Sucker Rod String Design Optimization Using an Innovative Finite Element 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 the one hand, the efficiency, on the other hand, the meantime 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 poor system efficiency. For improving the rod string design, the Finite Element Method (FEM) is used for modeling and analysing. 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 also the surface facilities. The tool can perform diagnostic analysis to evaluate the performance of existing units, as well as predictive analysis to optimise their performance and to design new units. The presented article 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. Also, the highest flexibility regarding 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 in 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 million bpd, which is an increase of 1.6 % in comparison to 2015. A closer look at the past shows that in the last decade the global crude oil consumption has risen from 86 million bpd by almost 10 %. Figure 1 indicates this growth in consumption. Also, the development of the proven oil reserves and the BRENT spot crude price 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 two years beforehand. Then the oil price dropped, and investments in exploration were reduced, which has significantly influenced the trend of the proven oil reserves.

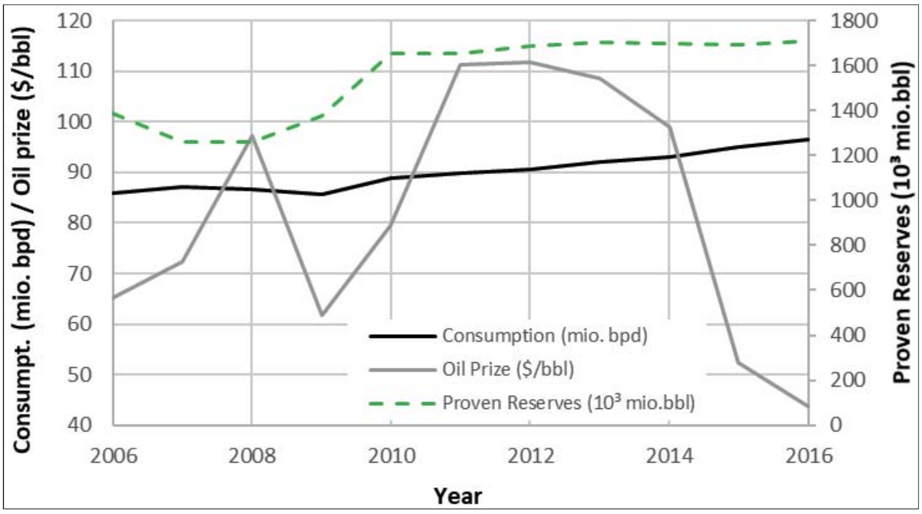

Fig. 1 Global daily oil consumption [1]

History has shown the dependency of proven reserves on oil price and the usage of new technology, which is necessary to meet the challenges for developing new fields, but as well to efficiently produce from 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 latter one has the major share. Nevertheless, several hundreds of thousands of sucker rod pumping systems are in use today because of their high flexibility regarding the high range of areas of operation as well as relatively low purchase and operation costs. However, water cuts in mature fields are normally high, and low-cost production is essential to stay economic. A 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 days is the target to reduce the workover costs. Also, 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 also 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:

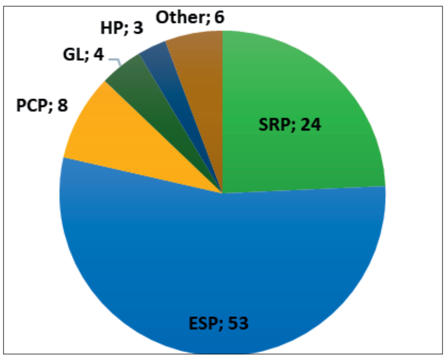

Fig. 2 Artificial lift systems market share [2]

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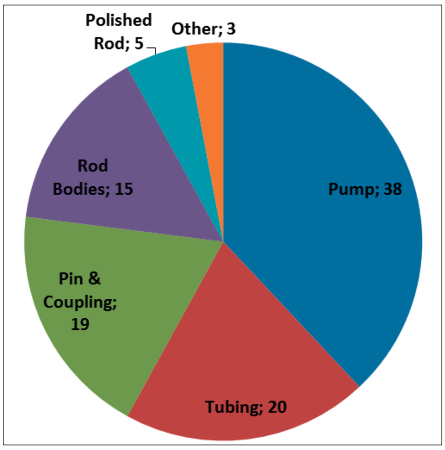

Fig. 3 Typical failures among the sucker rod pumping system [3]

Fig. 4 Typical tubing failure

Fig. 5 Typical subsurface pump failure

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

These failures resulted for 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 % of all failures of the sucker rod string might be associated with buckling (Fig. 3).

