Sucker Rod String Design Optimization using an Innovative Finite Elements Simulation Approach

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Abstract

Economic situations and governmental restrictions push the demand for efficient oil and gas production, especially in mature fields. The reduction of artificial lifting costs by increasing, on one hand, the efficiency, on the other hand, the mean time between failure, is essential for extending the economic limit and increasing the recovery factor of the reservoir.

One of the weak components of a sucker rod pumping system is the sucker rod string, suffering under stress reversals, caused by its reciprocating motion and contact forces when buckling occurs. In practice, the failure prevention ends in an oversizing of the rod string, resulting in a poor system efficiency. For improving the rod string design, the Finite Elements Method (FEM) is used for modeling and analyzing. Based on the results an optimization of the sucker rod string and the whole pumping system is performed, which does not only consider subsurface equipment but in addition also the surface facilities. The tool is able to perform diagnostic analysis to evaluate the performance of existing units, as well as predictive analysis to optimize their performance and to design new units.

The presented paper contains the concept and the capabilities, including downhole pump and surface unit improvements, of the sucker rod string FEM – simulation, as well as a case study from a mature oil field. DDS (Downhole Dynamometer Sensor) measurements, taken during a field test, are used for verification of the simulation by comparing surface and downhole dynamometer cards.

The accuracy of the presented simulation routine surpasses all currently available commercial software products. In addition, the highest flexibility in terms of sucker rod string composition, operation conditions, fluid conditions and the choice of installed equipment is guaranteed by this method. The performed case study indicates a significant increase of the energy efficiency and lifetime of the system.

Introduction

The latest BP statistical review (1) states a total global crude oil consumption of 96.6 mio.bpd, which is an increase of 1.6 percent in comparison to 2015. A closer look at the past shows that in the last decade the global crude oil consumption has raised from 86 Mio. bpd by almost ten percent. Figure 1 clearly indicates this growth in consumption. In addition, the development of the proven oil reserves and the BRENT spot crude prize are shown. The quantity of proven reserves has increased significantly between 2008 and 2010, which may be the result of a jump of the oil price from 65 $/bbl to almost 100 $/bbl the two years before. Then the oil price dropped and investments in exploration were reduced, which has significantly influenced the trend of the proven oil reserves.

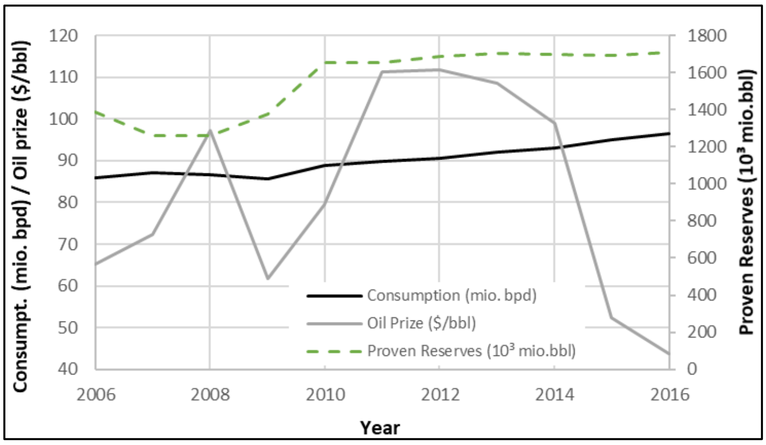

Figure 1: Global daily oil consumption (1)

History has shown the dependency of proven reserves on oil prize and the usage of new technology, which is necessary to meet the challenges for developing new fields, but as well to efficiently produce from to mature oil. Mature oil fields have a significant share to meet the crude oil consumption and a major percentage of all the productive wells use some kind of artificial lift system. The most relevant lifting systems are sucker rod pumps and electric submersible pumps as shown in *Figure 2*, whereas the second one has the major share. Nevertheless, in several hundreds of thousands of sucker rod pumping systems are in use today because of their high flexibility in terms of the high range of areas of operation as well as relatively low purchase and operation costs. However, water cuts of mature fields are normally high and low-cost production is essential to stay economic.

