velocity is linear for the majority of the stroke
- Can operate at depths up to 14,000 ft
- Can operate in high rate wells with thousands of bpd
- Can operate in shallow wells.
- Better paraffin, solids, and gas handling
- Has dual well capabilities

The two main limitations of the hydraulically actuated sucker rod pump include high maintenance cost and frequent failures compared to the conventional beam pumping unit.

Linear rod pumping

Linear rod pumping has the advantage of removing the bulky surface components of the conventional beam pumping unit.

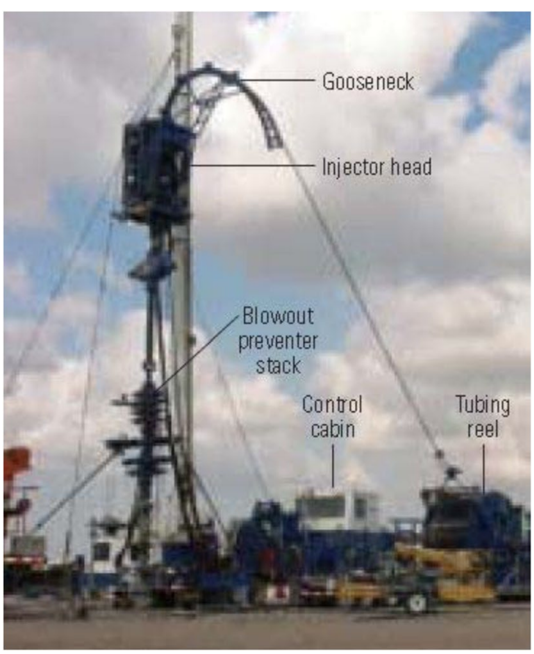


Fig. 3 Coiled tubing sucker rod (Parekh and Desai 2013)

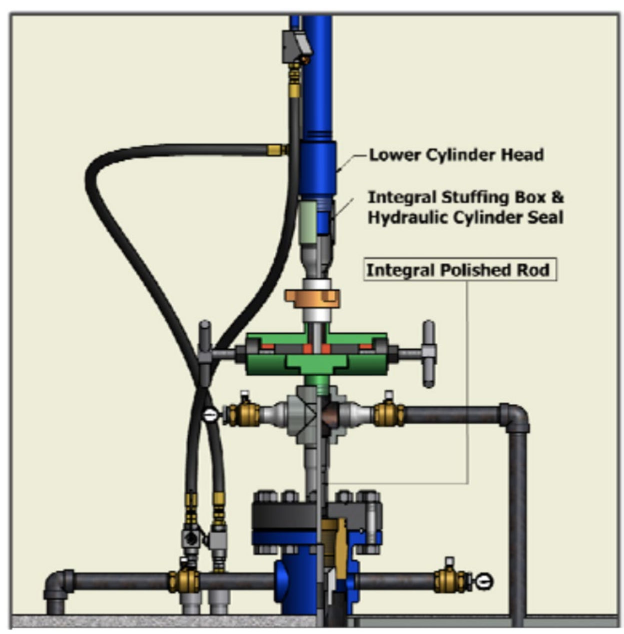


Fig. 4 Hydraulically actuated sucker rods (Phillips et al. 2013)

This increases the applicability of the sucker rod artificial lift method by allowing it to be used when the surface space is limited where size is important, most notably in offshore applications. The downhole components are very similar to those of the conventional beam pumping unit (Khadav et al. 2016; Lima and Neto 2020). An illustration of the linear rod pumping unit surface components is presented in Fig. 5.

Long stroke sucker rod

The long stroke sucker rod is one of the least utilized sucker rod methods. It could be considered a variation of the linear rod pumping. It is designed to increase the stroke length of the sucker rod string in order to increase applicability of sucker rod pumps in deeper wells with higher capacity and reduction in fatigue (Dave et al. 2017; Teodoriu and Pienknagura 2018). An image of the surface components of the long stroke sucker rod is shown in Fig. 6.

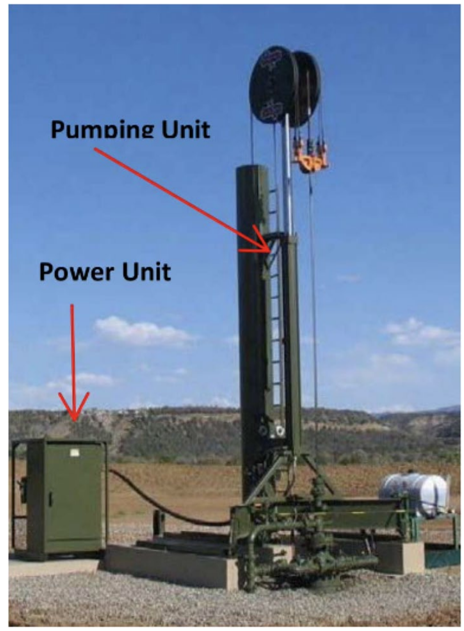


Fig. 6 Long stroke sucker rod (Dave et al. 2017)

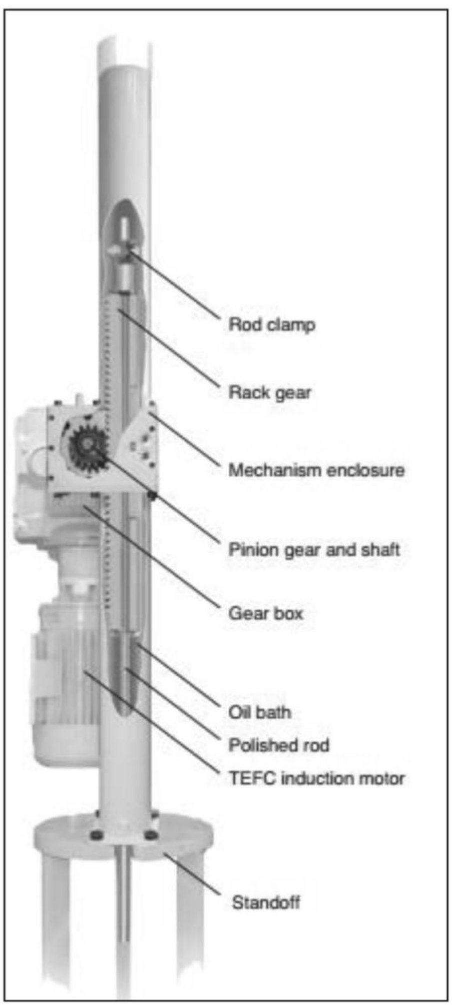


Fig. 5 Linear rod pumping (Khadav et al. 2016)

Adjustable counterbalance sucker rod pump

Oliva et al. (2020) developed an adjustable counterbalance sucker rod pumping unit that they referred to as "smart sucker rod pump" which can adjust the counterbalance and the polished rod stroke length without the needed for personnel to go to the field. The adjustable counterbalance sucker rod system has the advantage of being able to adjust the polished rod stroke range easily, and the counterweight can also be adjusted at any position inside the adaptable grid. A comparison between the conventional beam pumping unit and the adjustable counterbalance sucker rod pump is shown in Fig. 7.

