Innovative Sucker Rod Anti-Buckling System (SRABS) Developed on a Pump Testing Facility to Postpone the Economic Limit of Mature Oil Fields and to Increase the Recovery Factor

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Abstract

The falling oil prize emphasizes the importance of cost optimization with artificial lift systems. Especially in mature oil fields the reduction of lifting costs by increasing the meantime between failure (MTBF) and the overall efficiency is the mean to extend the economic limit and to increase the recovery factor of producing wells and fields.
Worldwide a big portion of artificially lifted wells use sucker rod pumping systems. Although their efficiency has been steadily improved, there is still room for improvement and system optimization.
This paper presents the benefits of the patented and already tested Sucker Rod Anti-Buckling System, which is able to prevent compressive loads almost completely from the sucker rod string. This is achieved by a redesign of the standing valve by an advantageous usage of the dynamic liquid level so that the SRABS system prevents the sucker rod string from buckling. Buckling is one of the major reasons for tubing leaks and fatigue failures of the rod string and represents therefore one significant negative influence on the MTBF. In addition buckling causes a reduction of the volumetric efficiency of the pump and initiates and accelerates corrosion and erosion effects.
Apart from extending the MTBF, the system displays one major positive effect - an increase in overall system efficiency. Simulations, laboratory tests and field test clearly showed that the SRABS system can raise the overall efficiency by more than 12%. This is achieved through a redesign of the rod string and an optimization of the pump.
The SRABS performance and wear tests under large scale conditions were performed at the University's newly constructed Pump Testing Facility, which was sponsored by OMV. This self-developed facility is able to simulate the conditions of a real world, including the effects of dynamic liquid pressure and temperature. The results of the intensive testing are used on one hand to optimize the geometry of the pump body itself and on the other hand to improve the wear resistances by selecting optimal materials for the individual pump components. Testing pumps at the Pump Testing Facility is way cheaper and faster compared to real field tests.
SRABS itself can be applied within every sucker rod pumping system, the installation is as convenient as for a standard pump and in addition manufacturing costs are also compatible with those of a standard pump.
This paper will describe the research processes, basic ideas and innovations as well as the final results of the SRABS system and will allow an outlook on the economic application in the world.

Introduction

The U.S. Energy Information Administration [1] estimates the total global crude oil consumption by about 92 million barrels per day, steadily increasing by 1,6 percent per year, which results in an average crude oil consumption of two litres for each single person on the planet per day. This fact makes crude oil irreplaceable today. Nothing can substitute its convenience in supply at the moment.
An essential portion of the consumed oil is produced from mature fields. The declined reservoir pressure and the increased water cut often require artificial lifting systems for delivering the crude oil from the reservoir to surface. In times of low oil prize the cost optimization of the artificial lift systems is of especial important. The emphasis is to increase the meantime between failure (MTBF) and the overall efficiency, to extend the economic limit and to increase the recovery factor of the producing wells and fields.
Beside others sucker rod pumping systems are installed in the majority of all artificially lifted wells. Hundred thousands of units are installed worldwide. Even a small increase in the systems efficiency results in an enormous economic impact. The understanding of the pumping operation and its influencing parameters are of essential importance for designing and operating the pump under best economic conditions.

Sucker Rod Pumping System

The sucker rod pumping system basically consists out of the surface pump jack, which drives together with the sucker rod string the subsurface pump. A standard subsurface pump consists out of the fixed barrel, within the plunger moves up and down. Check valves, connected to the barrel and the plunger alternately open by fluid flow and close by pressure. This working principle causes cyclic production, which means that the main production is achieved during the upstroke, but also a smaller fluid production during the downstroke.
Basically one has to distinguish between the production rate at the pump plunger and the production rate at the wellhead, which can differ significantly.
At the pump plunger the upstroke production rate is directly dependent on the cross-section of the plunger and the plunger rod, which connects the plunger to the sucker rod string. The upstroke production rate is equal to the annular volume between the barrel and the plunger rod, whereas the downstroke production rate is defined by the displacement of the plunger rod. Depending on the different standardised component sizes the volumetric ratio upstroke to downstroke production can vary between fifty and ninety percent, as indicated in Figure 1.

