Analysis and Simulation of a High-Performance Wire Rope as Continuous Sucker Rod String

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Abstract

Sucker rod pumping is the most common type of artificial lift systems deployed in oil and gas wells. The sucker rod string, transferring the reciprocating movement of the surface polished rod to the downhole pump plunger, is exposed to severe cyclic loads, causing several complications from damaged rods and broken couplings to time-consuming workover procedures. Hence, continuous strings like wire ropes can be a convenient replacement for conventional rod strings.

In this paper, a state-of-the-art wire rope is chosen for investigation regarding its applicability as a sucker rod string. It is intended to work in tandem with a sucker rod anti-buckling pump (SRABS) to facilitate its motion. The mechanical properties of the wire rope demonstrate high tensile strength and great resistance against creep and fatigue while its uniform design eliminate the chances of connection failure. The performance of this system is further analyzed and simulated with a novel computer software package in a remarkably detailed manner.

The results of several simulations confirm that this wire rope can indeed replace the rod string in a sucker rod pumping unit. Detailed stress, load and movement profiles were compiled to allow for a comprehensive analysis, leading to the fact that pumping with a wire rope can be just as productive, or can surpass the productivity of a system using conventional sucker rods. They indicate that the efficiency of this design highly depends on the geometry and depth of the well, type and size of the pump, compressibility of the produced fluid and string material elasticity; Moreover, to achieve the ultimate performance, a compatible pumpjack and proper downhole equipment, such as string protectors, must accompany this wire rope and operate together under an optimum pumping speed.

This paper presents a noteworthy comparison between the performance of a conventional rod string and a wire rope at two reference wells. Additional components, required for the field test of a full sucker rod pumping system operating with the new wire rope, are also included in the discussion.

Introduction

Artificial Lift methods are generally used to compensate for the losses in production of a well. When the natural drive energy of a reservoir is not sufficient or is diminishing, these processes are employed to sustain and recover the production rate. Sucker rod pumping systems are the most common type of artificial lift worldwide. These systems can be put into operation almost for every low-producing well as they are also the most cost-effective.

A sucker rod pumping unit consists of various components. In general, a surface unit or 'pumpjack' generates the driving force which is transferred through the sucker rod string to the downhole displacement pump, creating an up and down pumping action and allowing the entry of the reservoir fluid into the pump cylinder and its discharge to the tubing. This volume, which in fact has a higher potential pressure, is then lifted to the surface.

The sucker rod string is therefore constantly subjected to cyclic load-induced fatigue and numerous failures occur within its structure. The string consists of long steel rods with a diameter of 5/8" to around 1 ¼" and with the length of 25 or 30 ft., tapered downwards and screwed to one another with couplings.

The stress analysis and failure statistics for various parts of sucker rods demonstrate that the weakest point exists within its coupled connections (rod pin and couplings). Hence, it is clear that the fatigue resistance of the connections is inferior to the fatigue resistance of the rod body [1]. These damages can be caused by the improper make-up of joints in the field, operation in a hostile environment like sour conditions, the poor material selection at the manufacturing stage and the deformation of the threads inside the couplings [2].

The pie-chart (Figure 1) , provided by Weatherford, shows diverse sources of failure within the sucker rod string and proves the critical role of the connection areas in failure analysis:

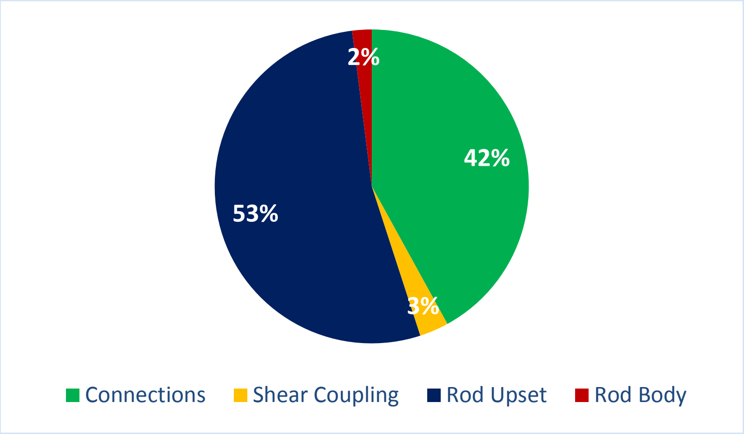

Figure 1. Failure Distribution by Location [3]

Another issue to consider is the time factor involved in handling and attaching/detaching the rods to form the string as well as any type of workover operation that would require a completely different setup at the well site, suspending regular operations and lowering the production and profits.

