Master Thesis

Alternative Valve Design for SRP Pumps

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Kurzfassung

Bei den Pumpsystemen im Öl und Gasbereich ist die Gestängetiefpumpe das meist genutzte Pumpsystem. Die Stärken des Systems sind der einfache Aufbau, die geringen Betriebs- und Wartungskosten und die Option von unterschiedlichen Energiequellen betrieben werden zu können. Die Nachteile sind, dass das System der Gestängetiefpumpen nur mit flüssigen Medien arbeiten kann. Schon kleine Mengen an Gas in der Pumpe können zu Förderproblemen oder einem Totalausfall der Pumpe führen.

Das Ziel dieser Arbeit ist es, eine Möglichkeit zu finden mit dem Gas, welches sich in der Pumpe ansammeln kann, umzugehen. Es wird dabei versucht die bereits bestehende Lösung zu adaptieren. Diese Arbeit baut auf der Sucker Rod Anti-Buckling System (SRABS) Pumpe von Dipl.-Ing. Dipl.-Ing. Dr.mont. Clemens Langbauer auf. Als Startpunkte wurden die Ideen eines oberflächenkontrollierten Ventilsystems, welches unabhängig der Last auf dem Ventil öffnen und schließen kann, und eines sekundären Ventilsystems, welches vor Aktuierung des Ventils den Druckunterschied abbauen kann, ausgewählt. Dies soll dazu dienen, dass im Falle einer Gasansammlung in der Pumpe diese funktionstüchtig bleibt. Auch wurde des Weiteren ein abgeleitetes Design des sekundären Ventilsystems entwickelt welches den Druckausgleich über das Gestänge führt, was technisch einfacher und unter den schwierigen Einsatzbedingungen unter Tage robuster ist.

Als zweiter Teil dieser Arbeit wird der Ansatz der Energieproduktion unter Tage beleuchtet. Die Bewegung des Stranges soll durch den Einbau von Spulen in elektrischen Strom umgewandelt werden um damit unter Tage die Messtechnik zu versorgen und eine unabhängige Messung und Speicherung von Untertagedaten bis zum nächsten Workover zu ermöglichen. In diesem Zusammenhang werden Lineargeneratoren in Erwägung gezogen.

Zudem wird diese Arbeit einen kurzen Überblick über den Stand der Technik bezogen auf Gestängetiefpumpen geben und deren Probleme und Schwachstellen beleuchten. Der Fokus liegt auf einer Lösung zur Vermeidung einer Gasansammlung in der Pumpe, welche groß genug ist um die Funktionsweise zu beinträchtigen. In diesem Zusammenhang werden alle gängigen Ventile verglichen um beurteilen zu können, ob die Möglichkeit einer Umgestaltung besteht. Nachfolgend wird die Realisierbarkeit des oben erwähnten Sekundärventilsystems erläutert.

Im zweiten Teil der Arbeit wird die Herstellung von Strom unter Tage genauer betrachtet. Die Implementation von Generatoren unter Tage wird zuerst theoretisch erläutert und des Weitern soll in einem Experiment geklärt werden ob die Umsetzung als Zubau zu bestehenden Gestängetiefpumpen realisierbar ist.

Abstract

One of the most common and widely used artificial lift system is the sucker rod pump. Its basic simplicity, cheap running cost and versatility in power supply makes it an often used choice for lifting oil. The downsides are that it is only usable for liquids and even a little amount of gas can render a pump unusable which makes a costly workover necessary.

The aim of this thesis is to find a way to handle gas interference and gas lock by adapting the existing design. The used sucker rod design in this case is based on the Sucker Rod Anti-Buckling System (SRABS) of Dipl.-Ing. Dipl.-Ing. Dr.mont. Clemens Langbauer. As a starting point the ideas of a secondary valve system to equalize pressure across the valve body or a surface controlled valve were chosen to get rid of the gas in the barrel if some is getting accumulated there. In the following thesis different approaches are explored and their feasibility is checked.

A secondary task is the investigation of the idea of using the motion of the string to produce electricity downhole. The aim is to use it for measurement tasks such as temperature, pressure and force. In this context the possibility of the integration of a linear generator is scrutinized.

This thesis will give a short recap of the working principle of a sucker rod pump and the common problems with gas interference. The focus is on the prevention of gas accumulation in the pump to keep it from failing. All basic valve types will be compared to see if there are other opportunities to control the valve action downhole independent of gravity and fluid loads. If there is the space and possibility to implement a secondary valve system as mentioned above is investigated, too.

In the second part the idea of a linear generator will be discussed in further detail. The implementation of a downhole generator will be discussed firstly in theory and secondly an experiment is set up to show if it is possible to implement this in an existing sucker rod pumping system.

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Abbreviations

SRP	Sucker Rod Pump
VSD	Variable Speed Drive
SRABS	Sucker Rod Anti Buckling System
ESP	Electrical Submersible Pump
PCP	Progressive Cavity Pump
MTBF	Mean Time Between Failure
V	Volt
A	Ampere
F	Farad
W	Watt

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1 Introduction

In recent years the diversification of the energy mix has changed continuously and it will continue to do so in the future. Renewable energy sources like wind, water and solar power are becoming increasingly important. Governments of wealthier countries in Europe, like Norway for example, are trying to supplement renewable energy sources for homes and cars. This tendency means that the share of fossil energy sources is declining in the first world countries.

Even though the shares of fossil sources are declining, the overall production is still increasing caused by the rapidly growing energy demand worldwide. This strong demand is largely driven by the robust growth of developing countries. In regards to oil and gas the demand in Europe is stagnating. The energy efficiency of machines and facilities whether of household appliances or industrial machinery is constantly improving. As a result of this fact there is no rise in energy consumption, despite increasing usage.

Most significant changes can be seen at the coal industry because of its substantial carbon footprint. Oil and gas are following closely on its heels. A big part of oil is being used in the transportation sector in various variants like kerosene in airplanes or gasoline in cars. In the transportation sector fossil energy sources are challenged by the increasing usage of electric cars because of political decisions like the ban on diesel powered cars or non-electric cars in general that is being discussed in some countries.

Gas still has a potential to gain in share because it is the cleanest fossil fuel and gas power plants have a very good efficiency compared to other sources. What might happen to the share of oil highly depends on the political development and how fast renewable sourced will be embedded in the transportation sector. A big part of the energy consumption still is the transportation of goods and mass transportation of passengers followed by individual transportation. [1, p. 26ff]

In addition to these changes the challenging economic conditions in the past ten years are a great problem for the whole industry. The fall from 140$/barrel to 30$/barrel hit a lot of the companies hard. The level of about 50 to 60$/barrel today is still challenging. More than ever this means the effectiveness of finding oil and lifting is gaining more and more importance. Focus is shifting on finding answers and solutions regarding to essential questions like how oil and gas can be found more effectively, as well as how a field can be developed better and last but not least how lifting oil and gas can be made better, longer and more efficient.

Oil and gas are far from extinction. The dependency on oil and gas will remain in coming decades. On the one hand side a lot of the developing countries will build their economies at least partly on fossil fuels. And on the other hand side the developed world will need it as long as any other suitable and affordable alternatives are available. Another important fact regarding this issue is due to the chemical industries where a lot of products are based on oil and gas products. [1, p. 12ff]

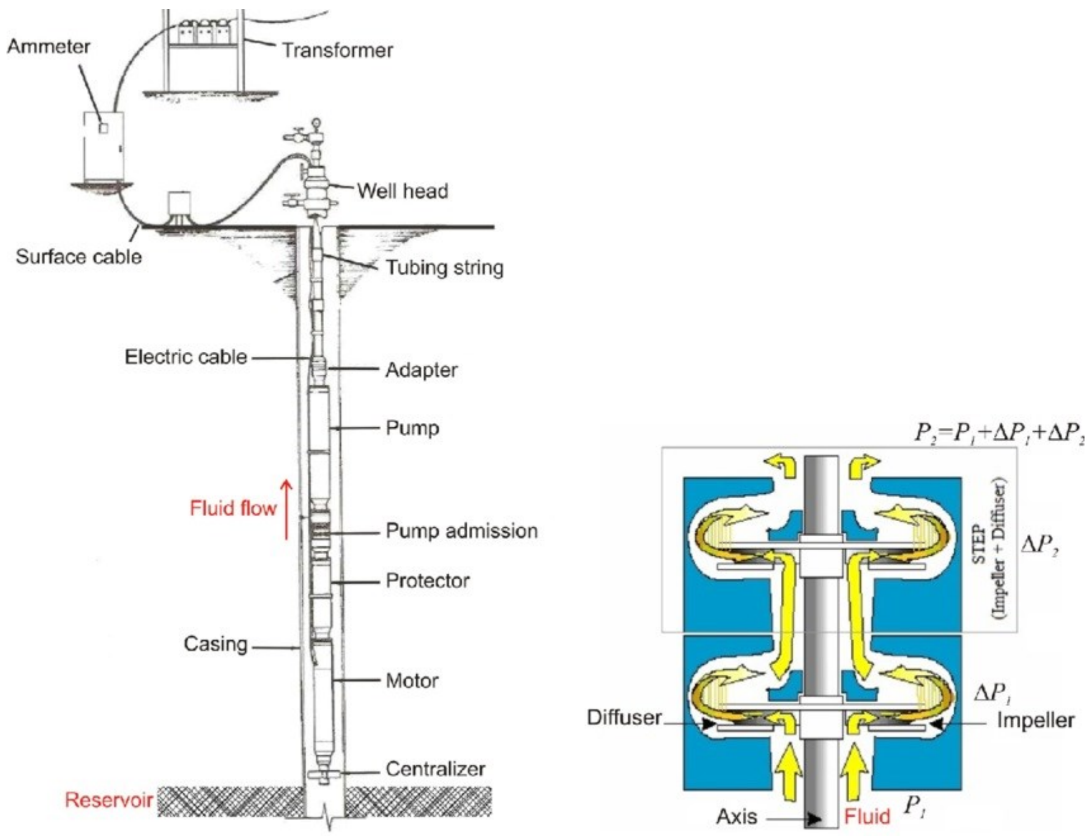
Nowadays it is more important than ever to work reliable and cost effective in the business to stay compatible with other sources of energy. Concerning the artificial lift sector, it is important to make the most of the existing resources. A lot of the money is put in the ground in finding new reservoirs and to develop them. The money is made during the production. They can go on for decades with the right artificial lift methods. The goal is to produce as long as possible from an existing bore hole without having to invest a lot of money in it. This means the artificial methods need to be relatively cheap and very reliable. The most common method amongst others is the sucker rod pumping system. Others include electrical submersible pumps, progressive cavity pumps, gas lift and hydraulic pumps. Depending on the used system they are applicable for light or heavy oils, for oil and gas mixtures, working with solids and fines, working with waxes and paraffin.