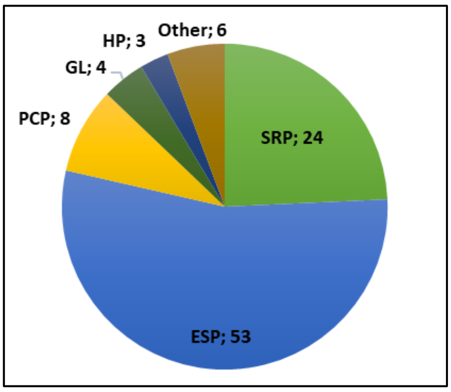

Figure 2: Artificial lift systems market share (2)

Meantime between failures, which is an indicator of the failure rate of a system and represents the operation duration between two subsequent system failures, of 1500 day is the target to reduce the workover costs. In addition, the efficient use of electrical energy for driving the pumping system must be kept low to reduce the supply grid load and to save costs. The energy consumption is not just dependent on the system design, but as well on the operational parameters and the driving mode of the pump.

Sucker Rod Pump Failure Analysis

A sucker rod pumping system failure analysis was performed by J.F.Lea (3) in the past. Failures were split into classes:

- Subsurface pump failures - 38%
- Rod string, couplings and polished rod failures - 39%
- Tubing string failures - 20%
- Others - 3%

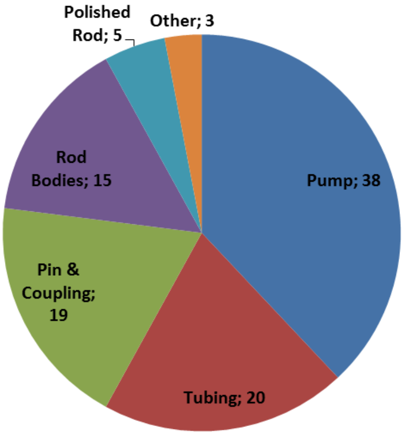

Figure 3: Typical Failures among the Sucker Rod Pumping System (3)

These failures are the result of various reasons: mechanical wear caused by contact and friction, fatigue of the material caused by cyclic load reversals and corrosion, and the effects of the produced sand. Various compositions of reservoir fluids promote these failures in different ways. An issue caused by the reciprocating motion of sucker rod pumping systems is the permanent load change in the rod string as well as on the pump jack. During the upstroke, the rod load, the fluid load, and the friction forces cause large tensile stresses in the complete rod string. In contrast, during the downstroke, buoyancy and friction forces dominate especially in the lowest section of the sucker rod string and cause compressive loads. As soon as these loads have reached a certain magnitude, buckling of the sucker rod string occurs. More than 50 percent of all failures of the sucker rod string might be associated with buckling (*Figure 3*).

Figure 4: Typical tubing failure

Figure 4 displays serious wear, caused by a rod to tubing contact, which can be a result of buckling or a false spacing of rod guides in deviated sections. A significant amount of tubing material was removed by wear and will definitely result in a leaking tubing string, as seen in the right picture.

Subsurface pump failures, which represent more than one-third of all failures, can also be a result of buckling of the adjacent sucker rod string. The seating mechanism and/or the plunger fit are negatively affected and may be destroyed. (*Figure 5*)

Figure 5: Typical subsurface pump failure

To prevent the sucker rod pumping system from failures like these, a proper system design, based on a fundamental understanding of systems needs and unique behavior, is required.

A design tool, which has become because of its powerful capabilities very attractive in the last decade, in other industries e.g. the automotive and construction industry, is the finite element method. The finite element method is based on a mesh, which represents the geometry of the model to be analyzed. The mesh consists out of small discrete individual elements. To describe the elastic-mechanical behavior 15 equations are required for each element that are six displacement-strain equations, six strain-stress equations, and three equilibrium equations. This formulation of the whole geometry results in a system of algebraic equations. The finite elements method applies variational methods to approximate a solution for the displacement by minimizing an associated error function.

Sucker Rod String Simulation

In the last decades, several different methodologies to describe the nature of a sucker rod string motion mathematically have been used. This paper presents the application of the finite element method for analyzing the behavior. Because of the disproportion between the rod string diameter and the rod string length the sucker rod pumping system itself is a very complex dynamic system.