As an outcome, a design which can substitute the tapered string with a continuous string, having a steady diameter and excluding the couplings, will not only minimize fatigue failures, but also reduce the contact forces resulting from the friction of these auxiliary components with the tubing and, therefore, automatically reduces wear. This means fewer workover operations and a reduction in the corresponding costs as well.

Materials and Setup

Selected Material: The product chosen for further investigation is a 15.7 mm stranded steel wire rope consisting of 7 wires, each with a diameter of 5 mm. The wires have a zinc coating and are covered with wax to reduce friction during movement. The wires are also pre-stressed, which results in the minimization of creep during operations, making it a much better option for sucker rod system's cyclic loading and reciprocating movement. Further mechanical properties of this rope compared to a conventional sucker rod (CSR) are shown in Table 1.

Table 1. Properties of the wire rope compared to a CSR

Material	Composition	Diameter	Density	Weight per Length	Elongation at Break	Break Load	Modulus of Elasticity	Tensile Strength
(Unit)	-	mm	g/cm³	kg/100m	%	kN	GPa	GPa
CSR	Steel	15.9	7.85	250	4.17	221.3	192	0.8
Wire Rope	Steel	15 (3 x 5)	7.81	117.2	0.99	251.7	187	1.8

Proposed Setup. To gain a better understanding of the wire rope system vs. the CSR in different operation scenarios, two different wellbore geometries have been chosen for analysis by numerical simulations. Specifications are shown in Table 2:

Table 2. Wellbore and pumping specifications of the wells

Specifications	*Vertical Well*	*Slanted Well*	*Unit*
MD	*739*	*893*	*m*
TVD	*739*	*877*	*m*
Inclination	-	*28*	°
Bottom-hole Temperature	*61*	*33.3*	°C
Tubing ID	*2.995*	*2.441*	*in.*
Dynamic fluid level	*456*	*879*	*m*
Pump specifications	*C-640D-305-168*	*C-320D-256-144*	
Pump type	*Tubing pump*	*Insert pump*	-
Surface stroke length	*168*	*144*	*in.*
Plunger diameter	*3.75*	*1.5*	*in.*
Plunger length	*4*	*4*	*ft.*

The strings operate with the following arrangements shown in Table 3:

Table 3. SR string orientation for the two considered systems

CSR	Vertical Well	452 m (7/8” rod), 267 m (5/8” rod), 26 m (1.5” sinker bars)
	Slanted Well	800 m (7/8” rod), 61 m (5/8” rod), 30 m (1.5” sinker bars)
Wire rope	Vertical Well	745 m (13.6 mm wire rope)
	Slanted Well	891 m (13.6 mm wire rope)

Each designed string was analysed by a novel software [4] for both the vertical and the slanted well. While the CSR is used with a standard pump, wire rope has been designed to work with an anti-buckling pump [5]. Two different pumping speeds (production rates), low and high, will be set for each system and each well. It is also considered that the tapered CSR and the wire rope use protectors for friction protection and centralization purposes.

Results

All simulations were successfully carried out by the software, proving the applicability of the proposed wire rope as a sucker rod string. However, as the simulations assumed conventional parameters and equipment, the full capabilities of a wire rope-operated setup are yet to be discovered. For the time being, the following observations were made within the simulation process:

String Stretch: Since the pump plunger is located hundreds of meters below the polished rod, the SR string tends to stretch due to its self-weight even before the pumping action begins. This stretch is also one of the reasons why the stroke length at the plunger is never equal to that of the polished rod.

String stretch also occurs as a result of liquid loads on the plunger and their dynamic effects. In better words, the deeper the pump installed, the higher the force required to move the plunger upwards (inertia effect). A sudden and significant stretching at the beginning of the upstroke can cause a lag between the polished rod stroke and the pump stroke. This phenomenon was observed in the simulation case of the wire rope in the vertical well (Figure 2). As can be seen, the string has already been elongated in the initial 3 seconds of static conditions. Once the polished rod starts the upstroke, the plunger is further stretched before it follows the movement of the polished rod. This also delays the initiation of downstroke, as can be seen in the difference of the curves' peaks.