1.1 Artificial Lift Systems

Depending on the conditions and requirements different artificial lift systems are available on the market to cover the challenges. A pump in general cannot “pull” fluid it can only “push” it. There is a certain height the fluid has to be pumped and that corresponds, depending on the density of the fluid, to a certain pressure, which is provided by an artificial lift system. Therefore, the fluid level in the hole is very important. The reservoir pressure determines the height the reservoir fluid rises in the hole. The pump of the artificial lift system has to be placed below the mentioned fluid level to be able to pump fluid to surface.

1.1.1 Electric Submersible Pump

The electrical submersible pump (ESP) is a centrifugal pumping system, which is powered by a motor that is mounted below the pump in the well. Figure 1a gives a basic overview over the assembly. The power supply the motor needs comes from a power cable laid from surface down to the pump. The centrifugal pump itself consists of stages, the number of impellers stacked together, which determines the height the pump can lift the fluid. Figure 1b gives an insight how the impellers work. One particularity of ESPs is that each stage measures its lifting power in head, whereas the unit is meters. Normally it is customary in other pumping systems to state the lifting power as units of pressure. Centrifugal pumps give meters as output, because the density of the fluid determines the height a fluid can be lifted with a certain pressure. A centrifugal pump also gains its lifting power over the same liquid forced to the outside, producing the lifting force over its inertia, which is linked to the density. So every fluid in an ESP can be lifted nearly the same height dependent only on conditions related to inertia and losses coming mainly from density and viscosity. The yellow arrows in Figure 1b show the path of the fluid through the ESP stages and where the outward forced fluid is redirected to lift itself to surface. ESPs are suitable for moderate up to high producing wells, deviated wells and sub-sea deep water wells. The system is quite safe and requires a small surface footprint. A potential disadvantage is that ESP systems work badly with solids and fines because the impeller blades will be eroded very quickly. Viscous fluids and high gas to liquid ratios degrade the performance of the pump as well. [2]



(a) (b)

Figure 1: (a) A typical centrifugal pump configuration and (b) two pump stages detailed [3]

1.1.2 Progressive Cavity Pump

Progressive cavity pumps (PCP) consist of a downhole pump and a drive system. The components of the downhole pump are a stator and a rotor where the rotor is helical in form and the stator has a helix design inside. The stator is a steel tube with an elastomer on the inside and has one more thread than the rotor. So a cavity is created which takes fluid from below the pump and pushes it upwards. PCPs provide a pulsation free linear flow. Figure 2 shows the system for better understanding how the helical transportation works. Important advantages of this system are certainly on the one hand that high solid and fines contents are not a limiting factor and on the other hand high operating temperature ranges are possible. The downsides are that the production limit is 800m³/day at a maximum depth of 2,000m. The tendency of the elastomer to swell becomes immanent especially in certain fluids. Vibrations might also become an issue in high speed applications. [4]

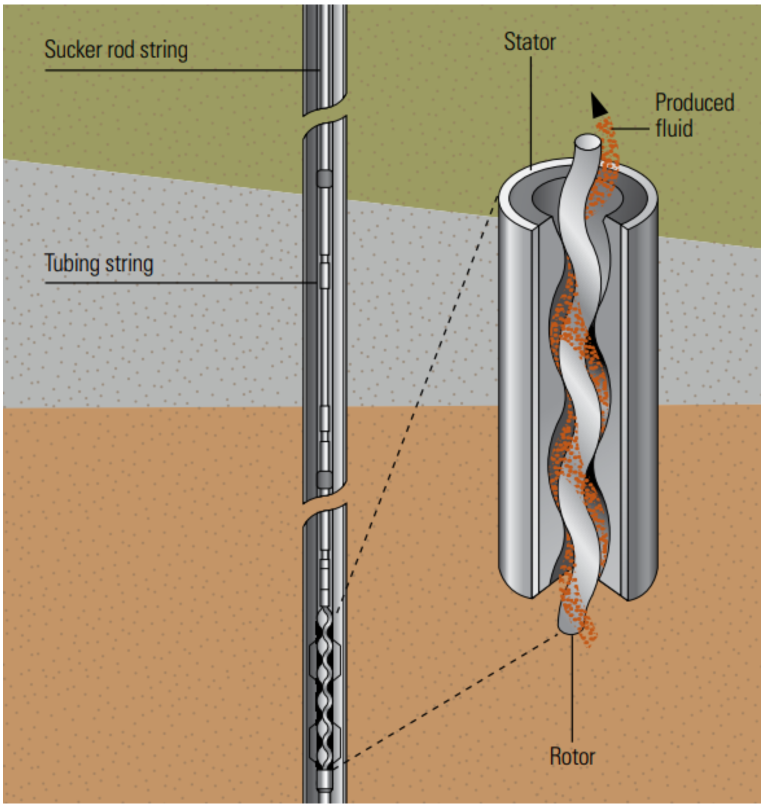


Figure 2: Rotor and stator of a PCP [4]

1.1.3 Hydraulic Pump

Hydraulic Pumps utilize a surface pump and a power fluid that is pumped into the well to power a pump downhole. This can be a rotating turbine, a piston pump or a jet. The reservoir fluid and the power fluid are produced back to surface in mixed form very often. Mixing occurs in jets where the energy is brought to the reservoir fluid by the power fluid injected via a nozzle in the stream. Other forms like the piston and turbine powered pumps have a separate power fluid circle and do not mix with the reservoir fluid. Hydraulic pumps have the advantage that the free floating subsurface pump can be pumped to surface and therefore the maintenance is cheap and easy. In most of the installed pumps power fluid mixes with production fluid and the result is refined oil which lightens the fluid column that reduces the hydrostatic pressure. Hence hydraulic pumps are frequently chosen for heavy oil applications. On the other hand, the power fluid leaves with the reservoir fluid and also has to be processed downstream again. Figure 3a shows a sketch of a hydraulic jet pump where the power fluid is injected via a nozzle downhole and the combined fluid of reservoir and power fluid is produced in the annulus between power fluid pipe and tubing. [5, p. 2]

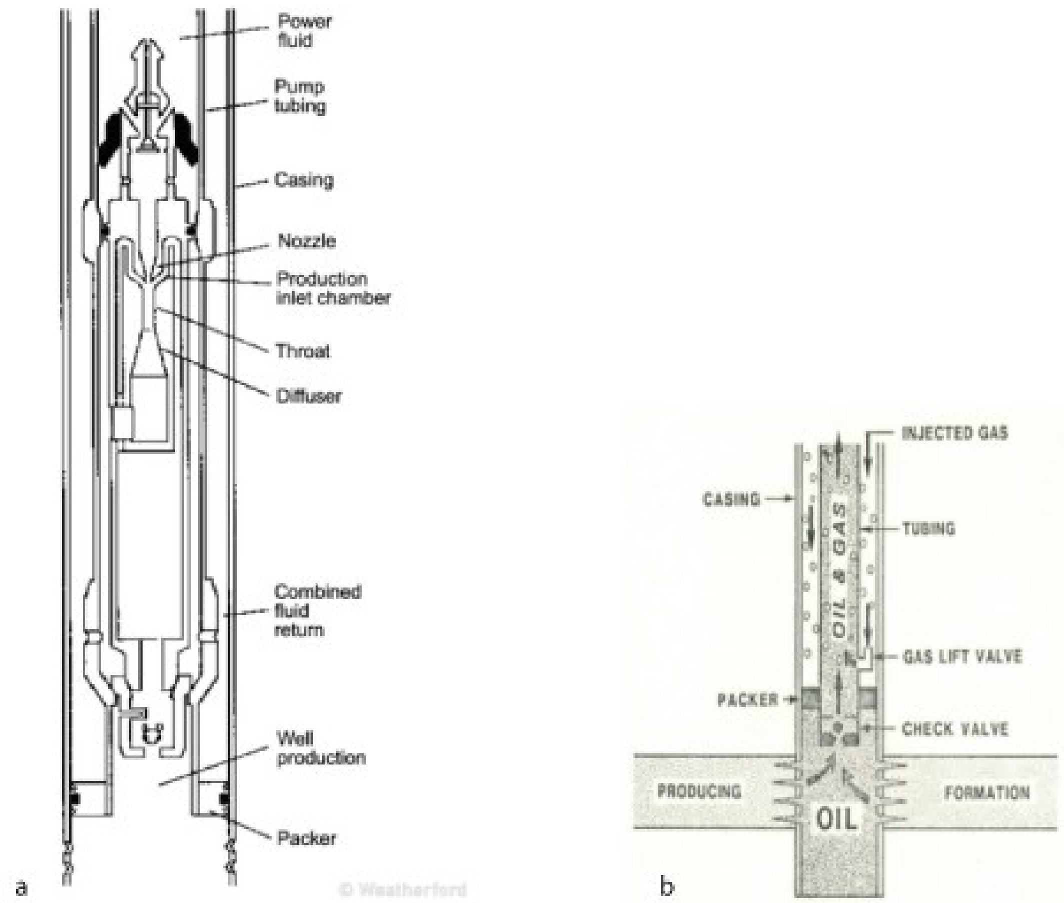


Figure 3: (a) hydraulic pump and (b) gas lift system [6] [7]

1.1.4 Gas Lift

Gas lift systems consist of several valves in certain depths in the well. They open by the pressure of the fluid column acting on them. When a valve is opened, gas mixes with the fluid that lightens it and therefore raises the whole bunch to surface. The lower hydrostatic pressure reduces the drawdown pressure allowing fluid from the reservoir entering the well bore. Gas lift has the advantage that it works well with solids and also works well in inclined wells. The downside is that on surface a gas oil mixture is present that has to be separated again. Figure 3b shows such a system. In the annulus gas is pressurized and this pressure combined with the setting of the gas valves determines when and where gas is injected into the stream. Depending on the lifting height there can be several gas lift valves, each set to different opening pressures to lift the fluid in stages. [5, p. 2]