The sucker rod string is exposed to distributed loads (Coulomb friction forces because of rod guide-tubing contact and fluid friction forces) and concentrated loads at the pump plunger that cause rod stretch or contraction and a change in motion of the rod string. Just a numerical FEM simulation is capable to consider all relevant forces on the rod string yielding reliable and realistic results. The finite element analysis software ABAQUS/Standard (4) has been used for solving the dynamics of the sucker rod string. The analysis software is having two options for manipulation: the software surface and the input file. The input file provides a high flexibility for modeling and analyzing complex structures and is used for this study. All the required information for describing the geometry and the operational parameters of the sucker rod string are included in the input file by the following structure (5):

Mesh definition:

The numerical mesh of the sucker rod string is based on the three-dimensional trajectory of the wellbore and models the geometry of the tapered sucker rod string and the tubing string. It consists of nodal coordinates in a three-dimensional Cartesian coordinate system, and elements, which have to be assigned their corresponding cross-section. The discretization is chosen such that two elements represent the portion of the rod string between two neighboring rod guides. B32 elements, i.e., three node quadratic beam elements in space, are defined to represent the sucker rod string. Components like couplings and rod guides are not modeled in detail, but their weight is considered by a so-called nonstructural mass.

To account for the stabilization effect of the rod surrounding fluid, spring elements having a varying spring constant as a result of with depth increasing hydrostatic pressure, are included in the mesh (6). Because the springs are only allowed to balance radial movements of the rod string, their attachment points have to move with the lateral motion of the sucker rod string, see Figure 6.

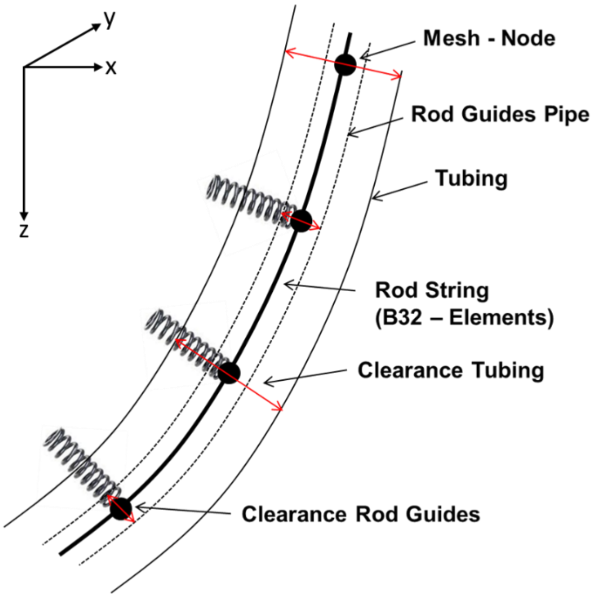

Figure 6: Rod string mesh definition (7)

Contact definition:

Rod guides are normally installed all along the rod string to guide it through the tubing by preventing radial oscillations and reducing the friction force. ABAQUS Standard allows modeling of this finite-sliding interaction by so-called tube-to-tube contact elements (8). These elements assume a predominant sliding of the inner tube along a predefined slide-line, in most cases defined by the outer tube and a relatively small radial movement. The radial clearance for nodes at the position of the rod guides and nodes in between is different since the rod guides only allow marginal radial displacements. Numerically, this is taken care of by adding a fictitious "Rod Guides Pipe" to the model that is in contact with the rod guide nodes only, in order to limit their radial displacement, see Figure 6.

Realistic friction coefficients for the two materials in contact, obtained from experiments, are defined. Figure 7 presents the results of static and dynamic rod guide friction force experiments submerges in different media. Lowest friction coefficients were obtained in a dry tubing, followed by the system submerged in water. Highest friction forces were measured for sandy oil conditions. The reason for rising friction forces when submerged completely in liquids is the additional force required to displace the liquid when moving.