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-hand 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. (Fig. 5). To protect the sucker rod pumping system from such failures, a proper system design, based on a fundamental understanding of system needs and unique behavior, is required.

A design tool, which has become very attractive in the last decades because of its powerful capabilities in other industries, e.g. the automotive and construction industry, is the finite element method. It allows reliable prediction of the deformation of structures, as well as the resulting stress and strain fields given external loading conditions.

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 article 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 (like 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. A numerical FEM simulation allows considering 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 input for the analysis software can be generated using a graphical user interface or more directly by providing an input code that can be interpreted by the solver. This second option provides high flexibility for modeling and analyzing complex structures and is consequently 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 represents 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 the hydrostatic pressure increasing with depth, 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.

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 frictional force. ABAQUS Standard allows modeling 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, to limit their radial displacement, see Figure

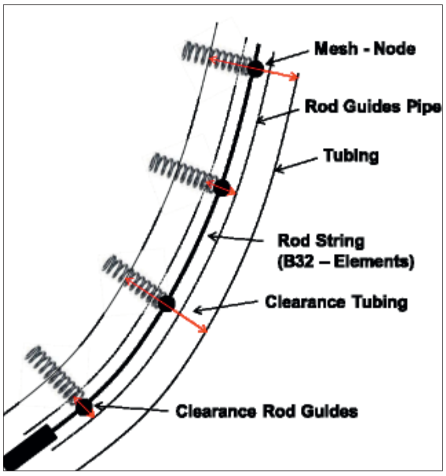

Fig. 6 Rod string mesh definition [7]

Fig. 7 Downhole dynamometer sensor

6.
Realistic friction coefficients for the two materials in contact, obtained from experiments, are defined. Lowest friction coefficients were obtained in dry and wet tubing, whereas the highest frictional forces were measured for sandy oil conditions.

Material property definition

The solver of the simulation software requires the definition of material properties for the beam elements. Because this study only considers steel sucker rods are 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. However, it should be pointed out that the finite element method is in general able to simulate a wide range of linear and non-linear material behaviors.

Boundary conditions and amplitude definitions

In three dimensions, each node of a structural element has three translational and three rotational degrees of freedom. As the tubing is assumed to be fixed, no motion is allowed, i.e. all six 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-directions is restricted. The motion in the z-direction is defined by an amplitude function, representing the motion of the polished rod.
Also, 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, on the one hand, be 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 (Fig. 7) 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 one tool at the surface, directly below the polished rod, at least one tool directly above the pump's plunger and one tool close to the neutral point in the sucker rod string. Additional tools can be placed in between, e.g. for deviated wellbores at the kick-off point from vertical. The outer diameter of the DDS allows the installation even in small tubing strings, like a 2 3/8″ tubing string.
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 shifted. Besides redundancy, the reason for three strain gauges is 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 afterwards. The software for the tool itself allows very comfortable handling. The tool can be programmed to sleep and wake up in time intervals by an alert. After data recording, it switches back to the 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 conversion to the desired units. The analogous sensors deliver Millivolts, which need to