1.1.5 Sucker Rod Pumps

Sucker rod pumping systems are the oldest and most widely used artificial lift systems in the world. The first sucker rod pump dates back to 1859 where Edwin Drake drilled America's first commercial oil well and used a water well head pump to lift oil from the 69.5ft deep well. [8]

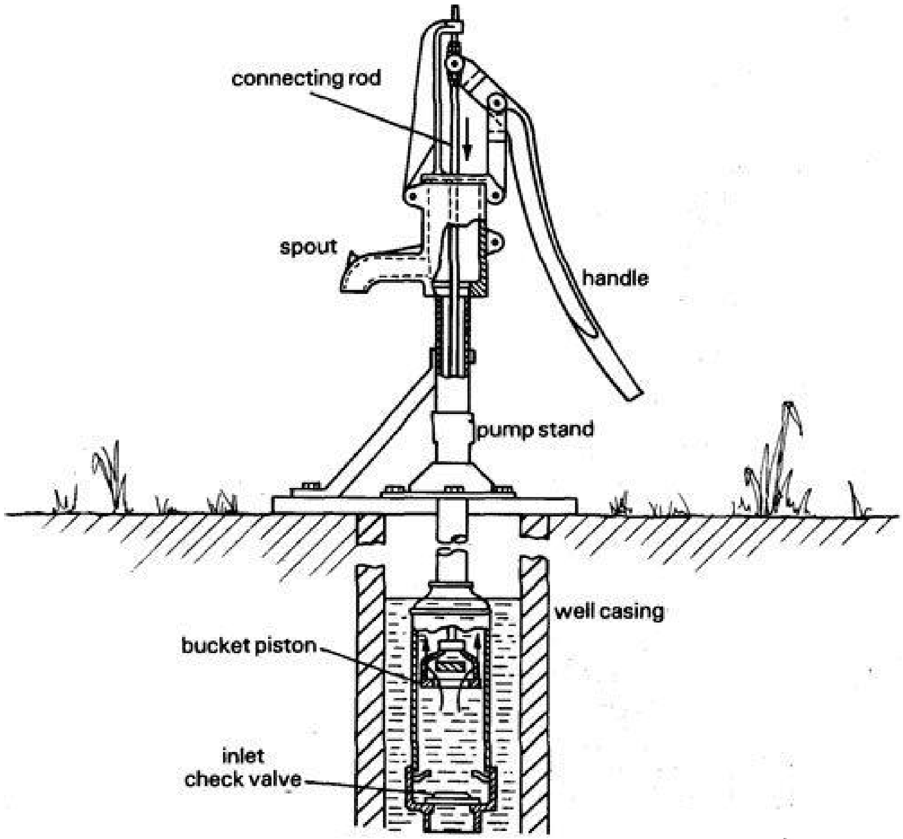


Figure 4: Water well head pump schematic [9]

The schematic in Figure 4 shows that the basic working principle of the water well head pump is the same as in a modern sucker rod pumping system. The handle works as the walking beam, the connecting rods function as sucker rods and there is a downhole pump composed of a bucket with an inlet valve (barrel with standing valve) and a bucket piston (plunger with a traveling valve).

This basic principle was adapted and automated subsequently in the last 160 years. In 1925 Lufkin designed the principle of the counterbalanced pump of today. In Figure 5 the detailed parts of the system are shown.

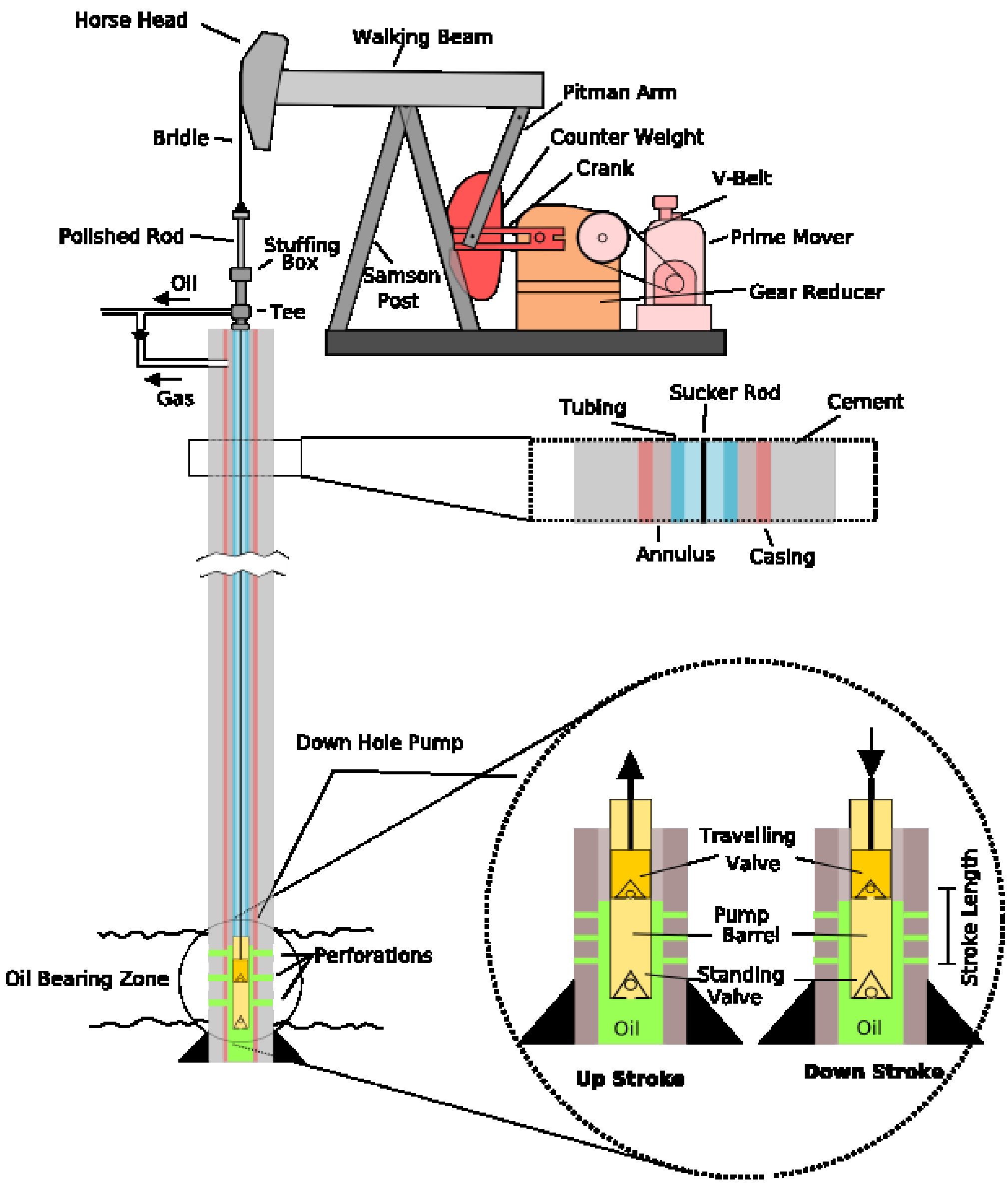


Figure 5: Pump jack schematic [10]

The working principle has the same basis as the water well head pump above but is more complex and versatile. Over 160 years of development went into the design of surface and downhole components and into improving their efficiency. But the main working principle has never changed. Even the design of the downhole pump is more or less still the same as it was nearly one and a half centuries ago in a water well. The system can be split in two main parts, one above ground and one below ground.

1.1.5.1 Surface System

A pump jack is a familiar sight today. If there is any movie that covers the USA and shows impressions of the landscape, there is a good chance one can see these lifting devices. But there is no need to cross the Atlantic Ocean to see these landmarks; while driving through the Vienna basin or other parts of upper and lower Austria they catch one's eye.

Figure 5 shows a very detailed picture of the pump jack and how sucker rod pumping systems work above and below ground. For the power supply of the pump jack three different options exist. Gas engines, diesel engines and electric motors are used for this purpose. Most commonly an electric motor is used today because it is easy to maintain. Additionally, it operates silently compared to gas and diesel engines as well as more environmentally friendly and more versatile in handling especially changing speeds. Also the remote control capabilities are better. The other two power supply options are used when there is no electric power supply or the local electric grid is not stable enough.

The motor unit itself is called the prime mover. Its power is transferred to the crank through a gear reducer and a belt. These components alter the rotational speed and torque of the motor depending on the requirement. On the crank the counterweights are seated and the two pitmans are connected. Both can be connected in several points depending on depth of the pump, desired stroke length, weight of the string and fluid column. A deeper well with a deeper sitting pump or heavier fluid requires heavier counter weights or a different location further away from the crank. The stroke length also depends on how far the pitmans are located away from the crank. Through the equalizer bearing the load is transferred to the walking beam, which rests on the Samson post. The Samson post itself supports the whole load. These parts are connected through the saddle bearing. On the other end of the walking beam is the hoarse head attached. Over the wireline hanger and the carrier bar it is attached to the polished rod, which goes through the stuffing box and the tee into the well itself. [10]

1.1.5.2 Downhole System

On the lower end of the polished rod sucker rods are attached. Sucker rods are 25 to 30 feet long and screwed together to connect the downhole pump with the surface equipment, to transfer the load and lift the fluid. There are various sizes available depending on the depth and subsequently the load applied to them. There are rod guiding systems commonly applied, too. The aim is to minimize wear of the rods and the tubing. When there are slight bends in the system the rods grind on the same position up and down wearing it out until there is a hole in the tubing or a worn rod snaps in two pieces. Therefore, polymer elements are placed on the string in defined distances to guide the rod and keep it in a central position.