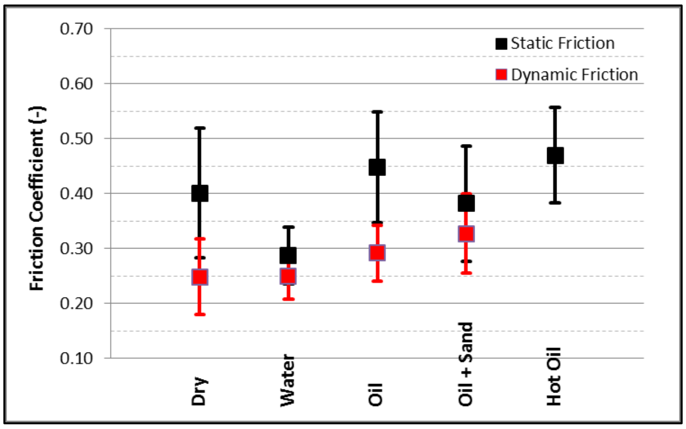

Figure 7: Rod string mesh definition (7)

Material property definition:

The solver of the simulation software requires material properties for the beam elements. Due to the fact that this study only considers steel sucker rods, showing a linear elastic material behavior, the material properties are defined by Young's modulus of 210 GPa and a Poisson ratio of 0.3. In general, this methodology is able to simulate the behavior of all kind of materials.

Boundary conditions and amplitude definitions:

In three dimensions, each node of a structural element has six degrees of freedom. As the tubing is assumed to be fixed, no motion is allowed, all degrees of freedom are constrained, and hence all nodes belonging to the tubing are fixed. The top node of the sucker rod string moves through the stuffing box only in the vertical direction, thus motion in x and y-direction is restricted. The motion in the z-direction is defined by an amplitude function, representing the motion of the polished rod.

In addition, displacement and load amplitudes have to be defined. The displacement amplitude contains the information about the motion of the polished rod and can be calculated, depending on the geometry of the pump jack and the strokes per minute, according to the model of J.G.Svinos (9). The load amplitude at the pump plunger is a result of the static and dynamic forces and the fluid friction acting on the rod string and rod guides. The load amplitude can be on one hand based on downhole load measurements or on the other hand on a mathematical model, approximating all relevant forces acting on the pump plunger.

Downhole Dynamometer Sensors

The Downhole Dynamometer Senor (DDS) is a self-developed, autonomously working, sealed data logger, which is used to measure the load within the sucker rod string, the motion in three directions and the temperature of the housing. The DDS (Figure 8) can be installed with rod couplings directly into the sucker rod string at any position and the body of the measurement tool conveys the rod load. For a full analysis of the sucker rod string, it is suggested to install several DDSs at different positions. Therefore, it is recommended to position at least two tools at the surface, directly below the polished rod and at least two tools directly above the plunger for redundancy. Additional tools can be placed in between e.g. for deviated wellbores at the deviation from vertical. The outer diameter of the DDS allows the installation even in small tubing strings, like a 2 3/8" tubing string.

Figure 8: Downhole Dynamometer Sensor

The DDS sensor itself contains four analogous and one digital sensor. The analog sensors are three temperature compensated strain gauges and one temperature sensor. The three strain gauges are positioned at the same axial position but radially are shifted by 120 degrees. Besides redundancy, the reason for three stain gauges it to use the measurements to evaluate the rod bending torque in the string. The recorded data are stored on a USB flash card and can be recovered via the USB connection. The conversion of the recorded data is not done directly at the tool, but afterward. The software for the tool itself allows a very comfortable handling. The tool can be programmed to sleep and wake up in time intervals by an alert. After data recording, it switched back to sleep mode until the next alert. The software at the microcontroller on the DDS itself is kept relatively simple, to reduce the probability of failures. Hence the stored data at the tool are the measured raw data and require a conversion to the desired units. The analogous sensors deliver Millivolts, which need to be converted to force and temperature, respectively Newton and degrees Celsius. The digital sensor delivers multiples of g, but the actual acceleration is required.

To verify the simulation results a field test was performed and six DDS were installed in an 890m long, deviated sucker rod string. The same wellbore and rod string configuration is simulated, using the FEM approach. Figure 9 presents the results of the DDS measurements. The left picture was obtained from DDS 1, a sensor close to the surface, whereas DDS 4 (diagram on the right) was installed next to the pump plunger.