Beam rod pump components

The conventional beam rod pumping unit consists of surface components and downhole components. These components all function together to allow for the production of the hydrocarbons from the wellbore to the surface (Di et al. 2018). The main components of the beam pumping unit, shown in Fig. 8, are as follows:

- *Prime Mover* The prime mover converts the energy provided through electricity or a diesel engine into motion that is transmitted to the gear box.
- *Gear Box* The gear box is the main mechanism by which the surface component motion is controlled.

Fig. 7 Conventional and smart sucker rod pump (Oliva et al. 2020)

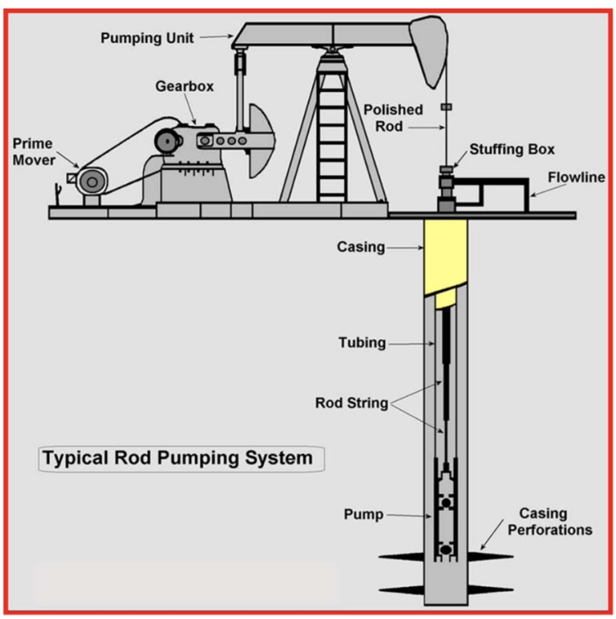


Fig. 8 Beam rod pump main components (Di et al. 2018)

- *Counterbalance* The counterbalance works to balance the weight of the horse head as it moves up and down to allow for smooth and regulated operation and to reduce wear of the surface components.
- *Horse Head (Pumping Unit)* The horse hear is the surface pumping unit that move up and down to allow the downhole pump components to operate. It carries the weight of the string.
- *Polished Rod* The polished rod is the topmost sucker rod. It is usually designed from more durable material compared to the other sucker rods since it is carrying the entire weight of the string.
- *Stuffing Box* Its main function is to prevent leakage of fluid by providing a seal between the components.
- *Tubing* The tubing is the piping through which the fluid is produced after it travels through the sucker rods.
- *Rod String (Sucker Rods)* The sucker rods make up the main length of the string. They are specially shaped in order to accommodate the fluids and work with the overall design.
- *Downhole Pump* The downhole pump is composed of several components mainly the traveling valve and the standing valves. During the upstroke, the traveling valve closes and the fluid above the plunger is lifted. This allows the barrel to fill up with fluid through the standing valve. During the downstroke, the standing valve closes and the fluid is compressed thus allowing the fluid to move through the traveling valve.
- *Flowline* The produced fluids flow into the flowline in the surface in order to be transported to the refinery.

Beam rod pump diagnostic methods

The main method by which beam rod pumps diagnostics is conducted is the dynamometer card. Other methods have also arisen to overcome some of the drawbacks of the dynamometer card. These methods include either updates or modifications of the conventional dynamometer card, or other methods not related to the dynamometer card. All of these methods, starting with the dynamometer card, are explained in this section.

Dynamometer card

Dynamometer is comprised of the word dynamo meaning power or force and meter which is a unit of length

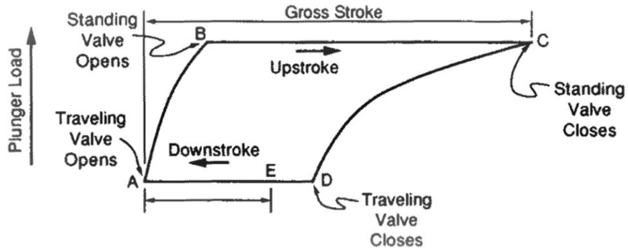


Fig. 9 Dynamometer card example (Peng 2019)

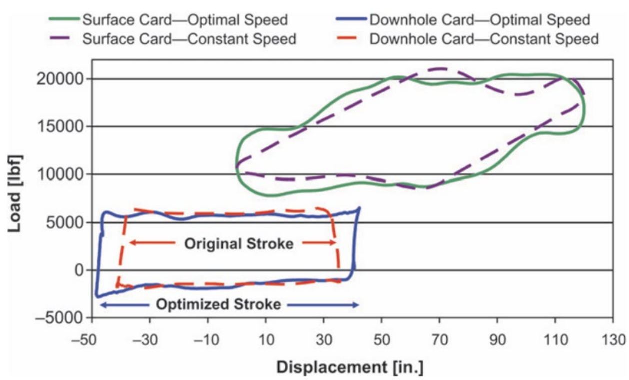


Fig. 10 Surface and downhole dynamometer cards examples (Palka and Czyz 2009)

measurement. Therefore, the dynamometer card is a measurement of the load of the entire cycle of the sucker rod pump as a function of the position at which the force is measured. The dynamometer card is a plot of the load and displacement at each time step during a stroke as a function of the plunger load (Palka and Czyz 2009; Tommaso and Marfella 2018; Peng et al. 2019; Ferrigno et al. 2018; Chen et al. 2018). An example of a conventional dynamometer card is shown in Fig. 9. The load on both the traveling valve and the standing valve can be determined as a function of position.

When generated, there are usually two dynamometer cards including the surface and the downhole. The surface card is plotted relative to the surface readings, whereas the downhole dynamometer card is plotted relative to downhole conditions. Figure 10 shows the difference between both. Most of the operators rely on the downhole card due to its higher accuracy in depicting real case conditions. The main drawbacks in the downhole card however are data delay, noise inaccuracy, and inaccurate readings (Palka and Czyz 2009).

Based on the readings of the downhole and surface dynamometer cards, several conventional charts have been found to be very similar regardless of the reservoir and wellbore being studied. A summary of these dynamometer charts and their equivalent description is shown in Table 1.

Other methods

Although the dynamometer card is the main method used for bucker rod diagnostics, it has some drawbacks which led to the rise of other methods for beam rod pump diagnostics. These methods include modification to the dynamometer card, and other methods not reliant on the dynamometer card. A description of these methods is provided in Table 2.

Beam rod pump mathematical models

Modeling of the behavior and properties of the beam rod pump can be done using different equations. The main equation used to model beam rod pump is the wave equation. Since this equation is a partial differential equation, several solutions to this model have arisen based on the initial and boundary conditions and assumptions used to solve the wave equation. Other mathematical equations not reliant on the wave equation also exist. The main mathematical equations used to model the beam rod pump behavior and properties are summarized in Table 3. The equation, terminology description, and usage are mentioned for each model.