The downhole pump at the lower end of the string consists of the barrel and the plunger. They are placed below the fluid level. Both have a ball check valve on the bottom which is actuated by the fluid load. This means the fluid is conveyed to surface periodically. There are different versions of the barrel-plunger combinations, most commonly the standing barrel below and the moving plunger above or basically inside the barrel like illustrated in Figure 6. Like the functioning principle the composition is shown in this illustration. The traveling barrel is connected to the sucker rods and moves up and down periodically. During the uplift the valve of the plunger is closed and lifts the fluid to surface. During the stroke the lifted volume is determined by the diameter of the barrel and the height of the stroke. While the downstroke takes place the standing valve is closed and holds the fluid level and the valve on the plunger is open to fill it up again. After that the cycle starts over again. [10]

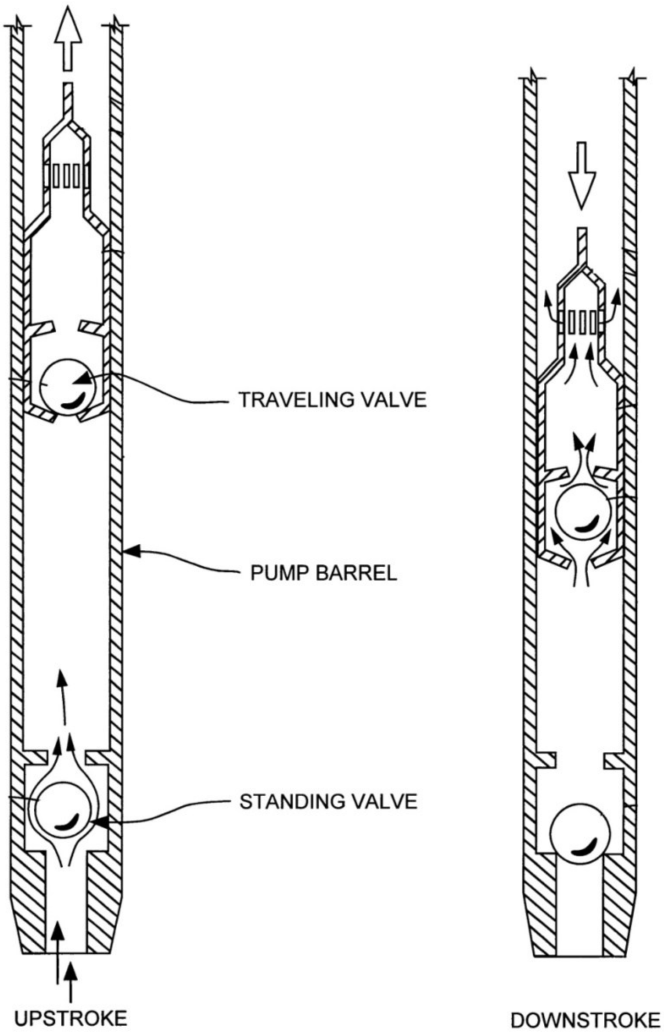


Figure 6: Illustration of a downhole pump [11]

In Figure 7 a schematic overview of a ball check valve, as it is mounted in the downhole pump, is shown. The ball is lifted when the pressure below the ball is higher than above it. The fluid in the borehole, if being oil, can be considered incompressible for the purpose of explaining the principle. During the downstroke the lower valve is closed and the upper valve open. The very beginning of the downstroke is at the upper dead center. At this point the lower valve closes and supports the fluid column. The upper valve opens as soon as the pressure in the pump exceeds the pressure of the resting fluid column above.

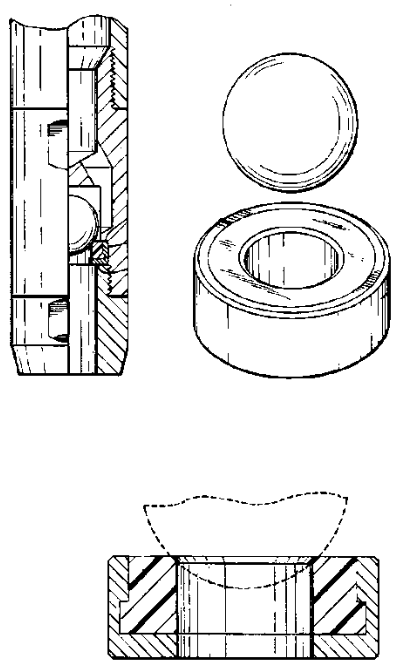


Figure 7: Check valve in downhole pump [12]

Various problems can arise from this working principle. If the fluid is compressible the time the upper valve opens can be delayed. This will cause the effective stroke to shorten. Gas is often present in a reservoir or in solution in oil. When the reservoirs are getting older the pressure drops and gas, which earlier was stored in the oil, gets free resulting in a gas oil mixture. Due to previously mentioned facts the pump valve opens later. It opens when the pressure of the compressed gas is equal to the pressure of the fluid column above. This specific problem is called gas locking and occurs when working with sucker rod pumps. If it gets too severe a workover is necessary which can lead to the abandonment of the well if it is not financially feasible any more.

1.2 Dynamometer Cards

Problems arising in the pumping system are hard to spot on surface. Therefore, dynamometer cards have been developed. These so called surface cards are recordings of a dynamometer, which is mounted at the polished rod and shows a graph of the polished rod load vs the polished rod position. The point of interest however is downhole where the downhole card is located which normally is calculated via a wave equation. To map the influences between the downhole pump and surface this mathematical approach is used. This clearly is not accurate because there are too many unknowns in between. These cards have to be interpreted. There are characteristic shapes based on what is happening. The so resulting card is very useful in spotting problems early on but it has said limitation in accuracy. The problem is that normally only a surface card is measured at the polished rod and the downhole card is calculated. This means an error is introduced. Measuring a true downhole card provides obviously the better dataset but is also much more expensive to do.

Figure 8 gives a detailed insight referring to this measurement. The graph on top shows the load and position of the polished rod in light blue; the surface card and the downhole card in green. The surface card is a parallelogram tilted to the right in an ideal case. The tilt comes from the fact that the rods are stretched at the beginning during the loading of the string. The position 1 correlates to the beginning of the upstroke where no load is applied to the string. Position 2 is after loading the string and stretching it. From 2 to 3 the actual lifting is done. This is the part where fluid is brought to surface. 3 to 4 is the unloading of the weight from the string and the beginning of the down stroke. The now closed standing valve takes over the load of the fluid column. From position 4 back to 1 the downstroke is happening, filling the downhole pump again. [13, p. 2]

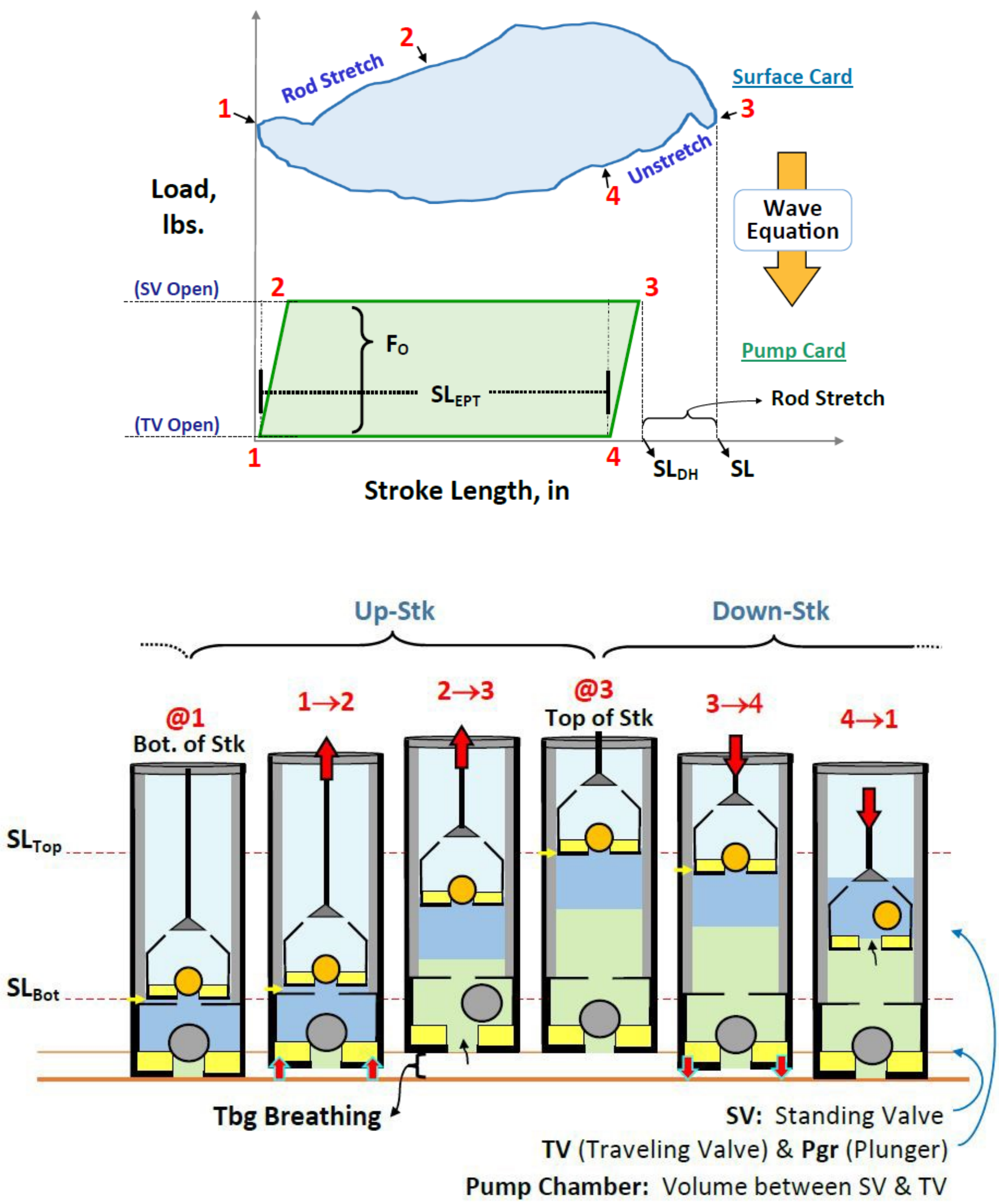


Figure 8: Explanation of dynamometer cards [13, p. 2]

If there is something wrong during operation, for example gas interference, the card is miss-shaped. For the polished rod load gas in the pump means that the load is not released from the plunger at the beginning of the down stroke. It decreases gradually when the gas is compressed until the valve opens and the pressure is released completely. This is visible on the card because it does not move on the upper right part downwards parallel to the part left but dents inwards instead. (Figure 9) [13, p. 2]