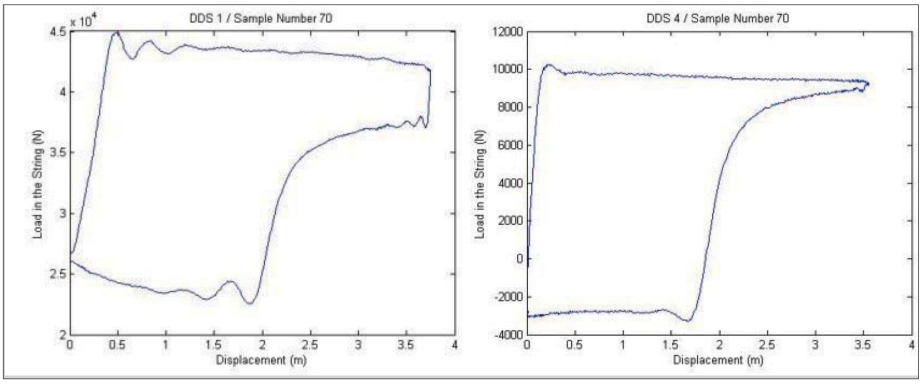

Fig. 8 DDS measurements at different positions along the sucker rod string

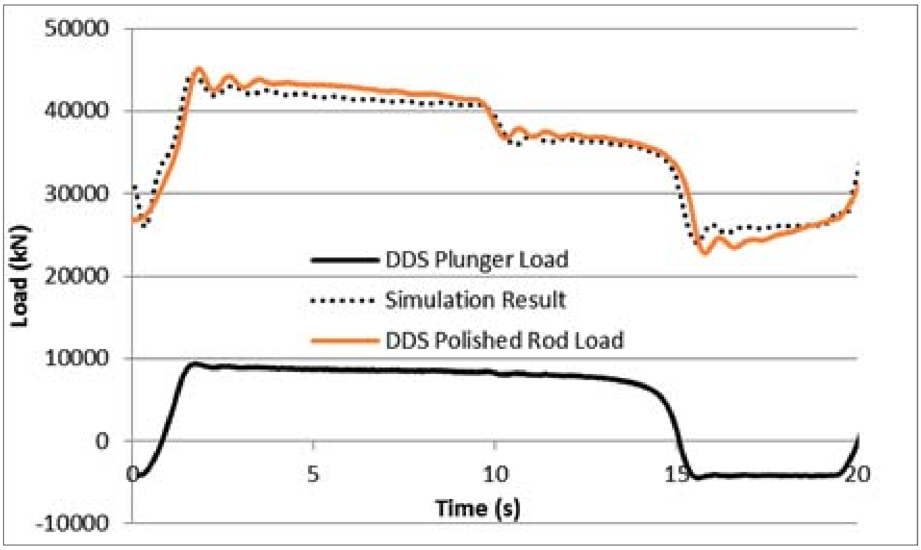

Fig. 9 Comparison of FEM Simulation – DDS Measurements [7]