Beam rod pump common failures and mitigation

The main failures of the beam rod pump can be categorized into three main segments including mechanical, operational, and electrical failures. With each segment, several factors can contribute to the failure of the beam rod pump. The main failure mechanisms for the beam rod pump are summarized in Fig. 11. A detailed description of each segment and its sub-categories will be explained.

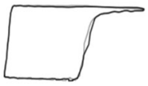
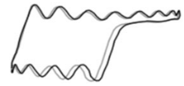
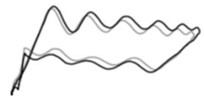
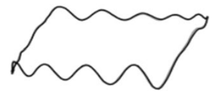
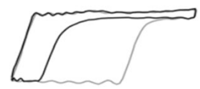
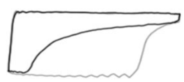
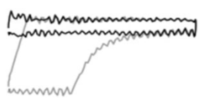
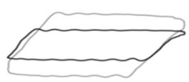
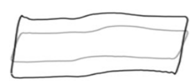
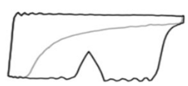
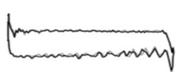
Mechanical failures

The main mechanical failures discussed in this research that occur with the beam pumping unit include tubing failure, friction, rod wear, pin and coupling wear, surface component failure, and pump failure.

Tubing failure and friction

During production, the downhole string of the sucker rod may sometimes collide with the tubing string. This friction may result in erosion and wear of both the tubing and the sucker rods. This could eventually lead to severe leakages and breakage of both components. Figure 12 shows an

Table 1 Dynamometer card common shapes and description (Wang et al. 2021)

Shape	Description	Shape	Description	Shape	Description
	Insufficient liquid supply		Severe insufficient liquid supply		Insufficient liquid supply and vibration
	Insufficient liquid supply and friction		Collide pump		Collide pump and vibration
	Gas influence		Gas influence and vibration		Vibration
	Severe vibration		Suspected carrier bar failure		Full load production
	Sudden slight fluctuations of liquid supply		Sudden large fluctuations of liquid supply		Sudden severe decline of liquid supply
	Sudden general gas interference		Sudden severe gas interference, air lock		Sudden traveling valve cannot open
	Sudden traveling valve leakage		Sudden standing valve cannot open		Sudden standing valve leakage
	Plunger pull-out from work barrel		Sudden tubing leakage		Sudden increase of friction
	Sudden sucker rod break		Foreign matter in the pump		Severe gas interference
	High performance production		Natural flowing		Pump leakage

example of an eroded tubing pipe due to friction. To reduce collision between both the sucker rods and the tubing, several components could be added to the downhole assembly. The main component that can be used is centralizers. Also, proper design of the sucker rod string can reduce the collision significantly (Langbauer et al. 2021).

Rod wear

The sucker rods may also wear down due to several reasons. Firstly, the rods will wear down eventually due to their continuous motion up and down. This can be reduced by using durable material and proper design. The second reason for rod wear can be due to friction with the tubing, as was explained above. Finally, fluid pound can also reduce the life of the overall downhole components of the beam rod pump greatly (Dave et al. 2017). Figure 13 shows an example of fluid pound and rod wear that led to string breakage.

Since the rod string is composed of several components, failure in one of the components may lead to leakage in the string or failure of the entire string. One of components that are prone to failure due to wear and tear is the rod guide, shown in Fig. 14. Avoidance of this failure is mostly related to proper operations and accurate selection of material (Dove et al. 2016).

Pin and coupling wear

Pins and couplings are what connect the downhole components together and maintain the integrity of the downhole assembly. Wear in these components can lead to severe leakages, failure of some of the other major components, and loss of components in the hole due to string breakage. Figure 15 shows an example of a worn-down plunger surface valve and a ball seat valve. Proper operational and design procedures can reduce the risk of pin and coupling wear (Langbauer et al. 2020).

Table 2 Other beam rod pump diagnostic methods

Method	Description	Reference
Modified Everitt Jennings algorithm	Alternative method for stress calculation	Pons (2014)
Polished rod and plunger position	Plot of position with time rather that stress with position	Tommaso and Marfella (2018)
Rod contact with tubing	To determine friction points between sucker rods and the tubing string	Tommaso and Marfella (2018)
Pump performance envelope	Determines lift efficiency, pump differential pressure, volumetric efficiency, motor power, and polished rod power	Tommaso and Marfella (2018)
Finite element method	Improvement of the sucker rod pump efficiency by increasing production and reducing cost and failure	Langbauer and Antretter (2017)
Cycle life	Could be used as an assessment of the performance for the sucker rod pump since it has a ground at which all pumps can be compared, measured in cycles per unit time	Mahoney and Fischer (2006)
Big data deep learning	Diagnosis model for sucker rod pumps	Wang et al. (2019)
Deep autoencoder and machine learning algorithms	To obtain features of the dynamometer card which can minimize information loss and improve data management	Peng et al. (2019)
Deep learning neural networks	Used deep learning artificial neural networks to analyze downhole dynamometer cards	Abdalla et al. (2020)
Surface analysis based on polished rod vibration	New solution to the one dimensional wave equation for sucker rod strings in vertical wells based on rod vibration	Yin et al. (2020)
Well pull-out causes correlated with well performance	Tracking well pull causes and pump parts replacements to determine failure causes in sucker rod pumps by correlating this data to well performance issues	Dove et al. (2016)
Electrical power curves	Diagnosed the working conditions of sucker rod pumps using electrical power curves through machine learning	Wang (2020)
API dimensionless curves	Derived dimensionless characteristic curves of subsurface sucker rod pumps	Zhao et al. (2018)

Surface components and pump

The surface components of the beam rod pump can wear down due to two main reasons. Firstly, long operations without proper maintenance can lead to efficiency decrease and eventually failure of some of the surface components. To avoid this maintenance of the components and continuous lubrication of the moving surface parts should be done. The second reason for surface component failure is environmental hazards, and man-made errors. The environmental hazards' impact can be reduced by prediction of weather patterns and being prepared for changes in weather. Man-made errors can be avoided by proper training of the handling and maintenance personnel.

The pump can fail due to mechanical failure of some of its moving or stationary components. If this occurs, operations will be impacted significantly and may cease in the case of complete pump failure. To avoid this, proper pump design should be conducted including proper selection of pump size and material. The most commonly used materials for the sucker rod pumps include (Pino et al. 2020):

- *Stainless steel (A1)* for balls and seats, both of which are heat treated to provide hardness.
- *Cobalt alloy (B1)* for ball and seats made from hard cobalt, chromium, and tungsten alloy. They are highly resistant to corrosion and abrasion, non-magnetic.
- *Tungsten carbide (C1)* is an extremely hard composite of tungsten alloy and cobalt. It is used in the most severe corrosion and abrasion applications.
- *Titanium carbide (C2)* is much harder and tougher than cobalt alloy. Recommended for extreme corrosion and abrasion.
- *Ceramic* made of partially stabilized zirconia. Highly resistant to corrosion, abrasion, fluid cutting, and impact, and it is non-magnetic.
- *Silicon nitride* is highly resistant to corrosion, abrasion, fluid cutting, and impact and it is non-magnetic.