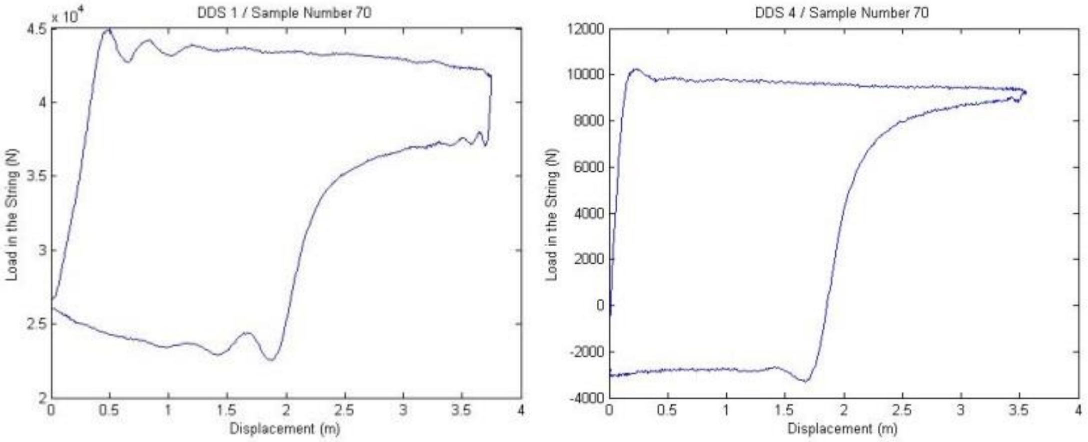

Figure 9: DDS field test measurements

Simulation Results

The objective of the applied FEM simulation for this study is the so-called predictive analysis of a sucker rod pumping system. This approach is used to design new pumping systems or to adjust and optimize existing ones, on the basis of the findings from the diagnostic analysis. Relevant boundary conditions are the surface motion of the pump jack and the resulting load behavior at the pump plunger.

To validate the simulation the field test results are compared to the simulation results. The specifications of the test well are:

7/8” rod string (2 rod guides/rod)	1,5” RHA pump	3,2 SPM
890 m rod string length	$p_{\text{well head}}$ = 4 bar	$p_{\text{casing head}}$ = 4 bar

The comparison, in addition, allows the detection of high accurate friction coefficients, as well as the material damping coefficients under real conditions. Figure 10 presents the simulation results and the measurements. The black line at the bottom represents the measured pump plunger load, the orange curve the measured polished rod load and the black, dashed line the simulation result. The close match of the simulated and measured polished rod load indicates properly selected friction and damping parameters.

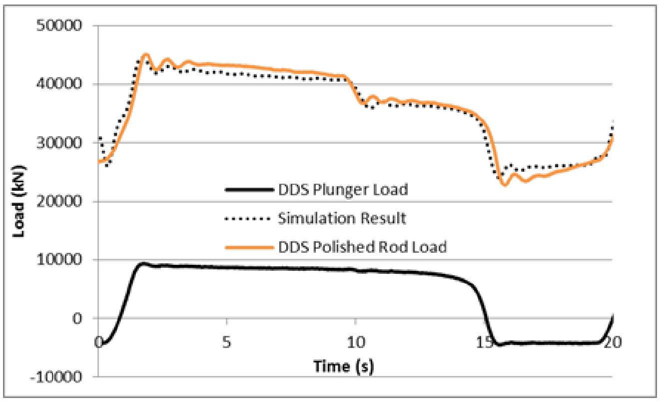

Figure 10: Comparison simulation – field test (7)

The performed simulation generates a big amount of data about the dynamic behavior of the sucker rod string e.g. stress distributions in the rod string, contact forces between rod string and tubing and the three-dimensional displacement of all nodes along the rod string. Based on this information power requirement for running the system, efficiencies and counterweight mass and position optimizations can be performed. Figure 11 presents the results of the reference sucker rod string, used during the field test.