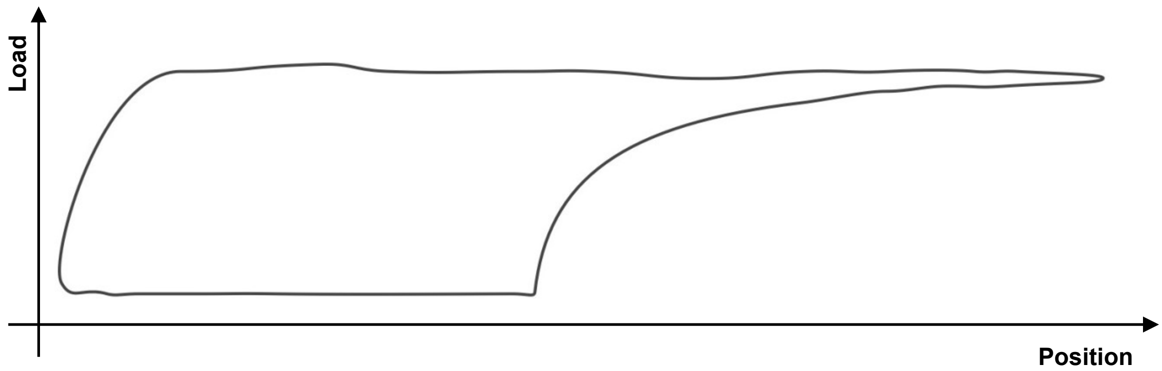


Figure 9: Dynamometer card with gas interference [13, p. 2]

This interference is a quite common issue to encounter during the life of a well. The discussed problem happens most likely at the end of the life of a well if the pump is not designed properly. It can happen prematurely because of oversized pumps or too fast pumping. It can lock the pump or decrease the efficiency to a point where a workover is not avoidable anymore. When this point has been reached the well has to be abandoned. By the development of the sucker rod anti buckling system (SRABS) an attempt to gain efficiency and to prolongate the lifetime of artificial lift systems was done.

1.3 SRABS

SRABS stands for sucker rod anti buckling system. As the name suggests it was developed to prevent buckling during operation in sucker rod strings. The sucker rod string itself is thin and prone to buckling. Buckling is the deformation of the rod under compression from straight to a sinusoidal or helical shape in the tubing. Normally sinker bars are placed on bottom of the string before the pump to get most of the string in tension and prevent buckling. But the lowest part is still in compression. Also depending on pumping speed the plunger is forced down against the fluid in the downhole pump and the string is more prone to buckling.

Buckling is one of the major reasons for tubing leaks and fatigue failure in sucker rod pumps. The SRABS system avoids compressional loads almost in the entire string, achieved by a new design of the standing valve and the possibility to put weight below the pump.

The mean time between failure (MTBF) of the system is increased and stretches therefore the workover intervals needed which means the costs come down for the artificial lift system and it has an economic benefit.

The SRABS system can be applied with every existing sucker rod pumping systems. It is a different downhole pump assembly. The working principle is that due to the fact that the string can be held under tension the pumping speeds can be increased without the risk of buckling on one hand and the fatigue and tubing leak issues are held back on the other hand.

The major difference to the conventional system is the possibility to hang weight on the sucker rod string below the pump and thus shifting the neutral point of the string below the pump. Usually the plunger is pushed into the barrel and in this system it is pulled through the barrel. So it minimizes wear in the pump components and gains efficiency.

To make SRABS possible the design of the standing valve was revised. At first the valve is above the traveling valve. To do so there has to be a connection through the valve to the system below which is achieved by a ring shaped valve body rather than the usual ball shaped one. So it allows the sucker rods to pass through the valve system. In Figure 10 a ring standing valve is shown. The red part is the moving part, which is ball shaped in a standard sucker rod pumping system. The grey part is the valve seat. The seat is more or less the same as in the usual ball check valve. The red ring in the SRABS is much longer because it has to seal towards the rod passing inside and the fit cannot be too tight to avoid high friction. To keep the slippage level low nevertheless the valve must have 150mm of contact to the rod in the middle. [14]

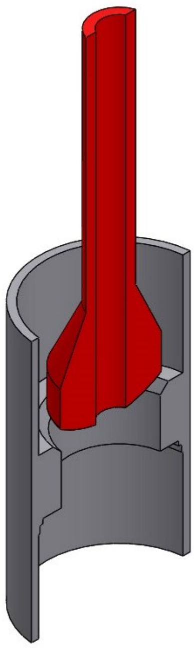


Figure 10: Cut through the standing valve [14]

The plunger with the ball shaped check valve looks mostly the same as the usual design. They are mounted upside down with the valve turned around to still work in the proper design. This means the valve is on top of the plunger rather than at the bottom.

At the bottom of the plunger sinker bars are mounted. Sinker bars are basically heavier, bigger sucker rods and normally mounted directly above the downhole pump to help to keep most of the string in tension. In the SRABS they are mounted below the pump and keep the whole string above the pump and the pump components themselves under tension. Below the pump the forces are much smaller than above because no fluid pressure is acting on the string during the down stroke and filling of the pump. So there is no issue of buckling in the parts below the pump and the pump itself is above the neutral point.

In Figure 11 a cut through the complete assembly is shown. In the following the illustration will be explained from top to bottom. The green parts in the very top are rod guiders to keep the rod central. The red part is the ring valve of the standing valve which is sitting in its seat depicted in grey. Below that the string is attached to the traveling barrel. On top of it the traveling valve, a standard ball check valve is mounted. The traveling barrel continues below and the sinker bars are screwed in at the bottom. [14]

Figure 11: Assembly of a SRABS pump [14]

1.4 Problem Definition

Gas interference is a major issue in sucker rod pumping systems. The end of a well's life is often heralded in by rising amounts of gas in the pump or fatigue issues. When gas starts to get in the pump it is nearly impossible to get rid of it again. Solving this issue could mean to prolongate a well's life and therefore produce more oil. At a time when oil prices are low it is even more necessary to squeeze out the maximum of an existing well without having the need to invest. The current approach to this problem is to work with downhole separators. These are functioning wells but their major disadvantage is that they need to be implemented from the beginning and when gas gets in the pump it never gets out again.

Desirably there would be a way to pump off the gas and continue working with the chosen assembly without needing a workover which is the aim of this thesis to show possible answers to this problem. Based on the SRABS the necessary adaptations are shown and compared to each other.

When working in such environments it is critical to get reliable information on how the downhole equipment is behaving meaning detailed measurements downhole. It is difficult to measure data downhole caused by the limited space. Normally in a sucker rod pumping system there is no power source and no connection to get the data from downhole to surface. To get power downhole is challenging and expensive. Putting a cable in the hole means that the whole installation process takes much longer and there is the possibility to damage the cable whilst running in hole. Batteries in the wellbore are possible and a source often used in LWD and MWD tools during a drilling operation where it needs to last only a few days. The high temperatures and long duration are unfavorable for batteries. An autonomic system downhole that supplies itself with energy, measures and saves the data, like temperature, pressure and load, over the whole operation, for 10 or 20 years would be a great opportunity to get insights in the life of a pump and the struggle in the end. The fact to see what happens leading up to problems and failures, stored in a data set that is obtained during a workover to learn from the detailed data and avoid problems in the future, would be a great benefit.

2 Valves

“A valve is a device that regulates, directs or controls the flow of a fluid by opening, closing, or partially obstructing various passageways.” [15]

To tie up with before a major part of all sucker rod pumping systems is the downhole pump. This is a set of valves consisting of two check valves in a row that takes the fluid to surface. One common problem is that gas, which enters the space between the two valves, hinders the upper one of the two valves in opening at the beginning of the stroke. Now the question is if there are any other options on the market regarding to valves that can possibly be used in such an application as the downhole pump. Valves can be sorted by their build or by their application. Ball check valves used in common sucker rod pumps cannot be controlled directly by the motion of the string itself. In the following section all common types of valves in use today are mentioned and their advantages and disadvantages will be discussed. Implementation possibilities will be contemplated.

Valves are also used in various other places, for example in the pipeline system from the well to the production or storing facility. When pressure management like choking is done, valves mostly are used for that purpose. The Christmas tree consists of valves to divert or regulate flow.

2.1 Functions and Types

Valve types can be subdivided into groups based on function. These groups and their containing valves are as follows:

- Primarily shut-off valves:
    - Ball
    - Butterfly
    - Gate
    - Plug
- Regulation of pressure and flow valves:
    - All shut-off as listed above
    - Globe
    - Piston
- Non-return valves:
    - Swing check
    - Axial flow check
- Safety valves:
    - Spring loaded
    - Diaphragm
    - Piston

2.1.1 Ball Valves

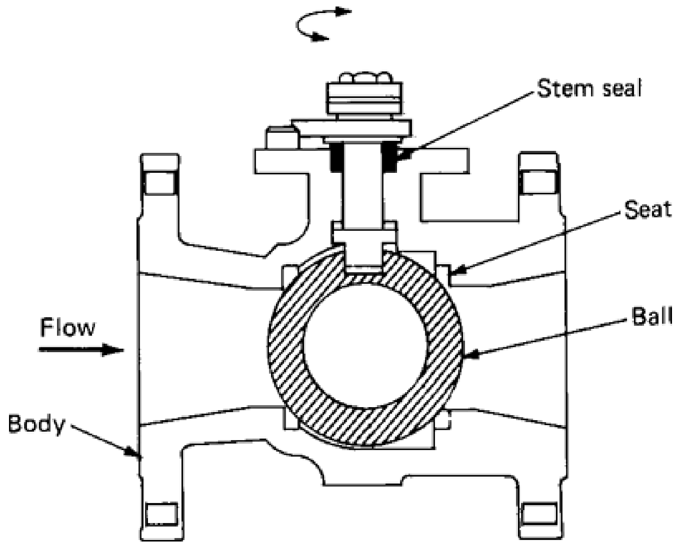


Figure 12: Ball valve [16]

The first category that is depicted here are ball valves. These types can be found under the category of quarter turn valves. Quarter turn means that 90° turning of the stem changes the flow path from fully open to fully closed. The advantage hereby is that shutting in a flowline can be done very quickly. Ball valves are available in full bore and reduced bore designs. Full bore means that the flow is not obstructed when the valve is open. Reduced bore is a smaller diameter of the valve compared to the pipe. In a ball valve there is no obstruction of the flow path and that means it is pigable (Pig: Equipment send through a pipe mostly for cleaning and measurement purposes). The fact that there is no obstruction has the positive effect that the pressure drop across the valve is very low compared to other solutions. The availability of ball valves in different sizes is great and they are relatively cheap, too. The downside of the design is that ball valves are not very well suited for throttling applications. Figure 12 shows the image of a ball valve.