Table 3 Beam rod pump mathematical models

Model	Description	Usage	Reference
$\frac{\partial^2 u(x,t)}{\partial t^2} = a^2 \frac{\partial^2 u(x,t)}{\partial x^2} - \frac{\pi a v}{2L}\frac{\partial u(x,t)}{\partial t}$	a is the velocity force propagation, ft/sec v is the damping factor, dimensionless $u(x, t)$ is the displacement of the sucker rod at arbitrary depth and time, ft L is the length of the sucker rod string, ft	Rod String Simulation using One Dimensional Wave Equation With Viscous Dampening to model the behavior of the sucker rod string	(Gibbs 1963)
$\mathrm{PPRL} = W_f + W_r(1+\alpha)$ $\mathrm{MPRL} = W_r(1-\alpha-0.127G)$ $\alpha = \frac{\mathrm{SN}^2}{70{,}500}$ $W_f = 0.433\mathrm{GL}(A_p - A_r)$	PPRL: Peak polished rod load MPRL: Minimum polished rod load *Wf*: weight of the fluid column *Wr*: weight of the rods in air *A*: area	Mills Method used to calculate PPRL: Peak polished rod load and minimum polished rod load for conventional Class I units	(Jennings 1989)
$\mathrm{PPRL} = W_f + W_r(1+0.7\alpha)$ $\mathrm{MPRL} = W_r(1-1.3\alpha-0.127G)$		For Class III Units	
$\mathrm{PPRL} = W_f + W_r(1+0.6\alpha)$ $\mathrm{MPRL} = W_r(1-1.4\alpha-0.127G)$		For Mark II Units	
$\frac{W_r}{g_c}\frac{\partial v(x,t)}{\partial t} - \frac{\partial f(x,t)}{\partial x} = -C_D\frac{W_r}{g_c}v(x,t)$	*Wr* is the weight of the rods in air, C_D is the viscous damping coefficient	General numerical solution of the partial differential equations that describe the motion of the rod system. Also referred to as the Gibbs Method	
$V_r = \sum_{i=1}^{n} L_i A_r$	L is the length of the rod, and *Ar* is the cross-sectional area of the rod	Is based on solutions for the damped wave equation which describes the motion of the sucker rod string. The API method involves correlations developed using dimensionless variables. To calculate the rod volume	
$S_a = \mathrm{SF}\left(\frac{T}{A} + \mathrm{BS}_{\min}\right)$	A and B are constants empirically derived, SF represents environmental effects, *Sa* is the fatigue endurance limit, and *S*min is the minimum rod stress	Modified Goodman Formula: Used to calculate the maximum stress allowed in sucker rod materials	(Takacs and Gajda 2014)
$L_i = \frac{\mathrm{SF}\frac{T}{A}A_i + \mathrm{BSF}d_i - b_i}{a_i - \mathrm{BSFc}_i}$	SF is the service factor, T is the minimum tensile strength of the rod material, A and B are empirical constants specific to the rod material, *Ai* is the metal area of the rod in the *i*th taper, *ai-di* are best fitting line parameters	For measurement of the sucker rod length and performance	
$P_{\mathrm{inflow}} = P_{\mathrm{wf}}(Q) - \Delta P_{\mathrm{dnow}}(Q)$ $P_{\mathrm{outflow}} = P_{\mathrm{wh}} + P_{\mathrm{up}}(Q) - \Delta P_{\mathrm{pump}}(Q)$	P_{inflow} is the inflow pressure, P_{outflow} is the outflow pressure, P_{wh} is the wellhead pressure, $\Delta P_{\mathrm{pump}}(Q)$ in the inflow equation is the pressure drop under pump in the wellbore which is calculated using the Beggs–Brill Model, $\Delta P_{\mathrm{pump}}(Q)$ in the outflow equation is the differential pressure provided by the pump and is calculated using the sucker rod performance curves downhole system	When the pump inlet is regarded as the node	(Zhao et al. 2013)
$P_{\mathrm{inflow}} = P_{\mathrm{wf}}(Q)$ $P_{\mathrm{outflow}} = P_{\mathrm{wh}} + P_{\mathrm{up}}(Q) - \Delta P_{\mathrm{pump}}(Q) + \Delta P_{\mathrm{dnow}}(Q)$		When downhole is regarded as the node	
$\frac{Eg}{\rho}\frac{\partial^2 u}{\partial L_r^2} = \frac{\partial^2 u}{\partial t^2}$	E is youngs modulus, g is the gravitational constant, Lr is the rod string length, t is the time, u is the elongation, ρ is the density	Used to measure the vibration of sucker rod strings	(Tripp 1988)

Table 3 (continued)

Model	Description	Usage	Reference
$W = \left[I - N\left(N^TN\right)^{-1}N^T\right]W^* + N\left(N^TN\right)^{-1} * N^TW$	N is a matrix that represents the wave equation, I is a unit matrix, $\left[I - N\left(N^TN\right)^{-1}N^T\right]$ is referred to as the filter matrix, W is the newly obtained set of data, and the asterisk "*" refers to data obtained with the least global error	Transfer matrix used to model the dynamic behavior of the rods in the sucker rod strings	(Hojjati and Lukasiewicz 2005)
$\rho_r A_r \frac{\partial v_r}{\partial t} = \frac{\partial f_r}{\partial x} + F_{\mathrm{rf}} + F_{\mathrm{cf}} + F_{\mathrm{rt}} - \rho_r g A_r$	ρ_r is the rod density, A_r is the rod area, v_r is the rod velocity, f_r is the fluid velocity, F_{rf} is the viscous force per unit length of rod, F_{cf} is the viscous force per rod coupling per unit length of rod, F_{rt} is friction force between tubing and rod per unit length of rod	Used to predict the behavior of sucker rod pumps	(Doty and Schmidt 1983)
$\frac{A_2}{A_1} \tan\left(\frac{\pi L_1}{2L} F_{c,\mathrm{API}}\right) \tan\left(\frac{\pi L_2}{2L} F_{c,\mathrm{API}}\right) - 1 = 0$	$F_{c,\mathrm{API}}=1$ for a uniform rod taper	A method for determining the equivalent properties of a tapered rod system	(Jennings and Laine 1991)
$\frac{\partial \vec{U}}{\partial t} = \frac{\partial \vec{G}}{\partial x} + \vec{H}$	U, G, and H are column vectors defined based on the initial and boundary conditions used to determine the equation	For rod and fluid behavior in wells produced using sucker rod pumps	(Lekia and Evans 1995)
$EA \frac{\partial^2 u}{\partial x^2}(x,t) = \frac{\rho A}{144g} \frac{\partial^2 u}{\partial t^2}(x,t) - c \frac{\rho A}{144g} \frac{\partial u}{\partial t}(x,t)$	C is the damping factor, A is the sucker rod cross-sectional area, E is the modulus of elasticity, ρ is the density of the sucker rod string	Used to measure stresses in sucker rod pumps with varying rod diameters	(Pons 2014)
$\frac{n}{n_o}$ and $\frac{F_o}{\mathrm{SK}_r}$	n is the stroke rate, n_o is the natural frequency of the rod string, Fo/K is the elongation of the sucker rod string and S is the polished rod stroke	The API dimensionless curves are mainly a function of the dimensionless stroke rate and the dimensionless elongation of the sucker rod	(Zhao et al. 2018)