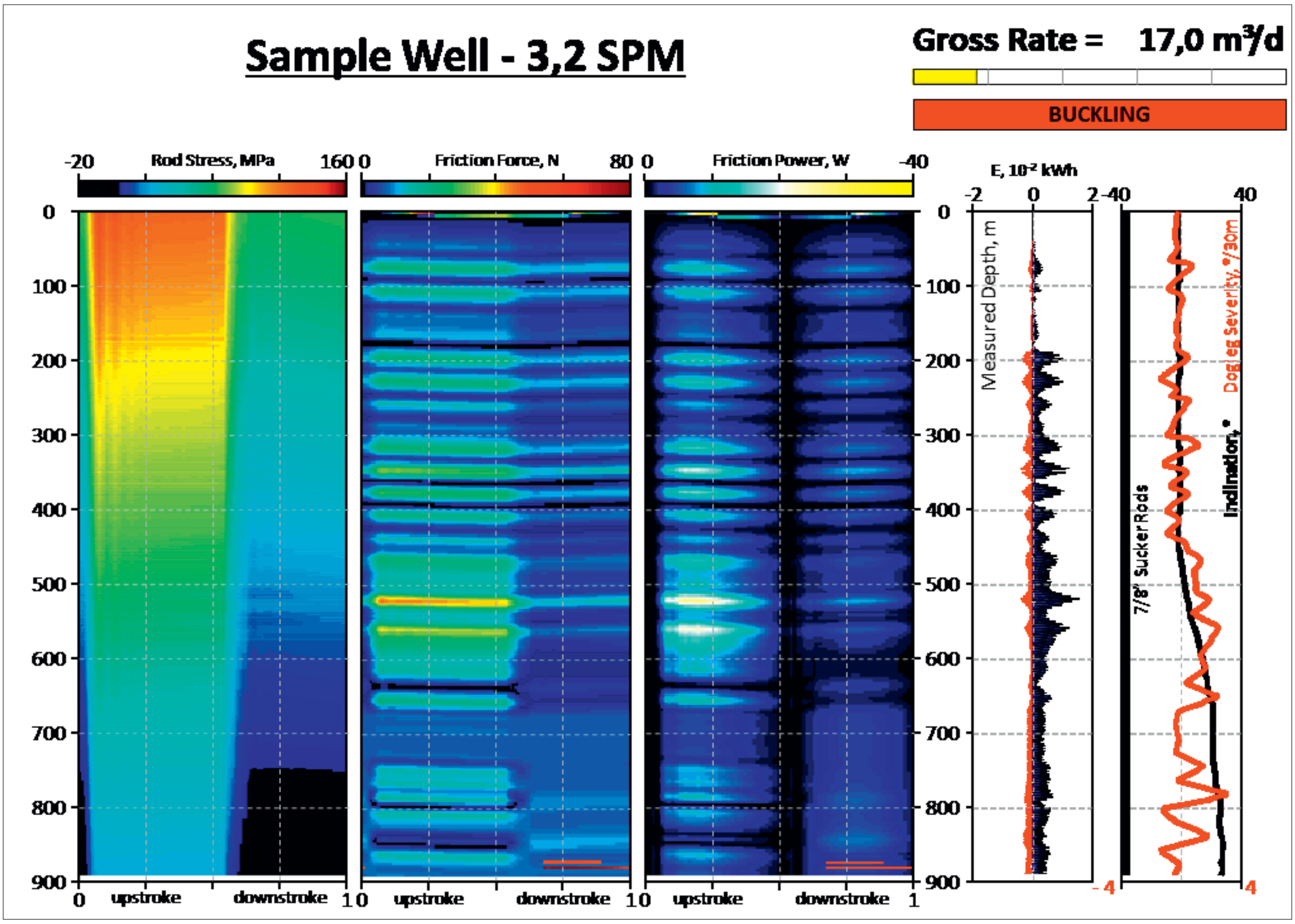

Fig. 10 Simulation Results 1 – initial sucker rod string configuration [7]

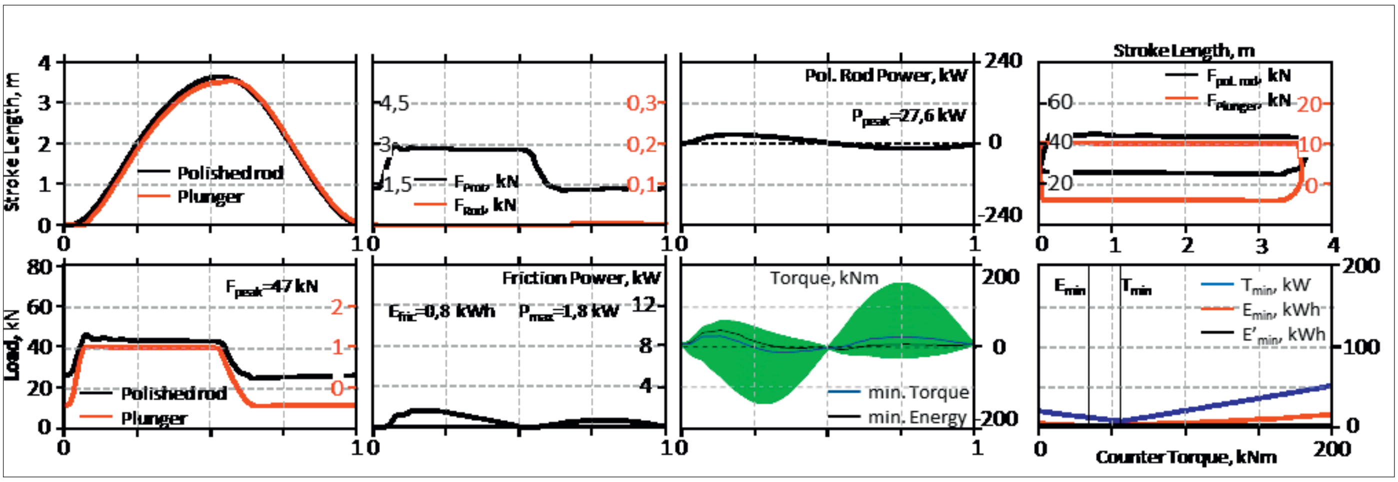

Fig. 11 Simulation Results 2 – initial sucker rod string configuration [7]