The main usage of this type of valve is to shut down flow. Households use water hoses with a ball valve at the end. When turning the handle 90° it fully opens or closes.

Looking at it from the perspective of downhole applications the fact that the operating mechanism is on the side and sticks out of the valve body is an issue. For the usage downhole the construction height of this valve is too big. The space to the sides is very limited underground and there is no space to implement big operating mechanisms. [16]

2.1.2 Butterfly Valves

A butterfly valve also belongs to the quarter turn valves. These valve types are mainly used for stopping, regulating and starting fluid flow. Butterfly valves are considered to be the most economic and reliable types of valves. The design is easy and consists of a plate that obstructs the flow path. A stem in the middle of the valve enables it to turn around this axis and gives way to the fluid. The downside of this type of valve is that at any given time a stem is standing in the middle obstructing and distorting the flow. The footprint is smaller compared to ball valves because there is no need to make room for the excess parts of the ball. As the control mechanism is also attached to the side of the valve body there is no possibility to implement this downhole. Figure 13 shows an image of a butterfly valve. [17]

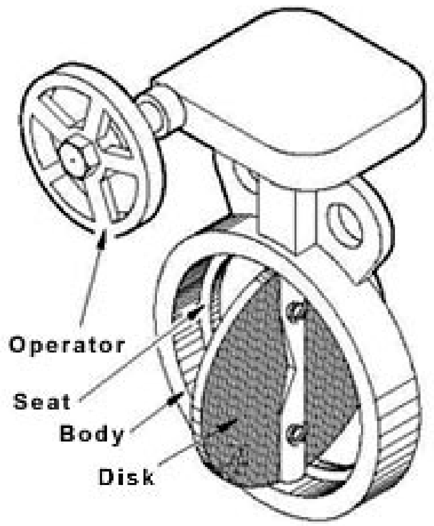


Figure 13: Butterfly valve [17]

2.1.3 Gate Valves

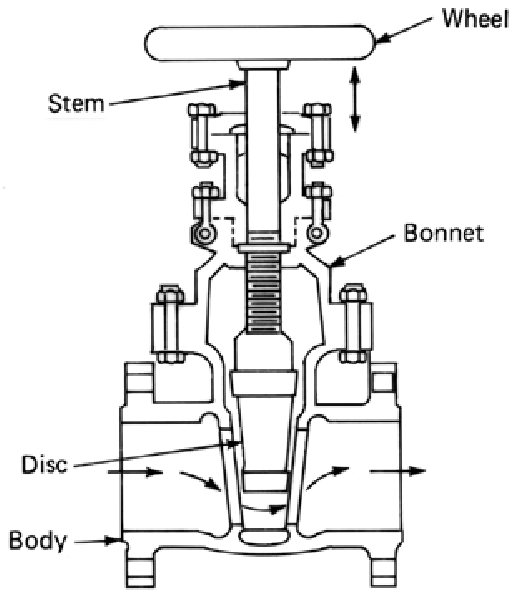


Figure 14: Gate valve [18]

Gate valves do not belong to quarter turn valves. They have a disc shaped closing element that is forced in the way of the fluid from one side, mostly the top of the piping. Depending on the ratio several turns may be needed to open or close the valve to its full extend. This type of valve can be used for throttling applications. On the other hand, there is an open body cavity to fit the gate which can be filled with solids hence impeding the function. The gate itself in most cases is wedge shaped. As in ball and gate valves, the problem of the mechanism which controls the valve is that it is sticking out to the side. A classic gate valve is shown in Figure 14. [18]

But there is a special form of axially operated gate valves. They work by two similar, overlaying discs which can be rotated in respect to each other so the holes are covered, incrementally open or full open. The downside is that there is always quite a lot of material obstructing the flow path. The upside is that it can be controlled by a mechanism mounted in flow direction which makes it possible to implement downhole regarding to space. Figure 15 shows the discs, which are in the flow of such a valve system. [19]

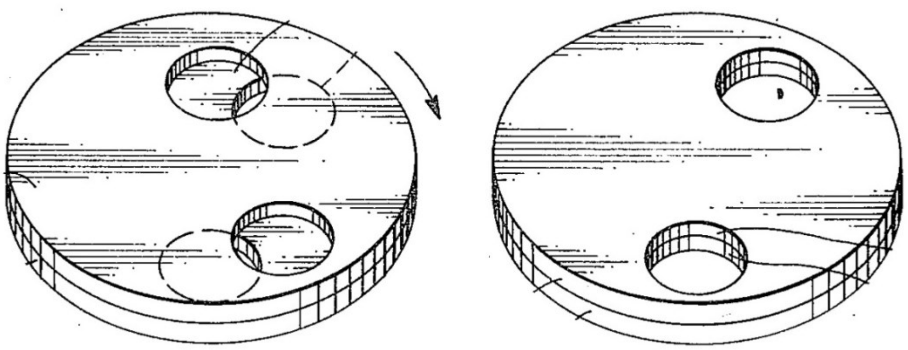


Figure 15: Discs of a choke valve [19]

2.1.4 Plug Valves

Cocks, that is an additional name for plug vales, are normally used for the same applications as gate valves. Their advantage is that they are able to perform a quick shut off. Flow regulation is not their main scope of application but there are some special designs particularly for gas flow throttling.

Their main field of implementation is in steam, water, oil, gas and chemical liquid service in piping and surface facilities. But they are not used in sucker rod pumping systems or any other lifting equipment. [20]

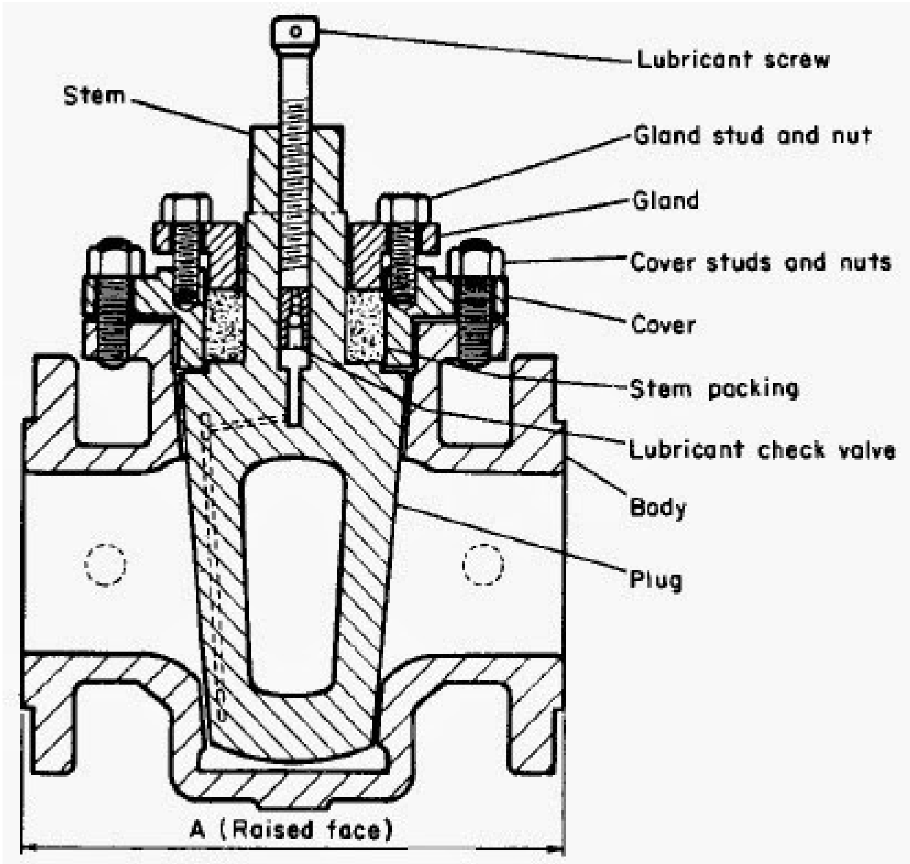


Figure 16: Plug valve [20]

2.1.5 Globe Valve

Globe valves got their name from the shape of their valve body. Classic valves are designed with a round and globular shaped valve body. There has been a development in recent years by changing the shape of the valve body but they kept their name. Globe valves need several turns to be opened and closed depending on the ratio of the stem similar to gate valves.

Globe valves have excellent and precise throttling capabilities for high pressure systems but on the other hand they have low flow coefficients and a longer opening and closing time caused by the many turns needed to fully open or close the valve.