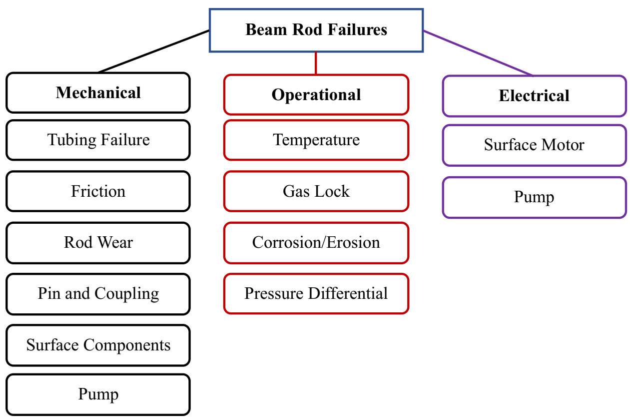


Fig. 11 Beam rod pump main failures

A summary of all the mechanical failures discussed along with a brief description of each failure is included in Table 4.

Operational failures

Operational failures are extremely common in beam rod pumping units. The operational failures discussed in this review include temperature failures, gas problems, corrosion failures, sand and erosion problems, and pressure differential problems.

Temperature failures

High downhole temperatures can lead to rapid material degradation and failure. This kind of failure is not a major concern with beam rod pumps however since most of the operations for this artificial lift method does not occur in very deep wells. Although beam rod pumps can be operated in viscous and reservoirs with a moderate sand and gas production, it is usually applied in moderate to shallow wells which usually do not suffer high temperatures. If temperature becomes an issue however, temperature resistant material can be a good method to avoid operational problems.

Gas problems

Although beam rod pumps can handle a considerable volume of gas without pump damage, a high volume of gas can reduce the overall efficiency of the pump by up to 40%. This reduction in efficiency is mainly due to late opening of the traveling valve in the down stroke due to compression of gas beneath the plunger.

One of the ways to handle gas production with sucker rod pumps is to place the intake beneath the producing zone. This allows the tubing-casing annulus to act as a separator and since the gas has a lower density, it will rise to the top. The intake, being beneath the production zone, will be submerged in the higher density liquid, and thus a minimum gas volume will be present in the pump. In horizontal wells, the pump cannot be placed below the producing zone, and thus a downhole gas separator is needed. At the intake of the separator, an annulus is created between the dip tube and the mud anchor body. This allows the heavier liquids to move down the dip tube while the lighter gas bubbles rise out of the separator (Allison et al. 2018). Figure 16 presents an illustration of a conventional downhole gas separator.

The two main types of gas separators include the centrifugal separator and the gravity separator. The centrifugal separator is based on centrifugal principle. It uses the difference in density of the water and oil and the difference in centrifugal force in the cyclone generated. Centrifugal separators usually the preferred method due to its speed however its efficiency is lower in wells that contain gas. The gravity separator relies on gravity separation based on density difference. This method is slower than the cyclone and has less efficiency (Jiang et al. 2020). Figure 17 presents an illustration of both types of separators.

Fig. 12 Tubing failure example (Langbauer et al. 2021)

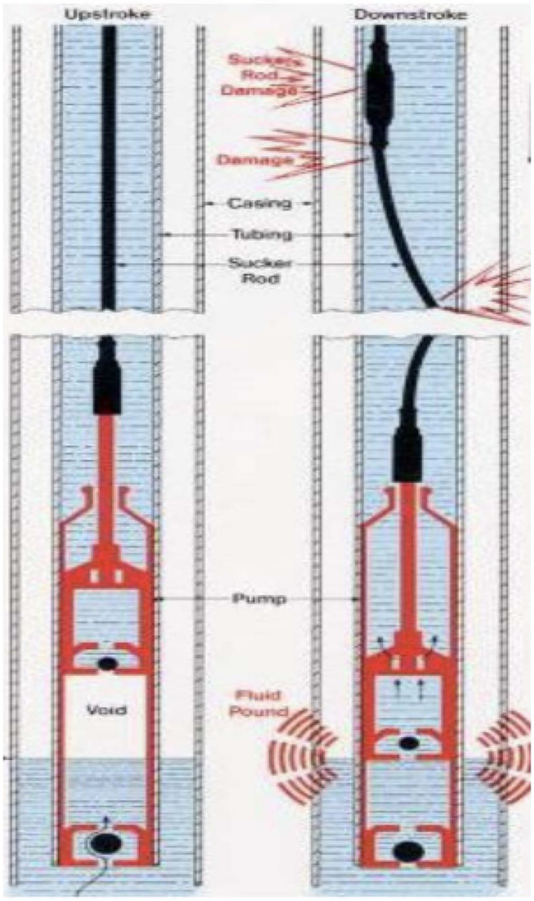


Fig. 13 Fluid pound and rod wear (Dave et al. 2017)

Fig. 14 Worn rod guide (Dove et al. 2016)

Corrosion failures

Corrosion can result in material failure and operational hindrance and cessation. Corrosion occurs due to several factors including metal incompatibility in the presence of an electrolyte, and presence of corrosive fluids such as high total dissolved salts brine, carbon dioxide, and hydrogen sulfide. Figure 18 presents an image of the damage that corrosion can cause to the downhole components of the beam rod pump. In order to avoid corrosion problems, proper selection of material should be used. This includes metal compatibility, corrosion resistant material, and metal substitutes when needed. Early detection of corrosion can also be vital in reducing the overall impact of the corrosive fluid (Zhang et al. 2020).

Erosion/sand problems

An excessive volume of sand can lead to two problems. Firstly, it can cause severe erosion of the sucker rods and the pump which may eventually lead to failures. Secondly, it can accumulate in some of the components such as the plunger, as shown in Fig. 19. This can cause plugging problems that are very difficult to mitigate. The three main methods by which sand production in sucker rod can be mitigated include (Langbauer et al. 2020):

- Cope with the sand production by altering the production equipment to withstand sand.
- Stabilize the formation producing sand using chemicals.
- Install gravel pack, sand screen, and downhole desanders.