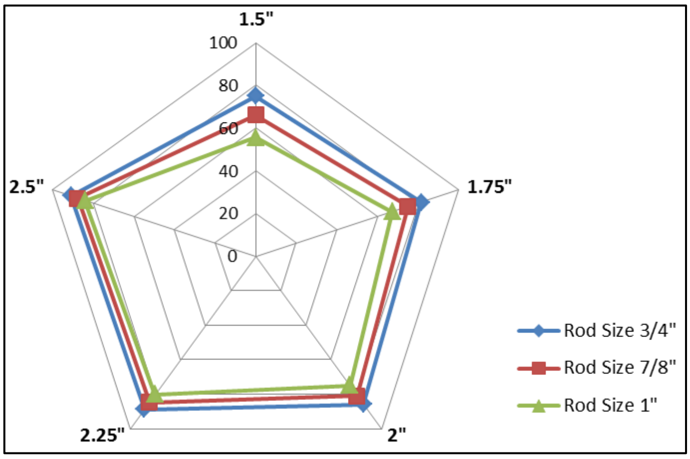

Figure 1: Up- and downstroke production rate at the pump plunger [2]

Despite neglecting the influence of liberating gas, the upstroke to downstroke production ratio is not dependent on the plunger rod size, but defined by the polished rod size. The upstroke production rate is equal to the annular volume between barrel and polished rod. The downstroke production rate is given by the displacement of the polished rod in the wellbore. Extreme combinations, which can occur for very deep installations, where small plunger sizes and a large polished rod is required, can even theoretically cause zero production during the upstroke. The whole amount of fluid is produced during the downstroke by the displacement of the sucker rod string. Figure 2 illustrates beside other sizes the combination of a 1 ½“ plunger and a 1 ½“ polished rod, which lead to such an interesting production behaviour.

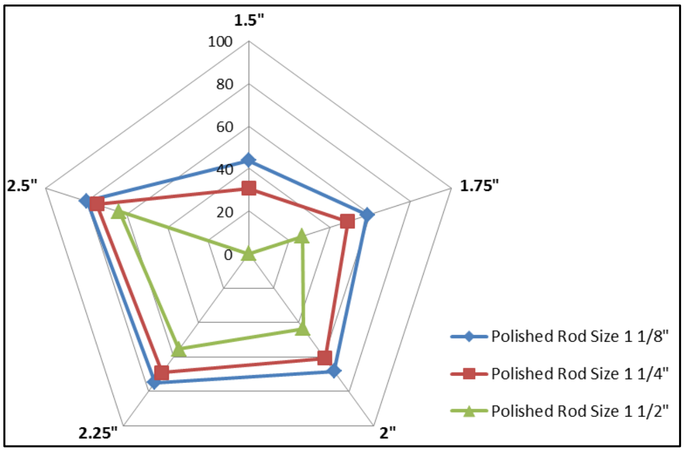

Figure 2: Up- and downstroke production rate at the wellhead [2]

Sucker rod pumping systems are very popular artificial lifting systems. The basic idea of this pumping system was already founded 2400 years ago by the Chinese for pumping water [3]. Continuous development and improvement made the system to what it is today. Their success is based on: [4]

- High system efficiency over a wide range of production rates and depths
- High flexibility in production rate
- Relatively low capital and operating costs
- Easy maintenance and operation
- Low footprint at the well site
- High range of applicability; heavy oils, asphaltenes, scales and sand can be handled within a certain range.
- Lifting compositions with high water cuts and moderate gas is possible
- Pump components are standardized, causing easy exchange of equipment

Beside these advantages, sucker rod pumping systems a still struggling under some limitations.

- Limited operation depth and pumping rate by exposure to stress of the sucker rods
- Installation and change of subsurface pump is time consuming and costly
- Corrosion, wear and fatigue of the components

Some limitations can be overcome by improving the used material e.g. a higher steel grade will allow the application of this system in greater depths, but one has to keep the higher costs in mind.

Corrosion, wear and fatigue are a big issue in sucker rod pumping. These failures can occur in the whole system. The pie chart in Figure 3 presents a breakdown of the major causes for failure of the beam pump systems. More than fifty percent of all failures occur in connection with the rod string. Leaking tubing, overloaded rods and broken couplings have an essential impact on the number of required workover operations to maintain this system. Pump failure, which are more than one third of all failures, are caused by wear of the equipment and produced sand.