Globe valves are well suited for systems, which require frequent stroking, vacuum systems, and systems that have a wide range of temperature extremes where they can be operated. Figure 17 shows the image of a nowadays currently used globe valve. [21]

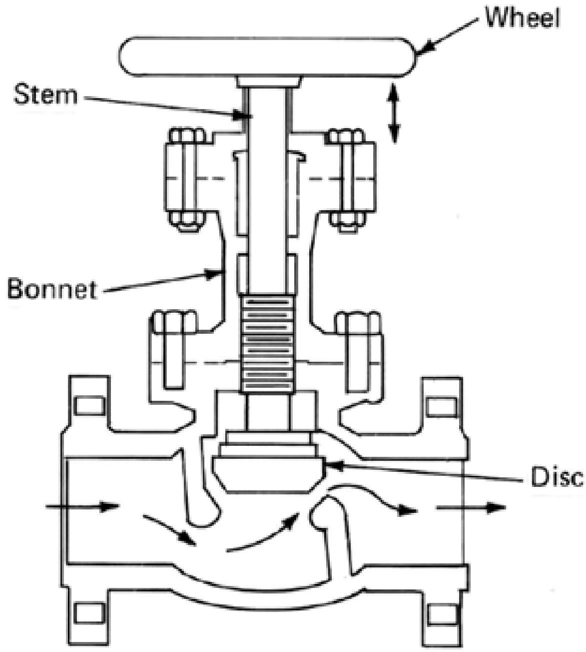


Figure 17: Globe valve [21]

2.1.6 Piston Valve

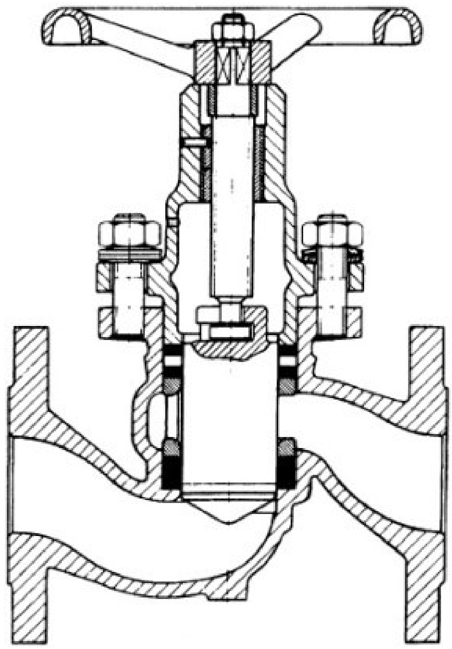


Figure 18: Piston valve [22]

The piston valve works similar to the globe valve but the difference is that a piston shaped sealing element intrudes or withdraws from a seat bore. The seal is achieved between the lateral piston faces and the bore. Flow cannot start until the piston is fully removed from the bore. Any erosion damage therefore occurs away from the seating surface. When closing the valve the piston normally wipes away solids that have been deposited on the seat hence not eroding or damaging the sealing area. Therefore, it can be used if solids or fines are present in the flow. [22]

2.1.7 Check Valve

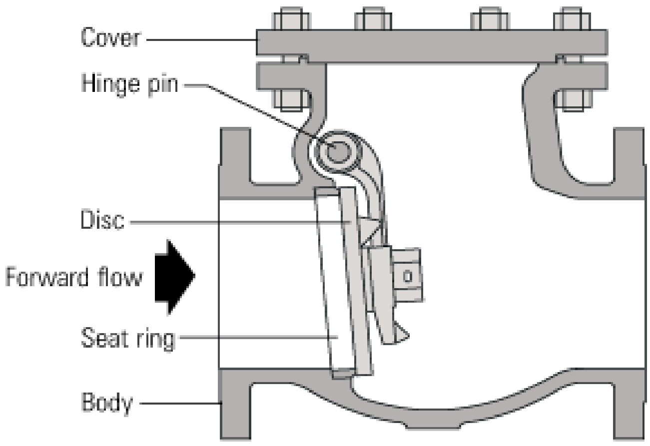


Figure 19: Swing check valve [23]

A check valve allows the flow only in one direction. It consists of a flap or disc with the same diameter as the bore of the flow path which hangs from the top in the flow path. The pressure provided by the forward flowing media lifts the flap. As a result, the media can flow forward. In the backward direction the flap is pressed on the bore and seals. If there is no flow, the weight of the flap ensures the seal.

These check valves are also used in sucker rod pumping systems. They consist of a ball and a ring seat as shown in Figure 20. Fluid from below is pressed against the ball and lifts it up so the fluid itself can pass. When the flow starts to move in the other direction the ball is forced down against the seal and shuts in the flow. As stated these valves open and close caused by the pressure difference along the valve. If there is gas present it will be compressed before it transmits the pressure. As a consequence, the valve opens at a later point in the working process. Ball valves are most effectively used in vertical flow directions. In horizontal directions the fixing of the ball is more difficult. In that case flaps work better. [23]

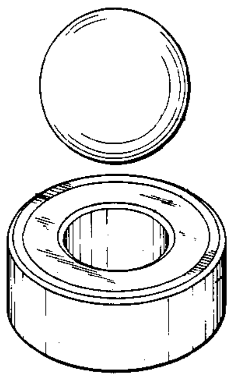


Figure 20: Ball type check valve [12]

2.1.8 Spring Loaded Valve

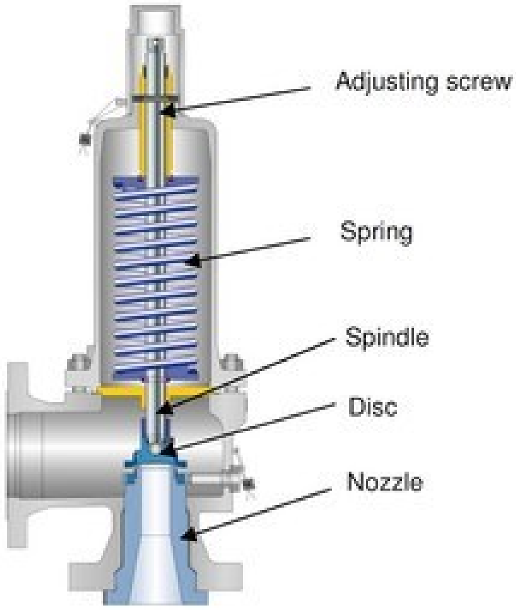


Figure 21: Spring loaded safety valve [24]

In this safety valve the force provided by a loaded spring ensures the closing of the valve. This is done via a helical spring and an adjusting screw. The valve stays closed until the force created by the fluid pressure exceeds the force of the spring. Then the valve opens and reliefs the overpressure to the surrounding environment or a designated pipe. When the pressure has equalized the valve closes again.

The main usage of this type of valve is to protect equipment from experiencing to high loads and avoiding damage, uncontrolled bursts or explosions. [24]

2.1.9 Diaphragm Valve

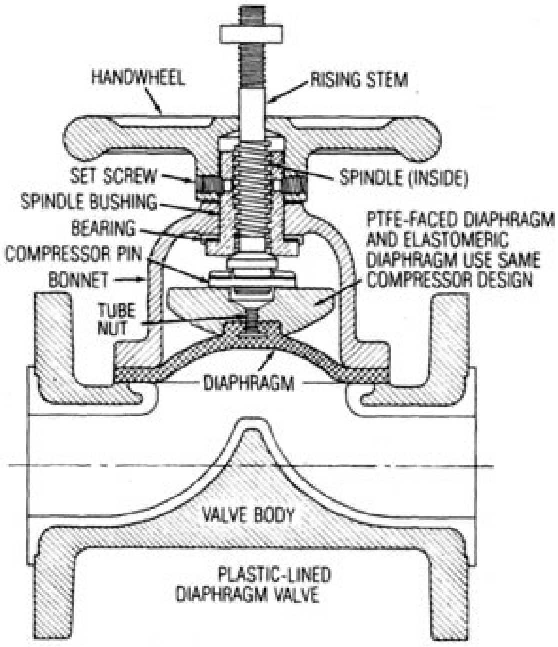


Figure 22: Diaphragm valve [25]

The seal is established with a diaphragm, which is pushed against a seat. A diaphragm is a flexible, pressure responsive element, its purpose is to transmit force to open, close or control a valve. The stem is screwed in and forces the diaphragm into the flow path. One of the benefits of this valve type is that the moving parts are sealed from the flow media. This means there cannot be any debris in the way of the opening and closing mechanism and there is no contact with fluids. There are fluids like H_2S or CO_2 which increase corrosion or destroy mechanical parts. [25]

2.2 Valves Types for SRP Applications

The basic valve type in sucker rod pumps are ball shaped check valves. Two of them are set in a row and open and close alternatingly. This working principle has the downside, that valves are operated by the fluid forces acting on it. In case of gas interference the problem is the pressure difference of the fluid column above the valve and the trapped gas below. This pressure difference hinders the valve from opening. Other valves may have the possibility to be operated independently from the fluid loads.

The main premise downhole is space. Most of the conventional valves cannot be used under this circumstance because there is not enough space to operate them. All stem operated valves, like the quarter turn valves, need the operating mechanism besides the valve.

After comparing all the concepts above, it obviously shows that only valves with a tiny construction and operating mechanism are possible to use. Axially operated gate valves in this regard are the first choice because the operating mechanism can be mounted in flow direction and in it can be linked to the motion of the sucker rod string, too.

3 Valve Re-Design

It would be desirable to find a way to operate the valves inside a sucker rod pump in a manner where they open and close even if there is gas in the pump. Subsequently the gas can be pumped off and the pump can stay in operation. Furthermore, in combination with a variable speed drive it is possible to modulate the speed at the edge of pulling gas with lower risk of locking the pump. This would increase production and efficiency.

The basic idea for the re-design is to use the up and down motion of the rod to actuate the valves. There are different ways to approach this problem. One is to use a set of springs and guiding grooves to actuate axially operated gate valves. Another one is to implement magnets in the string and use their force to operate a smaller valve with the aim of releasing pressure. Both approaches mean significant changes in the SRABS design. A third way is to build a channel into the rod which passes by the valve body. This leaves most of the design in the SRABS as it currently is and adds the capability of releasing pressure differences across the valve.

Following approaches mentioned before will be discussed in detail starting with the axially operated gate valve.

3.1 Axial Operated Gate Valve

This system implements an axially operated gate valve instead of the ring valve. The subsequently following system has the biggest design changes of all the following designs. Furthermore, it is the most complex as well. The benefit of this system is that the standing valve is now opened and closed via the rod motion and no longer via pressure differences. The difficulty is to devise a system that controls the motion. The details of how it works are explained in the next chapter.

3.1.1 Operational Principle

The big changes happen at the standing valve. This, as well as the seat of it, is completely exchanged. The up and downward movement of the string is translated to a slight clockwise or counterclockwise motion of the valve body. To achieve this rotation the rod has a guiding groove on its surface where a pin in the valve body can latch into. The valve has to have one setting during the upward motion and a different one in the downward one. As an example the standing valve has to be open to lift fluid to surface during the upward motion. On the other hand, the valve has to stay closed to fill the pump again in the downward motion. This means the same groove cannot be used for both directions. The valve has to follow some kind of a loop. Therefore, the pin on the valve has to be leaving the groove at some point. When the pin leaves the groove at the top dead center a spring pushes it back into the closed position. After the stroke the pin latches into the groove near the lower dead center of the stroke and at the beginning of the upward motion the valve is forced in the open-position. At the end of the stroke the pin leaves the groove again and snaps back into its closed position. The detailed changes to the design are described below.