Pressure differential problems

Beam rod pumps are designed to handle some pressure differentials, however a sudden change in pressure can lead to abnormal operations and thus problems. The main problem that can occur is buckling of the string especially during the downstroke. This can lead to severe collision with the tubing string, and eventually string and tubing wear and failure (Langbauer et al. 2021). Figure 20 provides an illustration of string buckling and collision with tubing.

Table 5 provides a brief summary of all the operation failures discussed in this review along with a description of each failure.

Electrical failures

Electrical failures are less severe compared to mechanical and operational failures in the beam rod pumping unit. This is mainly due to the limited areas where electrical failures may occur in the beam pump. Electrical failures can result in the surface unit or in the downhole pump. For electrical failures in the surface unit, remediation is simple and rapid due to the ease of access, and also due to the fact that beam rod pumps are well known technologies. The main downhole component that can fail is the pump. If the pump fails, string retrieval will be necessary in order to determine

Fig. 15 Plunger surface and ball seat valve damage (Langbauer et al. 2020)

Table 4 Summary of beam rod pump mechanical failures

Failure	Description
Tubing	Can result due to metal erosion between tubing and sucker rods, and due to corrosion resulting from corrosive fluids. Tubing can also fail due to pin and connection failure
Friction	Friction between metals and metal and liquids is one of the main contributors to mechanical failures downhole
Rod wear	The sucker rods have a unique design. This makes fixing them extremely difficult. Rod wear can occur due to many factors including excessive usage, corrosion, erosion, or improper design
Pin and coupling	Although these components are supplementary, failure of the pins and coupling can cause failure of the entire downhole string and may result in loss of material
Surface components	Due to wear and tear, and environmental impacts
Pump	Due to overloading and poor selection of pump

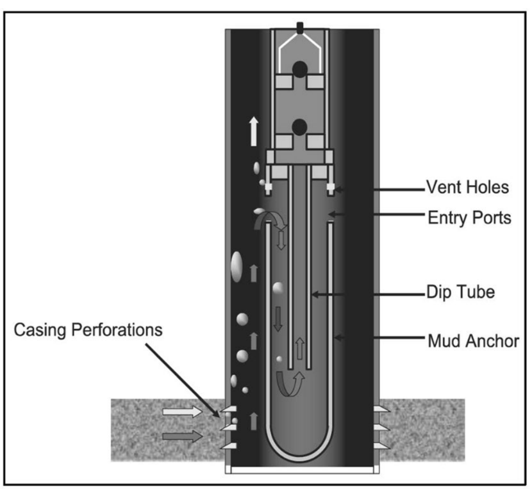


Fig. 16 Conventional downhole gas separator (Allison et al. 2018)

the failure and to mitigate it. Other components that can fail downhole due to electrical failures include sensors, and electrical gauges (Palka and Czyz 2008). Table 6 provides a summary of the main electrical failure in the beam rod pump and their description.

Advancements in beam rod pumps

Several advancements have been made to improve on the performance and durability of the beam rod pump. These advancements were made based on special needs, however, they managed to introduce paramount technological changes to the beam rod pump which increased its applicability range and improved its mean time between failure (Lui et al. 2007). Table 7 provides a summary of the main advancements for the beam rod pump.

Beam rod pumps case studies

As mentioned earlier, beam rod pumps are the most applied sucker rod methods worldwide. For this reason, thousands of case studies are present for the beam rod pump. This review includes some of the most prominent field cases for the beam rod pump which encountered a significant event or showed use of a new technology or outcome. Case studies were selected from different countries worldwide

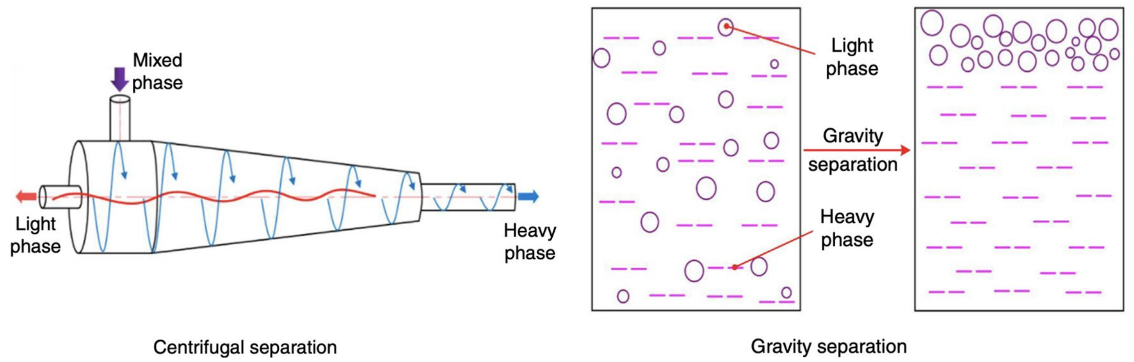


Fig. 17 Illustrations of centrifugal and gravity gas separators (Jiang et al. 2020)

Fig. 18 Corrosion failure in the beam rod pump downhole components (Zhang et al. 2020)

to cover a large span of beam rod pump usage. These case studies are summarized in Table 8.

Beam rod pump advantages and limitations

Beam rod pumps have several advantages and limitations that must be taken into consideration when choosing a suitable artificial lift method. These advantages and limitations are mentioned in this section.

The main advantages of the beam rod pump system include:

- Cheap, mechanically established, and easy to operate by engineers, technicians and company personnel
- Can operate under a very wide or applicably conditions including harsh conditions with heavy oil and sand
- Many of the components are placed on the surface which makes it easy to fix and replace components
- Can operate in gassy wells if gas venting is taken into consideration
- Can be applied in deviated and horizontal wells using the correct components and the proper assembly
- Has more than three different types which increases the range of choices and also applicably range
- Is one of the most widely used artificial lift method which reflects availability and component replacement ease

Fig. 19 Sand accumulation in the downhole plunger (Langbauer et al. 2020)

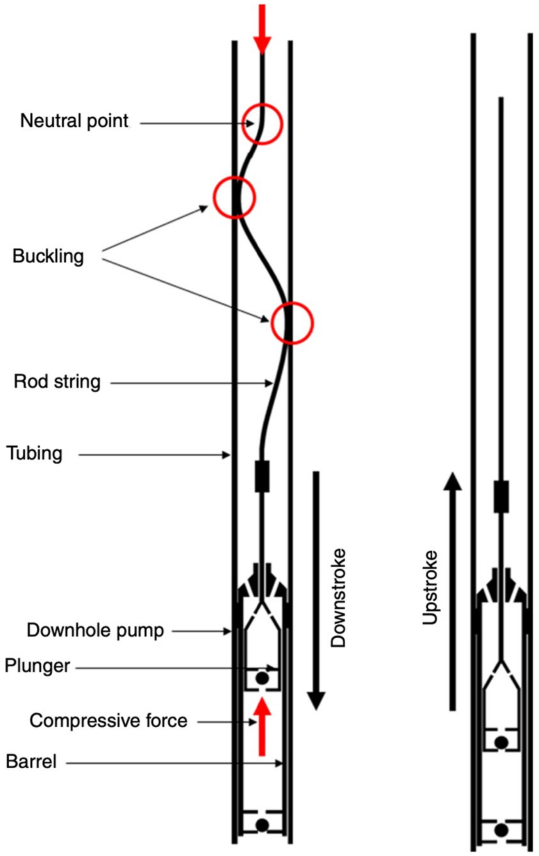


Fig. 20 Sucker rod string buckling due to pressure differential (Langbauer et al. 2021)