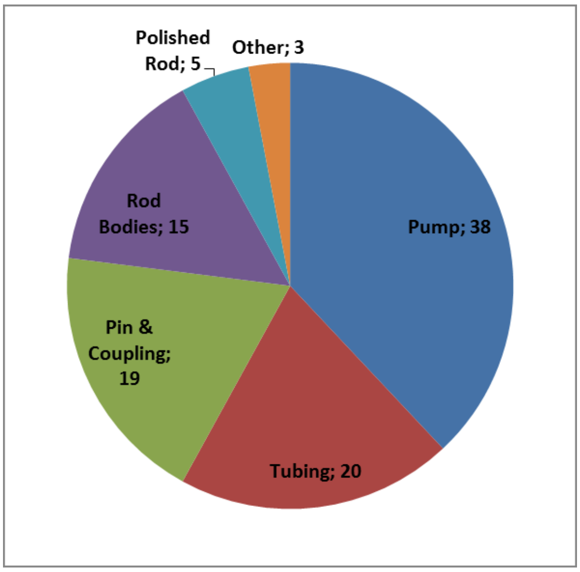

Figure 3: Typical distribution of failures among the Beam Pump System Components [5]

One circumstance that causes the above described negative effects on the equipment is buckling of the sucker rod string. Buckling is a result of high compressive loads on a slim rod string. Especially during the downstroke the portion of the rod string directly above the plunger, where the supported rod string weight is very low, is prone to be under compressive loads. The coulomb friction forces are acting upwards against the direction of motion and cause compression of the sucker rod string. The weight of the pump plunger itself in most cases is too low to keep the string in tension. Due to the fact that a slim rod string only can support a certain amount of compressive load before bending, buckling occurs if the compressive force surpasses a critical value, defined by the rod diameter and the material.[2]

In conclusion if the problem of buckling can be solved, the number of well interventions will be reduced essentially and the oil production costs are reduced.

Sucker Rod Anti-Buckling System (SRABS)

The Sucker Rod Anti-Buckling System is a specific pump construction to prevent buckling of the rod string completely. Two inventions [6], [7] are combined to prevent high compressive loads from the complete sucker rod string, resulting in essential benefits:

- No buckling of the complete sucker rod string
- No wear as a result of tubing / sucker rod contact
- Increase in downstroke velocity without buckling is possible to increase the overall pumping efficiency
- Rod string diameters can be reduced, thus self-weight of the system is decreased

The invention or physical principle “A pumping device for pumping fluids” concentrates on the liquid loads, which are acting on the plunger rod. Within standard subsurface pumps during the downstroke the pressure of the liquid in the tubing is acting on the plunger rod cross-section, causing compressive loads in the rod string, as well as on the mantle of the rod string, resulting in a stabilization effect, against buckling of the rod string. [8]
These effects equalize, according to S.A.Lukasiewicz, thus buoyancy does not cause buckling. The new system now takes advantage by the activation of the stabilization effect without allowing the tubing pressure to act on the plunger rod cross-section at the same time. The still remaining compressive coulomb and viscous friction forces as well as inertia forces can be compensated exclusively by the fluid stabilization effect until a critical number of strokes of the rod string are reached.

For achieving this benefit the standing valve of the pump is redesigned. The ball valve is substituted by a hollow cylinder valve, which allows the plunger rod to pass through it. As a result this plunger rod is no longer loaded by the tubing pressure during the downstroke, but loaded by the pressure generated by the dynamic liquid level in the casing-tubing annulus during the whole pumping cycle, which is essentially lower.

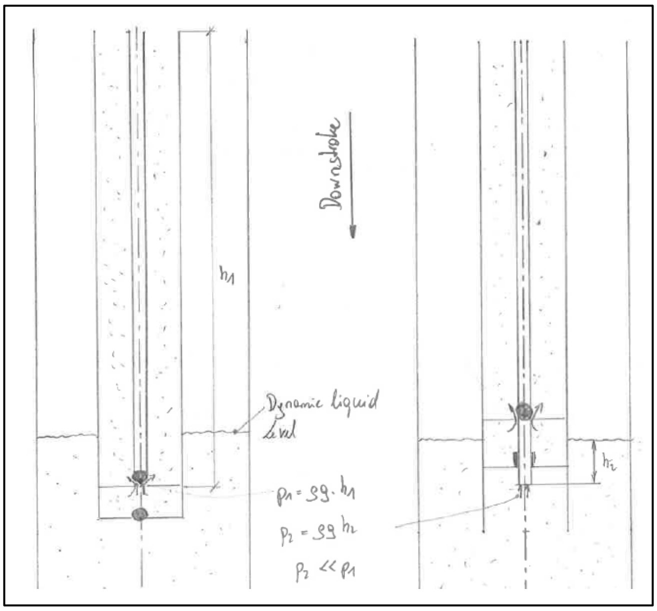

Figure 4: Liquid Loads on Plunger Rod [2]

Figure 4 presents the liquid loads on the plunger rod for the standard and SRABS design, where ρ is the density of the fluid at the pump conditions, g is the acceleration due to gravity, h_1 is the liquid level in the tubing, which normally extents up to the christmas tree and h_2 is the dynamic liquid level in the casing – tubing annulus.