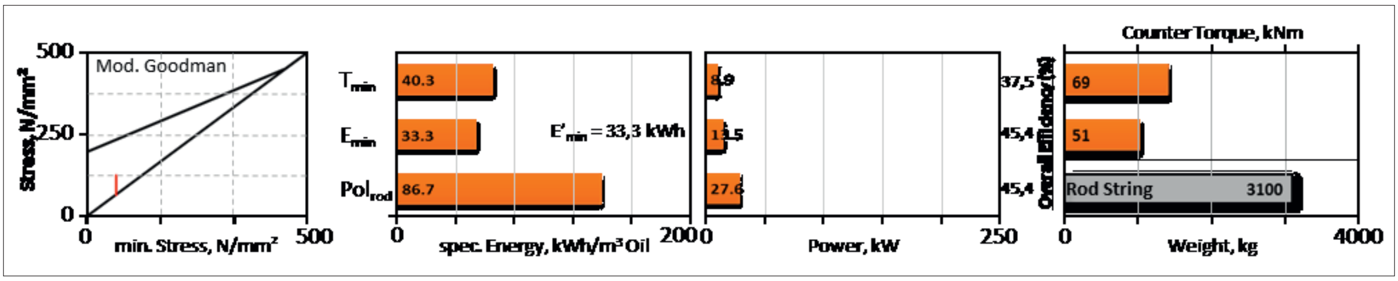

Fig. 12 Simulation Results 3 – initial sucker rod string configuration [7]

be converted to force and temperature, respectively Newton and degrees Celsius. The digital sensor delivers multiples of g.

To verify the simulation results several DDS measurements, obtained from tests, were used. The same wellbore and rod string configuration is simulated, using the presented FEM approach. Figure 8 presents the results of the DDS measurements. The left-hand 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. The measurements show that the pump is pumping off at a high degree, which allows the approximation of the plunger and rod string friction. Negative loads at the pump plunger, as a result of buoyancy, and the maximum loads that occur within one cycle can be identified clearly.