- Pump monitoring can be easily done using surface and downhole dynamometer cards
- Its equations and fundamental mathematical models are well established
- Can be easily modeled using many software that is readily available

Although the beam rod pumps have many advantages, there are also some key limitations for this type of sucker rod pump which include:

- Surface components may sometimes require large surface areas which may not be available
- Is not applied extensively in offshore reservoirs due to surface components size
- Is prone to gas lock and corrosion problems due to the conditions at which it is applied
- Excessive sand production can cause failure
- Sucker rods are prone to failure to fluid leaks through it
- Dynamometer cards do not always yield accurate results and are usually not real time
- Crooked hole application can be problematic which require the use of reamers
- The stuffed box on the surface can leak which results in environmental hazards. Polished rod failure and fitting tees failure can also result, or lead to, stuffing box failures.
- Can utilize excessive energy due to large number of losses in the surface and downhole components
- Retrieval and fixing of downhole components may require surface service unit

Advantages and limitation of current study

This research aims to provide a roadmap to sucker rod pumps' properties, diagnostics, modeling and recent innovations. The main advantages of this research are:

- Provides an up to date holistic review of the different types of sucker rod pumps.
- Gives a detailed explanation of beam rod pump diagnostics, modeling, and mathematical equations.
- Shows some of the main locations where sucker rod pumps have been applied and the main developments and innovations for each study.
- Highlights the main advantages and limitations of sucker rod pumps based on an updated database.

Table 5 Summary of beam rod pump operational failures

Failure	Description
Temperature	High temperatures can result in material failure if improper selection is done. It can also invigorate the impact of corrosion if corrosion occurs
Gas Lock	Gas lock can occur if the sucker rods are partially filled with gas. When the gas volume increases, gas lock may occur, that results in production cessation
Corrosion	The two main causes of corrosion is improper material selection through material incompatibility and erosion-based corrosion. It can also occur due to corrosive fluids
Erosion	Due to sand particles and silt. Since the sucker rod pump is used in conditions of heavy oils and sand production, erosion can cause severe problems in excessive sand production conditions
Pressure differential	This can result from several conditions in the formation most notably gas pockets

Table 6 Summary of beam rod pump electrical failures

Failure	Description
Surface motor	The sucker rod pump is powered by a motor on the surface that transmits power to the prime mover. The prime mover can fail due to several conditions such as overloading, environmental conditions, or failure of a surface component that may directly impact the motor
Pump	The downhole pump for the sucker rod pump is downhole, and thus is usually placed in harsh conditions. These conditions can result in pump failure. If the pump fails, production will cease since fluid transmission will be ceased temporarily until the pump is fixed, or permanently if the pump completely fails; in this case, pump replacement will be needed. Downhole sensors and electrical gauges might fail due to electrical failure

Although this research has several advantages, the main limitation of this research is access to data. Most of the field data in the oil and gas industry is considered classified and thus is unpublished. Also, most of this review is focused on the beam rod pump, which is the most common type of sucker rod pumps, since covering all the different types of sucker rod pumps in a comprehensive manner is beyond the scope of one manuscript.

Summary and conclusions

This research performs a detailed review of the beam rod pump and its applications, diagnostics, mathematical models, case studies, failure mechanisms and mitigation, and finally advantages and limitations. The main findings from this research are as follows:

- A new classification of sucker rod pump has been developed based on the novel technologies that fall under this artificial lift method.
- Beam rod pumps diagnostics can be done using dynamometer cards, however several other methods have been introduced that could rival the dynamometer card in the future.
- Mathematical modeling of the beam rod pump relies on solutions to the wave equation. Since it is a partial differential equation, different solutions arise based on initial and boundary conditions defined in the solution.
- Although the beam rod pump is a well-established artificial lift method, several technological advancements have been made to improve its applicability and extend its mean time between failure significantly.

Table 7 Main advancements in beam rod pump

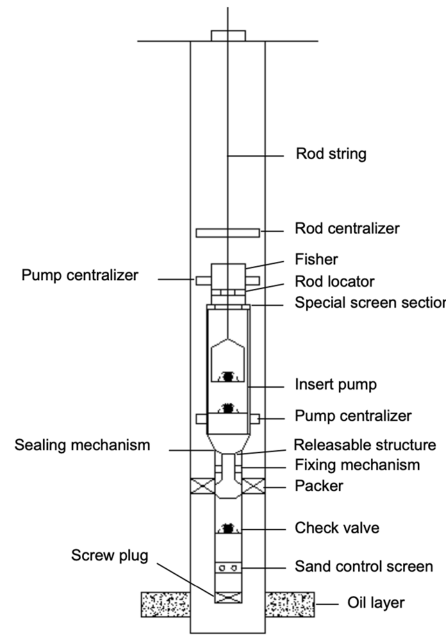
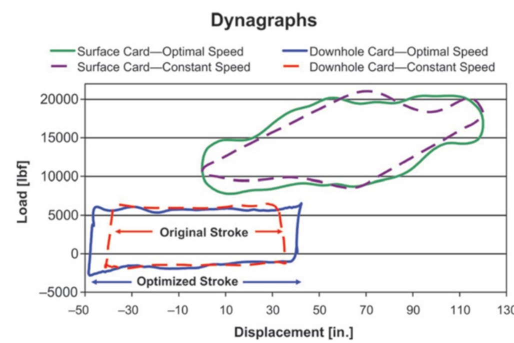
Technology	Advancement	Illustration	Reference
Tubingless sucker rod pump system	A new tubingless sucker rod system in slim holes with a nominal diameter of the production casing being less than 5 inches		(Yonghui et al. 2007)
Variable motor speed sucker rod pump	Changing the motor speed with a single stroke using a variable motor speed improved production and reduced the stresses in the sucker rod and also reduced motor energy consumption		(Palka and Czyz 2009)

Table 7 (continued)