The stabilization effect, caused by the liquid, drastically reduces the buckling tendency, especially for low stroke numbers. Higher stroke numbers, starting with 8 to 9 SPM increase the system dynamics essentially and the second patented invention [6] must be considered to still prevent buckling of the sucker rod string – the tensioning element. The tensioning element is basically a mass below the pump plunger, which tensions the rod string and thereby completely prevents compression of the rod string. The actual weight of this mass is highly dependent on the pumping speed and a design parameter of the system.

A limitation of the SRABS pump is a slight reduction of the production rate. Whereas the standard pump produces during up- and downstroke as presented at the beginning of this manuscript, the SRABS pump produces exclusively during the upstroke. To obtain the same production for the SRABS pump, compared to the standard pump, the only way is to slightly increase the number of strokes.

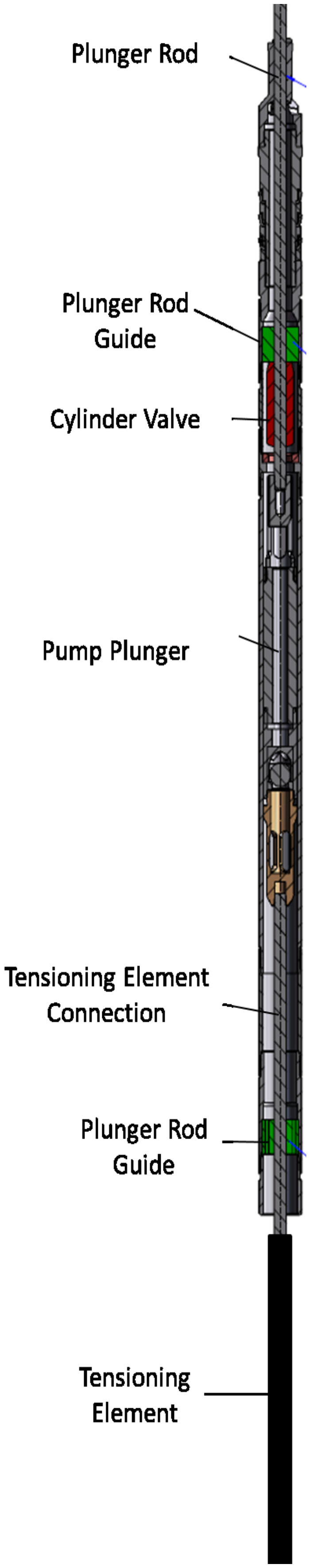

Figure 5: Reverse SRABS pump design [9]

Therefore a major objective is the reduction of the plunger rod diameter to design a SRABS pump with almost the same production rate as a standard pump. The minimum plunger rod diameter is balanced between the lifted liquid rate and the danger of buckling within the barrel, as well as the shape stability of the plunger rod itself, because its surface is the seal against the hollow cylinder valve. To reduce the necessity of guidance of the plunger rod, the pump is designed reverse, which means that the plunger is installed below the standing valve.

System Analysis

Sucker rod pumping systems are very complex systems. In former days analytical solutions were employed to describe the behaviour of the sucker rod string. Nowadays more and more complex wells are equipped with sucker rod pumps; especially inclined well trajectories increase the complexity of the system analysis – hence only numerical simulations are able to give precise and realistic results [10]. Therefore a model based on the Finite Elements Method was used to evaluate the performance of SRABS, compared to a standard pumping system. The developed model is able to consider any trajectory, rod guides, rod couplings and the viscous drag generated by the fluid production. The results of the simulation allow beside others, the evaluation of the stresses all along the sucker rod string, the frictional losses in the system, the polished rod load behaviour and the system efficiency for minimum torque at the crank shaft and minimum energy consumption. The optimum counterweight torque can be evaluated.
Several rod string compositions, number of strokes and plunger rod diameters were simulated for comparing SRABS and the standard system. The optimization of the plunger rod diameter is the key to increase the produced volume per upstroke of SRABS, thus reducing the required number of strokes per minute. The plunger rod is stressed by tensile loads, caused by the fluid load during the upstroke and stressed by compressive loads during the downstroke, caused by viscous and Coulomb friction. As a result the minimum diameter of the plunger rod is required to prevent its demolition by tension and buckling.