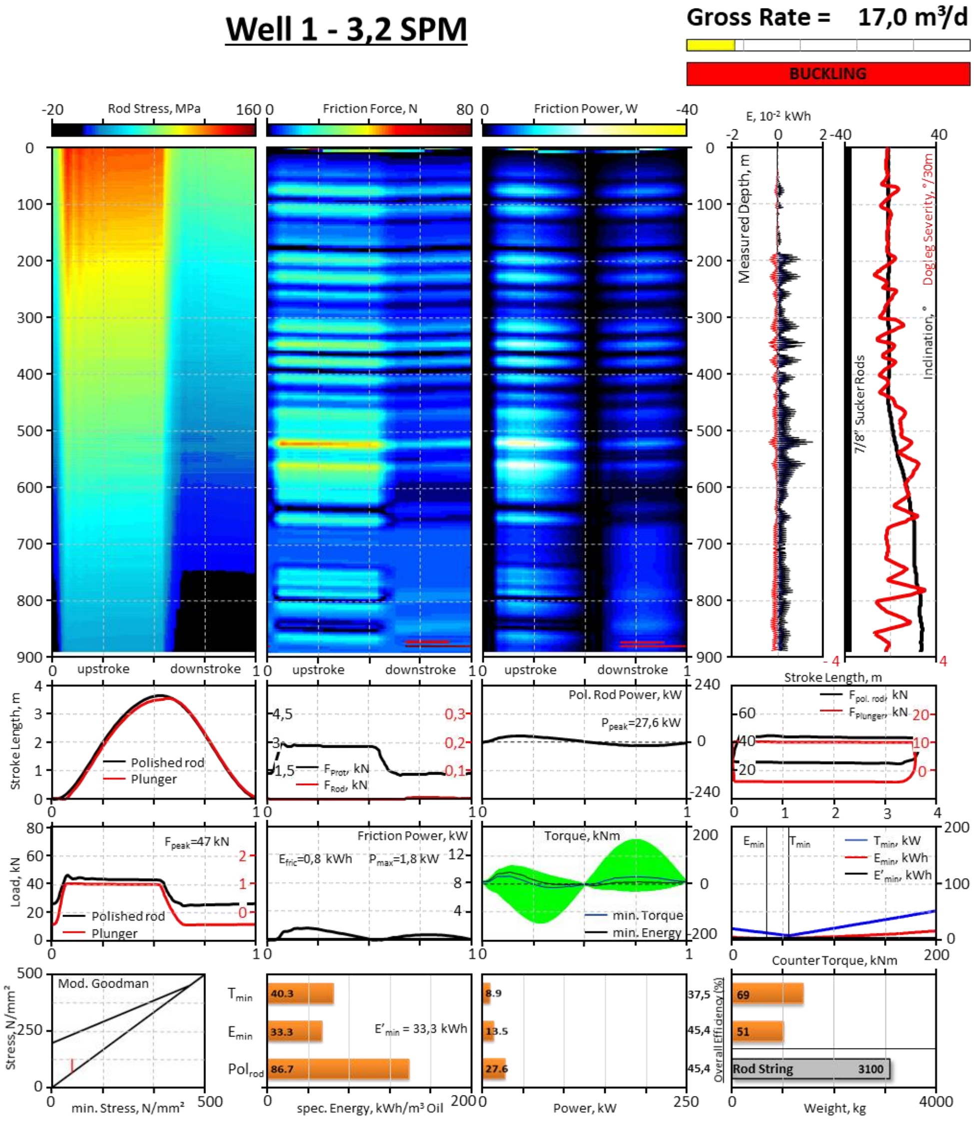

Figure 11: Design evaluation results – reference case (7)

The most interesting results are on the one hand the fact that the rod stress all along the string is at a very low range, thus a reduction in rod diameter may increase the efficiency of the system. High friction forces occur at that depth, where the wellbore starts to build up. On the other hand, the red bars in the friction force diagram indicate buckling of the rod string on top of the plunger. In general, sucker rod pumping systems can be optimized for minimum torque T_{min} at the gearbox of minimum energy consumption E_{min} of the electrical engine. The T_{min} case optimizes the counterweights in a way that the total torque at the crankshaft, resulting from the polished rod load, the torque caused by the structure and the counterweight torque, is a minimum. For the E_{min} case, the mass of the counterweights is selected in such a way that the total energy without energy recovery is a minimum. The crankshaft torque is normally higher than for the T_{min} case. E'_{min} represents the energy consumption if recuperation technology is applied to the system. The reference configuration results in system efficiencies for T_{min} of 37.5% and E_{min} of 45.5%.

Figure 12 presents the results of a simulation case where the rod string diameter is reduced to 5/8” rods, instead of 7/8” rods. The assumed increase in rod stress can be seen in the rod stress diagram as well as in the Modified Goodman diagram. Nevertheless, maximum allowable stresses are not exceeded and friction forces in the build-up section are reduced, which decreases the total frictional losses.