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

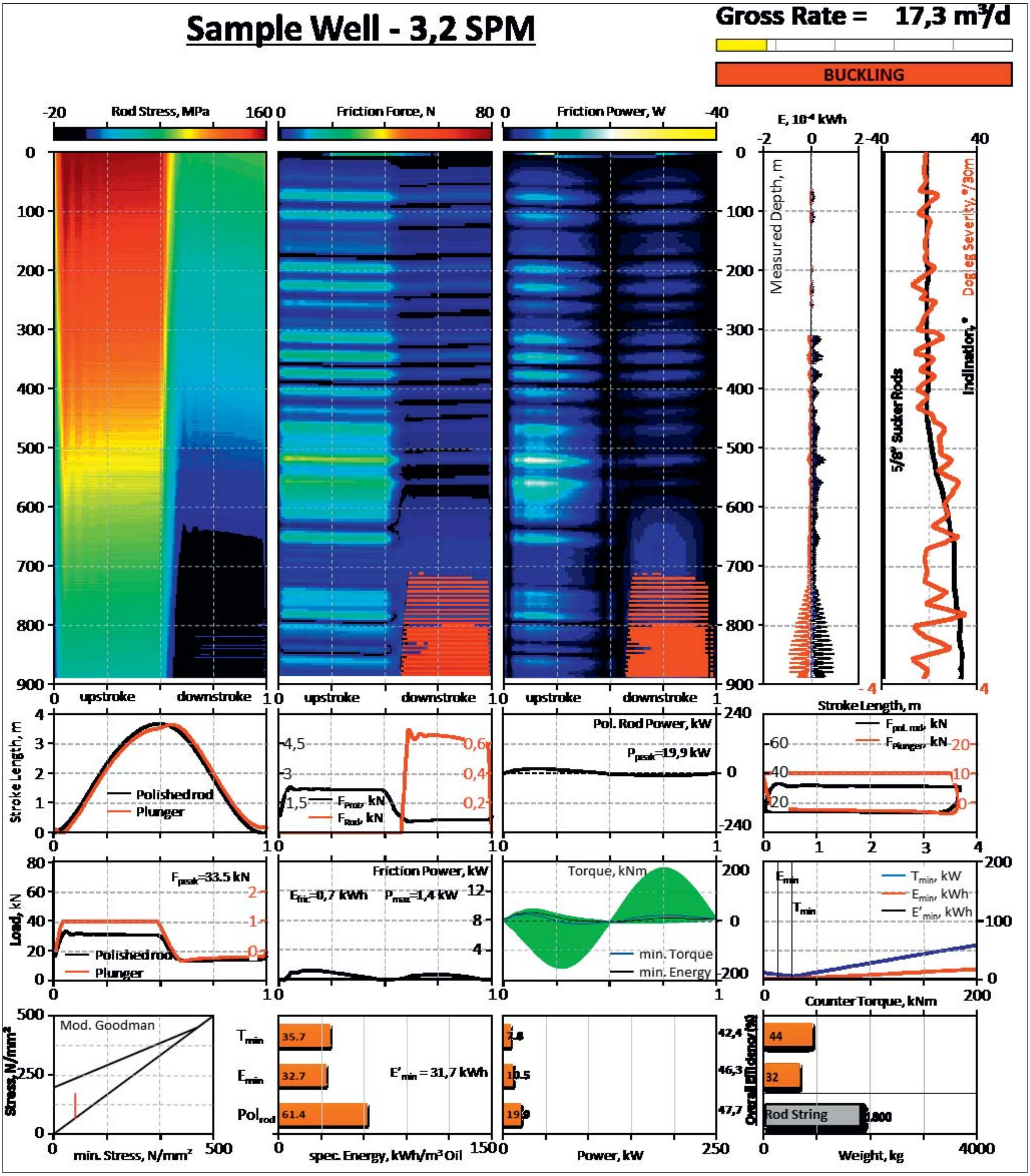

Fig. 13 Simulation results – rod string adjustment

design new pumping systems or to adjust and optimize existing ones, by 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, as already mentioned above, DDS measurements are compared to the simulation results. The configuration of the simulated well includes:

- Pump setting depth at 890 m measured the depth
- 7/8˝ rod string (2 rod guides/rod)
- 25-150-TH-18-4
- 3,2 SPM
- $p_{well\ head}$ = 4 bar
- $p_{casing\ head}$ = 4 bar
- 35° API & 86% WC

The comparison of DDS measurements and simulation, also allows the identification of highly accurate friction coefficients, as well as the material damping coefficients under real conditions. Figure 9 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