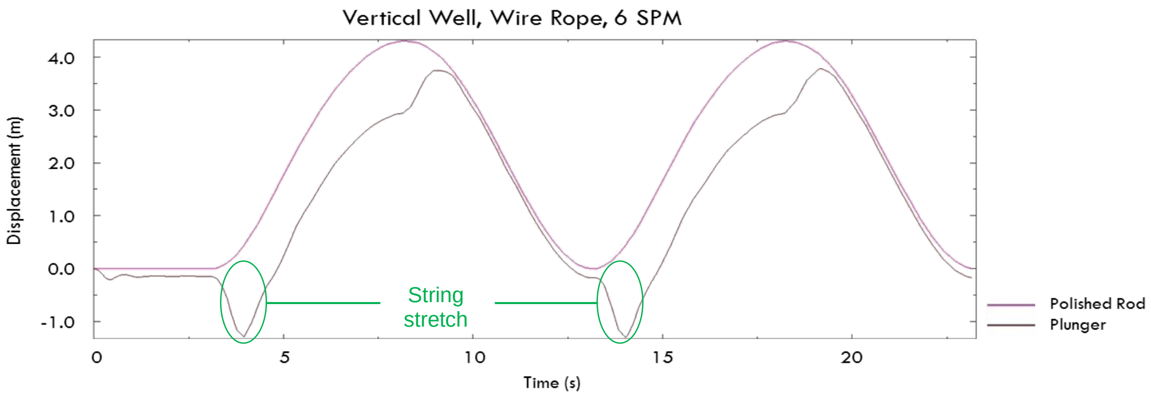

Figure 2. String stretch in the CSR, in vertical well and with low SPM

There are four criteria in this project's simulation cases, all of which can contribute to stretching:

1. Low compressibility of the produced liquid – in this case, with 90% WC
2. Plunger size (group 2 wells[1]) – in this case, 3.75" plunger for a 739 m deep well
3. Type of well (vertical or non-vertical) – in this case, full liquid load on the plunger
4. String material's elasticity – wire rope has lower elasticity than the sucker rod

The lower effective stroke length can reduce the production rate slightly, however, the extended MTBF, in comparison to a conventional system, can certainly make up for this setback in the long run. In addition, using long-stroke pumping units with stroke lengths as high as 10 m can improve the productivity of the wellbore even further.

Load and Energy over Time: The load behavior versus time for each simulation case shows that owing to the presence of the dynamic fluid load, the polished rod load profile is more distorted than the pump's, with the unsteady pattern increasing as SPM peaks. This comparison can be seen in Figure 3 and Figure 4 for wire rope in both wells.

It is important to state that due to the smaller self-weight of the wire rope, the system's picked up load and thus its energy consumption can be reduced. This reduction will be even more prominent if a more appropriate pumpjack is installed for the wire rope system.

[1] Wells less than 4000 ft. deep with plunger diameters higher than 2 in.

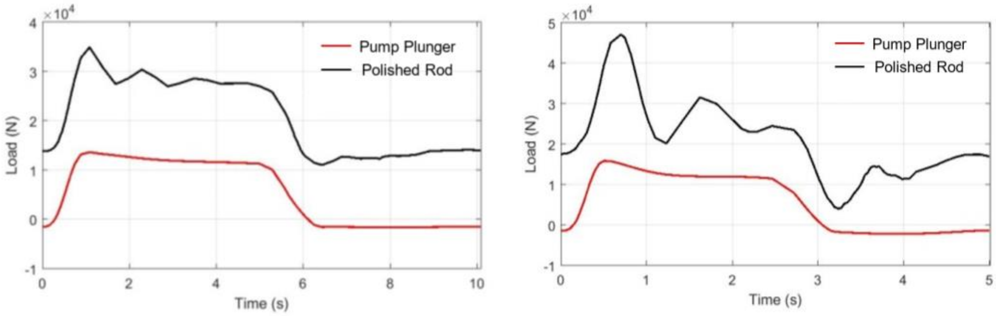

Figure 3. Wire Rope in a slanted well, low speed/production (left), high speed/production (right)

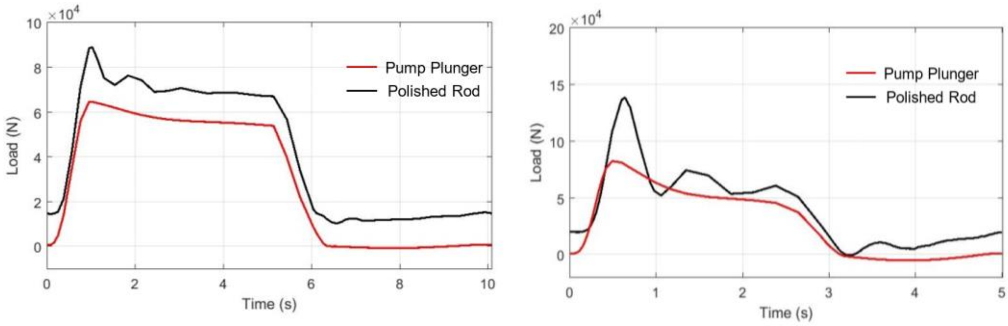

Figure 4. Wire Rope in a vertical well, low speed/production (left), high speed/production (right)

Stress distribution: Figure 5 shows the stress distribution along the entire length of the wire rope. As expected, the loads and stresses increase in the extreme case of the vertical well due to larger dynamic liquid loads.