The most interesting case is the comparison of 3,2 SPM for a standard system and 3,5 SPM for SRABS, delivering 17 m³ per day with a water cut of 85% from a 900 meter deep reservoir. The simulation for the SRABS rod string, consisting of 5/8” sucker rods, shows that the peak polished rod load can be reduced to 30,9 kN, compared to 46,7 kN for the standard system. The most important findings are that the specific energy consumption is reduced to 35,5 kW/h per m³ of oil, resulting in an overall efficiency of 42,6%.

Table 1: Case study SRABS system

Description	Energy Consumption (kWh/m³ oil)	Energy Reduction (%)	Efficiency η
Standard System	**40,8**	**-**	**37,1**
SRABS	**39.1**	**4,2**	**38.7**
SRABS 170” Stroke Length	**40,6**	**0,5**	**37,1**
SRABS 12 mm Plunger Rod – 5/8” Rods	**35,5**	**13,0**	**42,6**
SRABS 170” Stroke Length –13 mm Plunger Rod	**37,4**	**3,4**	**40,3**

Pump Testing Facility

The Pump Testing Facility is the result of the strong collaboration of the Montanuniversitaet Leoben and OMV. The development of new technologies in the field influences the regular field operations, is very costly, time consuming and has an impact on HSE. To overcome these limitations the Pump Testing Facility was designed and constructed at the Montanuniversitaet together with the experience of the field engineers at OMV. The main objectives were low risk evaluation of new technology, low cost equipment testing and optimization as well as fast development of innovations and the application in the field.
Together a testing unit was developed that is able to simulate the oil and gas flow under real

well conditions up to a depth of about 500 meters. The developed pump testing facility comprises of a 6 5/8", 8 meter long casing string and is installed in a 10 meter deep shaft at the Montanuniversitaet Leoben. Measurement systems for evaluating the flow rate, pressure and energy consumption are installed to evaluate the performance of existing and new developments. The Pump Testing Facility itself consists of a modular design for allowing the highest flexibility of testing new technology. Artificial lifting systems can be tested as well as well stimulation equipment, etc. to satisfy the needs of the field engineers.

The Pump Testing Facility is currently used for improving SRABS. As a result the actual capabilities are:

- Performance and wear testing of Sucker Rod Pumps
- Optimization of the SRABS pump
- Testing under vertical and deviated (<= 30°) conditions
- Simulation of oil and gas production
- Easy variation of well & reservoir parameters – e.g. dynamic liquid levels, influence of scales, sand, GOR, etc.
- Evaluation of energy consumption, pump efficiency under sandy and/or gassy conditions
- Calibration of the Downhole Dynamometer Sensors (DDS)
- Downhole Dynamometer Card Model Verification
- Asymmetric stroke profile development
- Test alternative rod string materials (wires, plastics)

Figure 6: Pump Testing Facility at the Montanuniversitaet Leoben

Economic Evaluation

The economic evaluation shows a comparison of the costs for SRABS and a standard sucker rod pumping system, based on a 10 years period.

The total costs for a sucker rod pumping system can be split into the following components:

- Mean Time To Repair (MTTR) - Cost of Loss of Production
- Mean Time Between Failure (MTBF)
- Subsurface Equipment Costs
- Electricity Costs

Mean Time To Repair – Costs of Loss of Production:

The MTTR is the time duration required to maintain a system. For workover operations it consists of two components.
The first component is the time span of planning the workover job and getting an available free workover unit to the well site after an error occurred. Due to different company philosophies this duration is omitted, resulting in a more conservative cost comparison of the systems.
The second component represent the required number of days is to repair the system, causing a loss of oil production. Especially for wells suffering under high water cuts, this component is of minor importance and defined with three days for tubing changes and two days for rod changes.

Mean Time Between Failure:

The average MTBF is assumed to be about 1130 days for the lifetime of the tubing in a standard sucker rod system application. Practical experience shows that sucker rods can withstand at least 16 million pumping cycles, thus the actual lifetime of the sucker rods is SPM dependent, if there is no earlier failure due to erosion or corrosion. SRABS is able to increase the lifetime of the tubing, but not all tubing failures are purely related to buckling. As a result every second tubing change within the 10 years' time period is also performed for the SRABS installation, as a result of non-buckling related events.