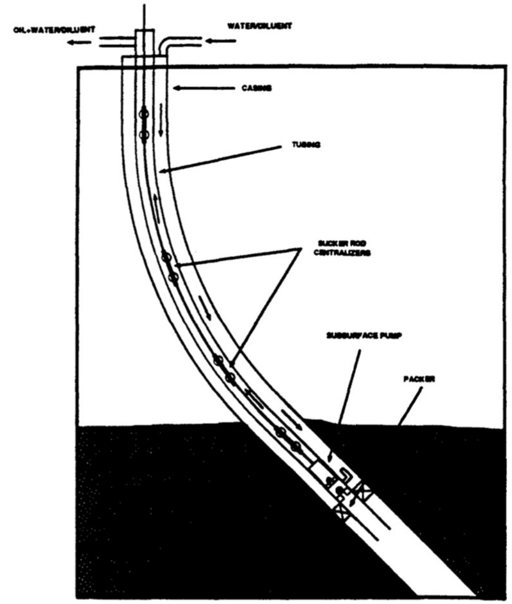
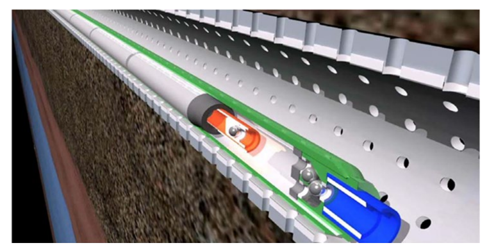
Technology	Advancement	Illustration	Reference
Sucker rod centralizers for directional wells	Centralizer for sucker rod pumps to improve its application in deviated and horizontal wells by reducing tubing, sucker rod string, and subsurface pump wear		(Rivas et al. 1990)
Self-positioning valve for horizontal wells	A stem is attached to the plunger from beneath in order to allow proper operation of the valve regardless of the well angle and its position		(Kitapov and Gilfanov 2018)

Table 7 (continued)

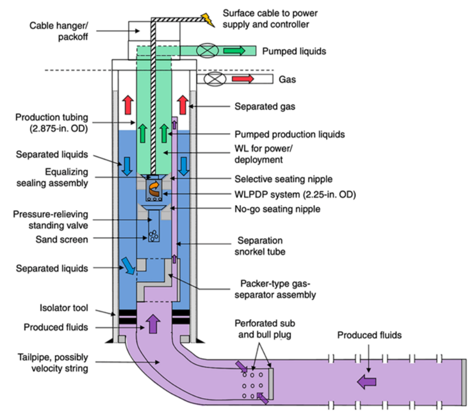
Technology	Advancement	Illustration	Reference
Novel sucker rod pump downhole desander	Development and testing of a novel desander for sucker rod pumps with high efficiency and durability		(Langbauer et al. 2020)
Wireline deployed positive displacement pump	Developed and tested a sucker rod pump that can be deployed using wireline for faster and higher applicability ranges		(Romer et al. 2021)

Table 7 (continued)

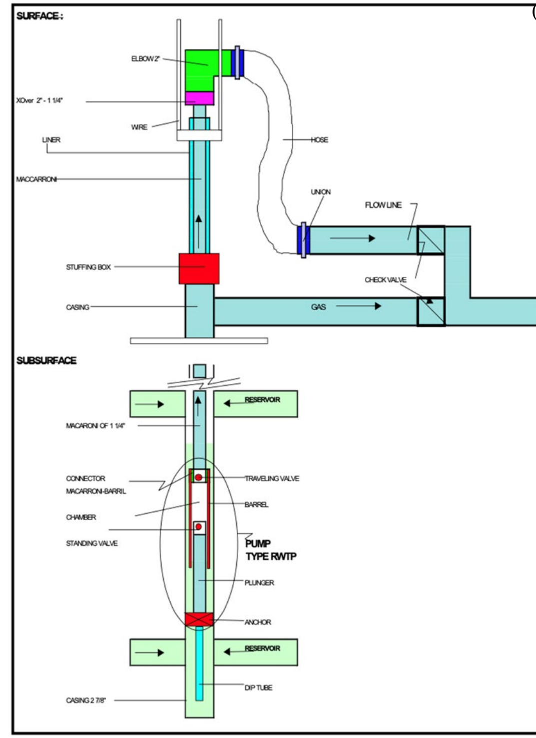
Technology	Advancement	Illustration	Reference
Sucker rod pumping for slim hole wells	The sucker rods were replaced by 1 inch macaroni tubing which reciprocate the pump plunger and direct the flow to the surface		(Alva and Alfaro 2001)

Table 8 Beam rod pump case studies

Country	Name	Description	Reference
USA	Huber Harrison	Developed a novel guide to handle high axial loads in severe downhole environments when using sucker rod pumps	Murtha et al. (1987)
Venezuela	Orinoco belt field	Developed centralizers for sucker rods for applications in deviated wells	Rivas et al. (1990)
USA	Pearsall field	Provided one of the first review of the performance of sucker rod pumps in more than 150 deviated wells	Cortines and Hollabaugh (1992)
Venezuela	Boscan field	Production optimization of two sucker rod pumps using new production scheme	Guirados et al. (1995)
USA	San Jorge Basin	Utilized coiled tubing as a sucker rod in slim holes to increase recovery	Solanet et al. (1999)
China	–	A new type of magnetic clutch in the surface components of the sucker rod pumps to improve performance. The magnetic clutch increased pumping speed by 9%, increased liquid production by 30%, and improved power savings by 23.6%	Guo et al. (2002)
Colombia	Guando oil field	Used continuous sucker rod configuration to reduce failures and increase recovery	Ariza et al. (2006)
China	Zhongyuan oil field	Developed a new tubingless sucker rod for application in slim holes	Yonghui et al. (2007)
Argentina	North Sana Cruz	Introduced a new adaptor that can allow for the downhole lubrication of the plungers of the sucker rod pump	Dottore et al. (2007)
China	Shengli oil field	Designed a sucker rod string for applications in high gas oil ratio wells	Wang et al. (2015)
Ecuador	Gustavo Galindo Velasco	Demonstrated a method referred to as Pull and Push to extract hydrocarbons from shallow wells located at a short distance from the surrounding wells using sucker rod pumps	Tigrero et al. (2015)
USA	Eagle Ford	Application of sucker rod pumps in unconventional shale reservoirs	Clarke and Malone (2016)
India	Barmer Basin	highlighted the economic impact of insert anchor and portable foundation of the application of sucker rod pump in marginal fields	Khadav et al. (2016)
Kuwait	Great Burgan field	Showed the results for a field application of a sucker rod pump installation on a dual string well inside a 3.5 inch tubing which managed to increase recovery and eliminate the need for a workover rig	Al-Dousari et al. (2017)
Kuwait	Ratqa field	A case study on the performance of a sucker rod pump after steam injection in a heavy oil field	AbdulHadi et al. (2018)
USA	Permian Basin	Focused on the design of the gas separators, variable speed drives, and backpressure valves for the sucker rod pumps	Allison et al. (2018)
Brazil	Caisson field	Used a rigless intervention linear sucker rod pump for oil recovery from an offshore field	Lima and Neto (2020)
Italy	–	Designed a new insert sucker rod surface controlled subsurface valve	Pilone et al. (2020)
Austria	Leoben	Developed a method to avoid buckling in sucker rod string	Langbauer et al. (2021)

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