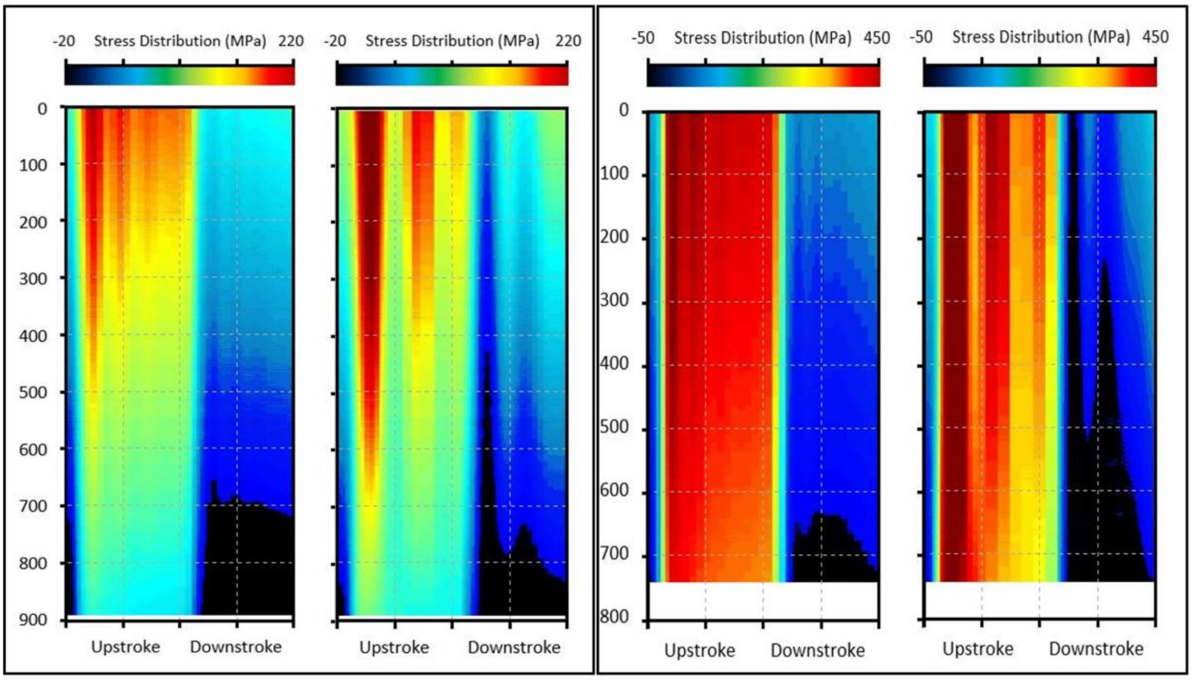

Figure 5. Stress distribution for wire rope in the slanted well (left box) and vertical well (right box), low speed/production (on the left) and high speed/production (on the right) inside each box

Yet, even in the most extreme scenario, the maximum tensile stress is still less than one-third of the wire rope's tensile strength, meaning that the rope is fully operational where large stresses are involved.

Buckling has also been avoided in almost all cases of using the wire rope. Nonetheless, in case of occurrence, tensioning elements can be installed below the anti-buckling pump to mitigate the string damage.

Conclusions

Comparing the results of 6 simulations on implementing a high-strength wire rope with an equivalent conventional sucker rod verifies that its performance is strongly dependent on wellbore geometry and pump specifications. Nevertheless, the wire rope simulated in combination with special protectors and an anti-buckling pump proved its applicability as a sucker rod string.

There are still uncertainties with regards to some mechanical values, e.g. friction factor of the material with steel. Yet, the following advantages of the wire rope will come to shine once proper components are employed along with it in the system:

- Lighter weight
- Higher Tensile strength
- No couplings
- Reduced string damages
- Increased MTBF
- Simpler transportation and deployment
- Adaptable to small footprint long-stroke units
- Smaller counterweight requirements
- Lower energy requirements

References

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