Subsurface Equipment Costs:

The subsurface costs consider the costs of the equipment that is installed during the workover jobs, like tubing string, sucker rods, pump, etc. It is assumed that the costs of the SRABS pump are close to the costs of a standard pump.

Electricity:

Electricity costs are a big share of the total costs. More efficient systems can contribute essentially to a total cost reduction. 7 Cent/kWh are used as reference industrial electricity costs for today. The optimized SRABS is by 12 percent more efficient than the standard pumping system.

A comparison of the costs within a 10 year timeframe (Figure 7) shows under the stated assumptions a total saving potential of about 40 percent. Using SRABS the costs per produced m³ of oil can potentially be reduced drastically.

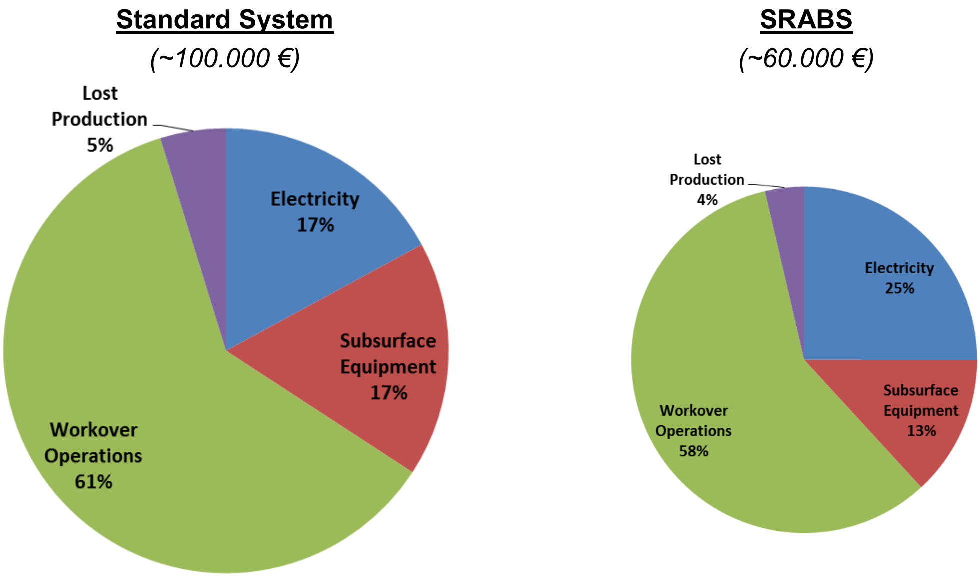

Figure 7: Cost comparison – standard system / SRABS

The economic analysis is a result of parameters, having some uncertainties. An uncertainty is on one hand based on the assumption that the lifetime of the new SRABS pumps is as long as the lifetime of a standard pump, which results in a halving the required number of well interventions. Long-time field tests are planned to confirm this assumption. On the other hand a constant oil prize is assumed for the next decade. The past shows that the oil prize is fluctuating and will not stay constant over the next years.

Other parameters which can hardly be expressed in terms of cost are Health, Safety and Environment. Experience shows that well interventions belong to the most dangerous operations in the oil business in terms of risk of accidents.

Health: The number of accidents is based on the number of well interventions; hence a reduction of well interventions will directly cause a reduction of injuries of employees or contractors.

Safety: Tubing leaks, caused by buckling for instance, can cause special well interventions. Each intervention comes along with the risk for destroying or in the worst case losing the wellbore. If there is a system in place that reduces fatigue and failures, there is less probability for destroying equipment.

Environment: A reduced number of intervention leads to less emissions, like CO_2, caused by prime movers, trucks, etc..

Outlook

SRABS has already been tested successfully in the field. Currently the optimization of the pump itself takes place. The geometry of the pump is improved employing a computational fluid dynamics analysis, to prevent excessive velocities in to pump, which can accelerate together with sand grains erosion. The pump testing facility is used to evaluate the volumetric efficiency, the power consumption and the erosional behaviour of SRABS in comparison to a standard pump. The SRABS pump consists of numerous standard components. Just some parts are adjusted. The proper selection of these components is essential to increase the lifetime of the pump and therefore the material selection of critical importance. The next step is to bring the results together and to perform a second long time field test, which is already planned with our industry partner OMV.

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