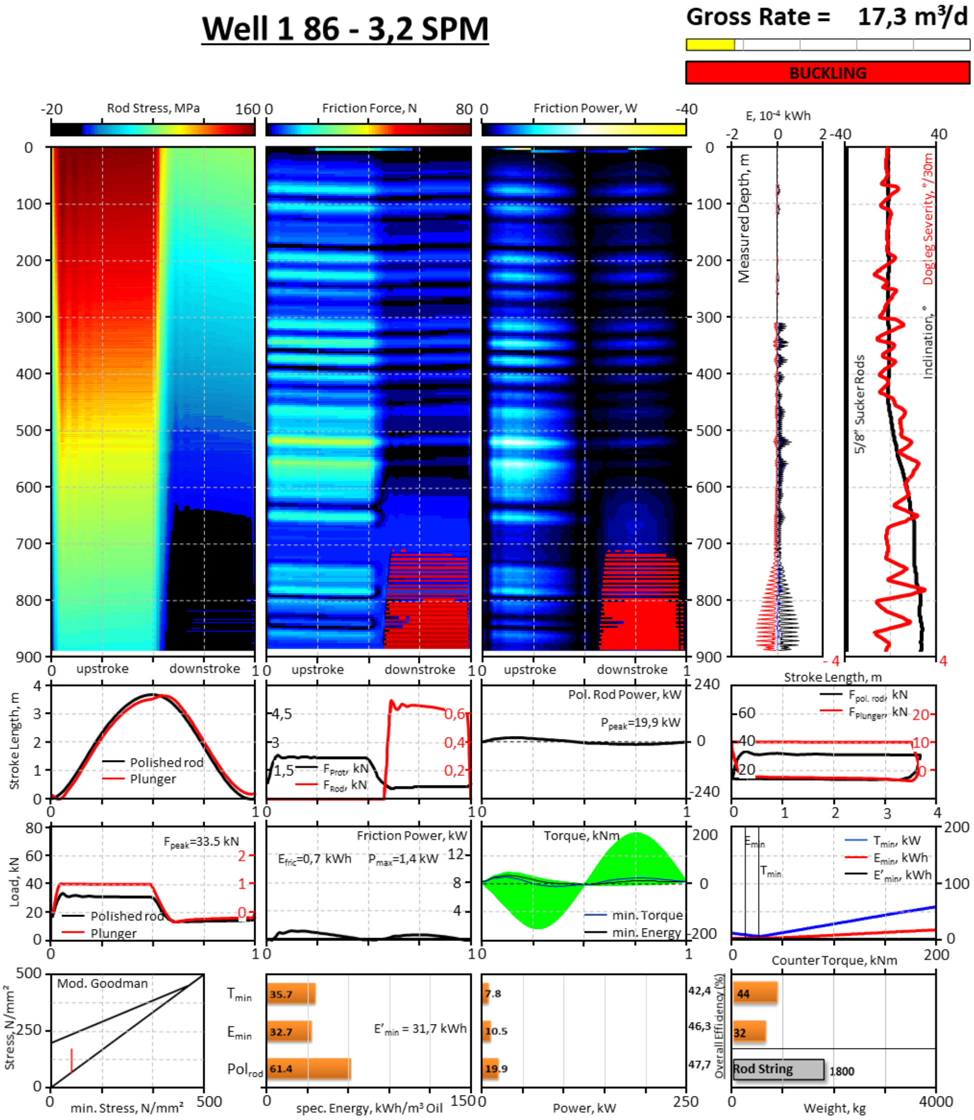

Figure 12: Design evaluation results – rod string adjustment (7)

A clear disadvantage of smaller rod diameters is the fact that excessive buckling occurs, starting in a depth of about 700 meters and extends to the pump plunger. But system efficiencies for T_{min} of 42.4% and E_{min} of 46.3% are increasing with smaller rod diameters.

To overcome buckling sinker bars are often installed on top of to the plunger. Figure 13 shows the results. The total production rate is reduced from 17m³/day, respectively 17.3m³/day, to 16.8m³/day because of a change in the plunger motion. 23 meters of 1.5” sinker bars are effectively preventing the rod string from buckling, but in combination with the used 7/8” sucker rod string, the total friction forces are increased and the efficiencies are reduced: T_{min} of 37.1% and E_{min} of 43.7%.