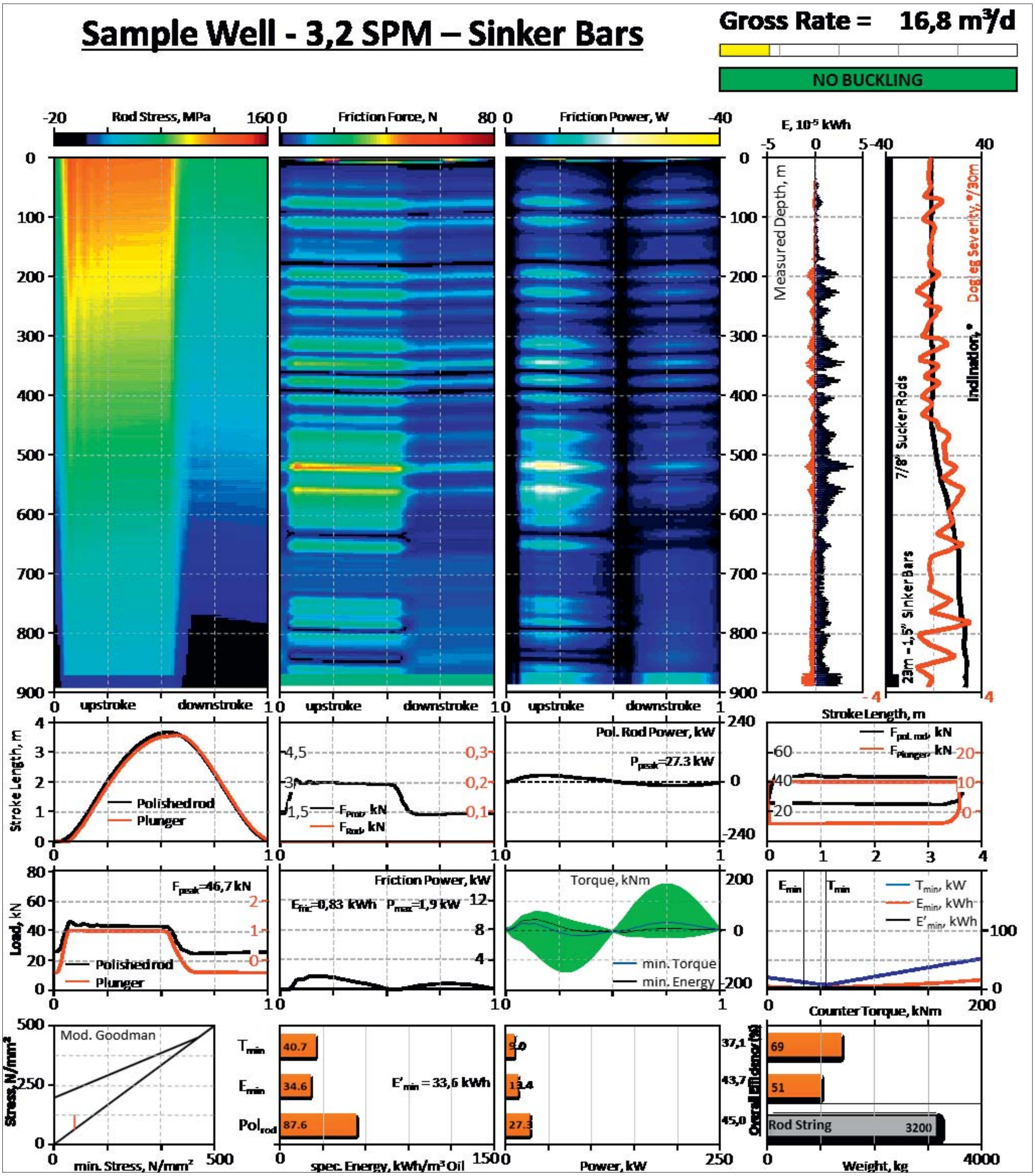

Fig. 14 Simulation results – sinker bars

the simulated and measured polished rod load indicates properly selected friction and damping parameters.

The performed simulation generates a large 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 the power requirement for running the system, efficiencies, counterweight mass and position optimizations can be performed. Figure 10 presents the results of the initial sucker rod string configuration. The picture on the very left presents the rod stress for the full stroke at any position along the sucker rod string. The highest stress occurs at the beginning of the upstroke close to the polished rod, whereas the lowest stress occurs during the downstroke, next to the plunger. The plot in the middle indicates rod string friction forces. It can be seen that doglegs and the deviation of the wellbore cause relatively high contact forces at certain points. Also, the red bars at a depth of about 850 m indicate buckling of the sucker rod string. The third picture presents the power requirements to overcome the frictional forces. The two figures on the right-hand side present the energy loss versus depth and the dogleg as well as the trajectory of the wellbore.

The data, obtained from the simulation, allow the evaluation of the full performance of the sucker rod pumping system. Figure 11 presents, starting at the upper diagram on the left, the plunger motion, the total frictional forces, the required polished rod power without considering the counterbalancing effect, the dynamometer cards, the load vs. time behaviour at the plunger and at the polished rod, and the torque evaluation at the gear box for several counterweight mass scenarios to investigate the optimum balancing effect.

Figure 12 presents the Modified Goodman Diagram of the rod string, the specific energy consumption, the power requirements and the optimum counter torque. 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 Tmin 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 Emin 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 initial configuration results in system efficiencies for T_{min} of 37.5% and E_{min} of 45.5%. As a next step, the performance change is investigated, when the initial rod string design is modified by just one characteristic, e.g., sinker bars or rod string size.

Figure 13 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 frictional forces in the build-up section are reduced, which decreases the total frictional losses. It can also be seen that the total production rate is increased from 17 m³/day to 17,3 m³/day as a result of the higher elasticity of small diameter rods.

A clear disadvantage of smaller rod diameters is the fact that excessive buckling occurs, starting at a depth of about 700 m and extending to the pump plunger. However, system efficiencies for T_{min} of 42.4% and E_{min} of 46.3% increase with smaller rod diameters.

Figure 14 presents the effect of using sinker bars on top of the plunger with the original 7/8˝ sucker rod string to overcome buckling. The total production rate is reduced from 17 m³/day to 16.8 m³/day because of a change in the plunger motion. 23 m of 1.5˝ sinker bars effectively prevent the rod string from buckling, but in combination with the used 7/8˝ sucker rod string, the total frictional forces are increased, and the efficiencies are reduced: T_{min} of 37.1% and E_{min} of 43.7%.

Several cases, not just optimizing the rod string size or the usage and length of sinker bars, but also the rod guide position, need to be considered to get an optimized system.

Conclusion

The presented numerical simulation model can analyse 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 concerning 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 be significantly reduced when optimizing the system electricity consumption can be reduced, and system efficiency increased essentially. ■

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