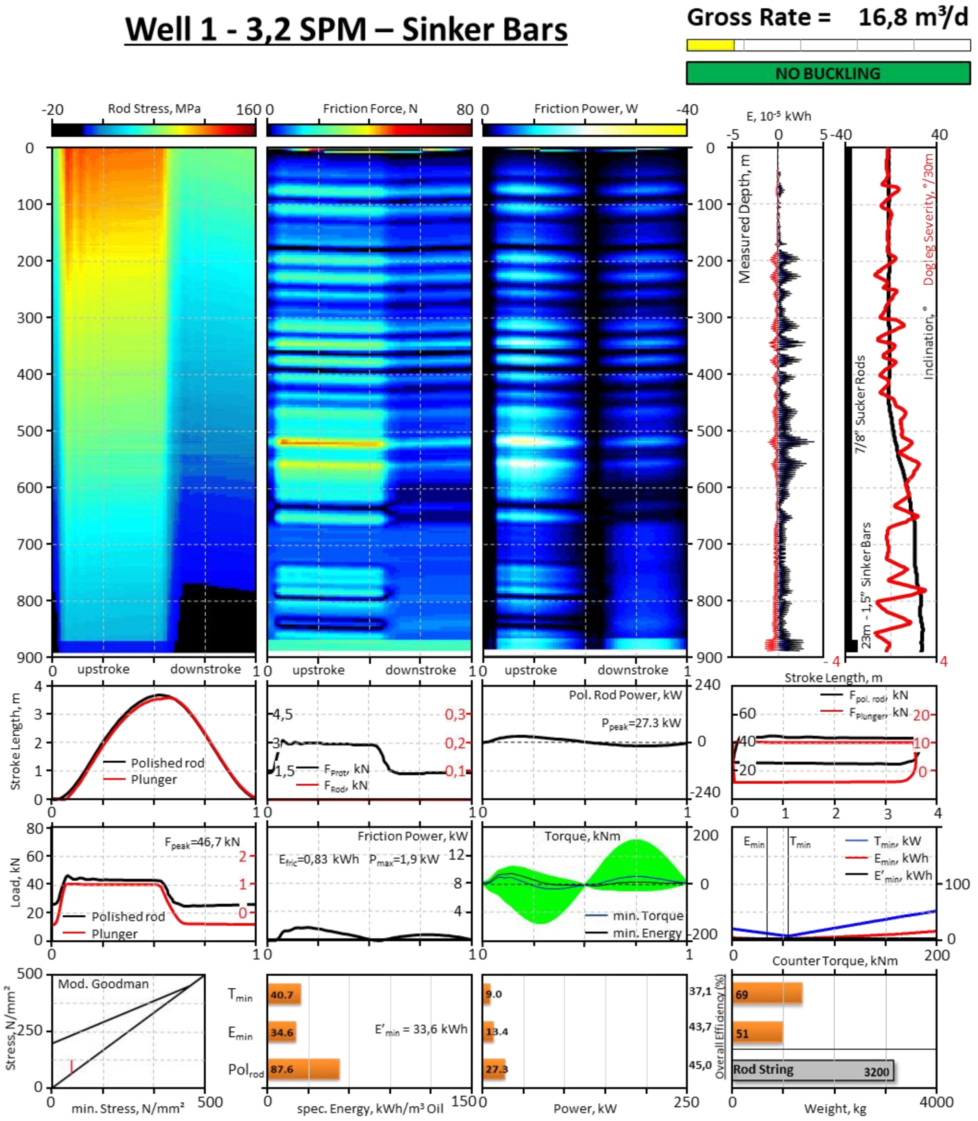

Figure 13: Design evaluation results – sinker bars (7)

Conclusion

The developed numerical simulation model is able to analyze the sucker rod string under various conditions (trajectory, equipment dimensions, fluid properties, boundary conditions), which makes the model more flexible than other existing methodologies.

- The comparison of the load amplitude model at the plunger and the measured downhole data, recorded by Downhole Dynamometer Sensors (DDS) shows a remarkable match.
- The simulated surface dynamometer card matches the measured surface dynamometer card and enables a full analysis of the sucker rod pumping system with respect to power requirements, efficiencies, etc..
- The usage of sinker bars prevents the rod string from buckling but decreases the system efficiency.
- Thin rod diameters promote buckling.
- The tubing and rod wear can significantly be reduced when optimizing the system.
- Electricity consumption can be reduced essentially.

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