3.1.2 Valve Design

The approach of implementing an axial gate valve replaces the standing valve including its seat. The only thing that is staying the same is the length of the tube of 150mm to avoid too much slippage along the valve. Other than that the complete design has been changed.

The former ring that is lifted to allow flow is now a disc that is rotated. The rotation needed to change from the closed to the open position should be small to ensure a quick and smooth operation. 22° of rotation cover the full range in this design approach.

The shape of the cutouts on the valve and seat are trapezoids to maximize the available cross section for fluid to pass. Figure 23 shows a picture of the new gate valve. The design of the valve and seat are the same and the amount of overlap determines if the valve is opened or closed. A benefit for the sealing of the system is that the fluid load pushes the closed valve onto the seat and improves the sealing capabilities. In the open-position the cross section available is larger than in the ring valve system.

Figure 23: Axially operated gate valve

Figure 24 shows the machining drawing of the axially operated gate valve with all detailed information available. The height of the valve is 155mm which gives the same amount of overlap between the rod and the valve to ensure decent slippage protection as the original SRABS. This is done because there is no other sensible possibility to ensure a decent metal to metal seal between moving parts. If the tube is shorter it has to fit tighter to ensure the same seal meaning the friction would rise. The valve consists of a 150mm long tube on top and a 5mm thick disc on bottom. The tube has an outside diameter of 22mm and a wall thickness of 3mm. The disc has cutouts in the shape of trapezoids like mentioned above. The trapezoids are 29mm high and 21° wide. They are not perfect trapezoids because the top and bottom are circle segments and not straight lines. The distance between the cutouts is 24°. The outside diameter of the disc is 60,5mm. The base disc sits in the same valve seat assembly as the ball check valve did before. It is mounted stationary in the tubing. The valve body performs the rotation with every stroke at the upper and lower dead center.

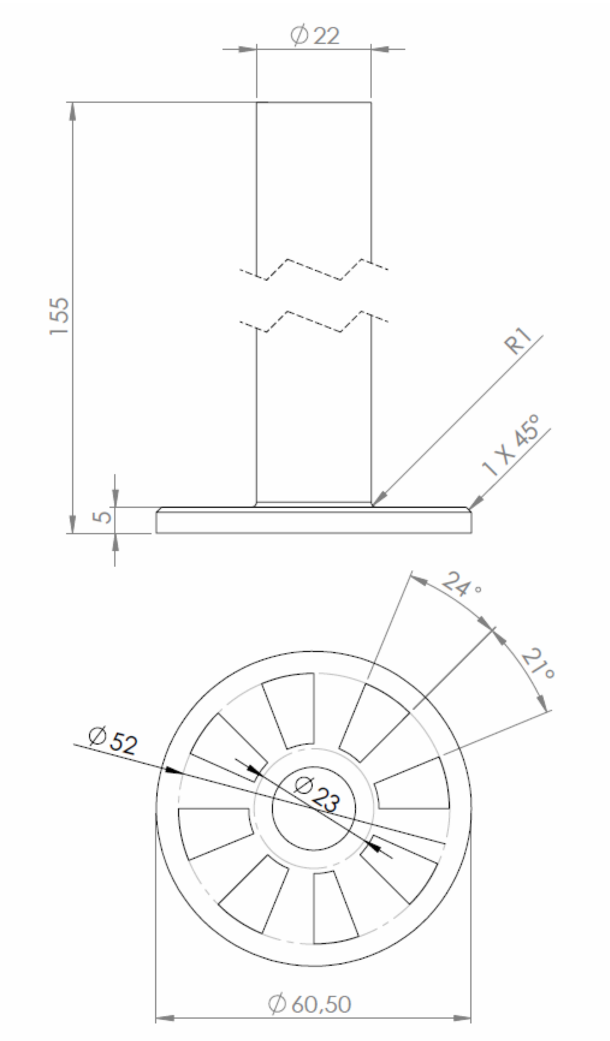


Figure 24: Drawing of the axial operated gate valve

3.1.3 Pin and Groove Design

To perform the rotation of the valve the rod has a guiding groove which grabs the pin at the lower dead center of the stroke. After latching in, the valve is rotated to allow the liquid to pass. The length of the groove needs to be designed to the exact length of the stroke. Otherwise it is not possible for the pin to engage at the bottom and be released at the top. On top the groove just ends 10cm before top dead center and the valve closes as soon as it leaves the groove. On bottom, at the beginning of the upward motion, the groove intercepts the path the pin travels in the closed position and forces it into an open position.

The pin is realized with a spring loaded ball. This has the benefit that if something is broken and the force on the pin is too high it just leaves the groove without damaging the system. The force when the ball leaves the groove is determined by the pre-tensioning of the spring. Figure 25 shows how a cut through the valve body looks like with a spring loaded ball and guiding groove. The part that contains the spring and the ball is mounted on top of the disc functioning as valve. It is obstructing one of the trapezoid shaped openings.

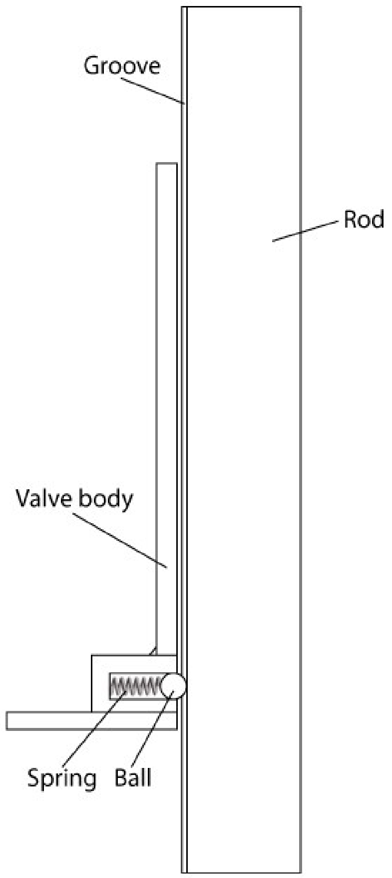


Figure 25: Spring loaded ball in guiding groove

3.1.4 Issues

Slippage is a problem previously addressed. The 150mm high cylinder has the purpose to prevent slippage as good as possible. Due to the implementation of the groove a new path for slippage is introduced and this lowers the efficiency of the whole system. Furthermore, sand in the system can lead to high wear in this area.

Another problem that should also be mentioned is the implementation of springs. In an environment where H_2S, CO_2 and H_2 can occur it is crucial to protect metals like the ones used in springs. Even slight amounts of these chemical compounds can lead to corrosion, hydrogen and sulfur stress cracking. This can result in the failing of the whole system. It is very difficult to prevent these harmful substances from entering a confined space which means the spring is a weak spot of the system.

Additionally, the upper and lower dead center must be known quite precise and they must not change. Like in over and under travel issues this becomes an issue. Otherwise the proper function of the groove and hence the valve cannot be guaranteed.

Very common issues in sucker rod pumping are fatigue failures of sucker rods due to wear resulting from contact with the tubing or reoccurring bending in the same direction. This was improved with the implementation of rod rotators. What is done to prevent these failures is rotating the string slightly with each stroke in one direction to avoid the rod rubbing on the same side on the tubing each stroke. Bending does not occur always in the same direction with rod rotation in deviated wells. Rod rotators keep the wear uniform and extend the time until the rods fail. A downside of the surface actuated valves is that rod rotators cannot be used with this system because the control mechanism has to stay at a defined angle and cannot rotate with the string. This means if the well is not vertical the wear of the rods can become an issue quickly.

The force acting on the rod also can be problematic when opening the valve. At the end of the downstroke the hydrostatic fluid load is sitting on the valve and when there is gas in the pump it has to turn under that load. If there is no gas the closing traveling valve and the beginning upward motion will release the load from the valve and make it much easier to turn. For the case of gas a pressure of about 70bar is assumed. This corresponds with a fluid of sg 0.8 and 900m setting depth (TVD). The pressure acting on the valve is the pressure that acts on the available surface. Pressure equals force per area. So it can be said that force equals pressure times area. The force resisting the turning action is the friction force between the valve body and the seating element. It is determined by the friction coefficient and the normal force. In that case the normal force is provided by the pressure. In the following the formulas are shown.

$$F_N = p * A$$

Where F_N is the normal force, p is the pressure and A is the area. All values are provided in SI base units. For the force resisting the motion the normal force times the friction coefficient μ is calculated. This results in the friction force F_R.

$$F_R = F_N * \mu$$

Due to the fact this is a rotational application the torque is more interesting than the force. To get the torque (T_R) it necessary to multiply the force times the distance it is away from the point of interest. For a disc lying flat on a surface the distance for calculating the torque is 5/7 of the diameter. This leads to a distance of 15.7mm to the groove. Table 1 gives the friction torque to overcome for turning the valve for dry and lubricated surfaces. The produced oil in this case is the lubrication.

Table 1: Force acting on the axial gate valve

Pressure [Pa]	**Area** [m²]	**μ dry**	**μ lubr.**	**F** [N]	**T_R dry** [Nm]	**T_R lubricated** [Nm]
7,00E+06	1,35E-03	1,20E-01	1,00E-02	9468	17,8	1,5

The groove is 2mm deep and the ball moving in it has 8mm in diameter. Via trigonometric functions the rotational torque working on the ball can be translated to the force that is necessary to hold the ball in place. This are 41N for the lubricated case and 491N for the unlubricated case.

3.1.5 Conclusion

The superiority of this system would be the possibility to operate the valve based on the rod motion and not to be dependent on the fluids in and above the pump. This would mean the complete elimination of issues regarding gas in the pump.

The torque acting on the valve is low when the system is lubed and not an issue during the normal operation. When the surfaces are dry the friction is quite high. If solids or fines enter the space between the valve body and the valve seat, the friction would rise and most likely destroy the system. This is a big problem in the long run regarding reliability. Sand is often present in sucker rod pumping and even little amounts can destroy the system. If the torque of turning gets too high the ball leaves the groove and the valve does not operate anymore. It is very difficult to implement a direct control mechanism to the rod of the SRABS pump without sacrificing its reliability.

Furthermore, a high slippage rate is introduced with the groove because nothing can be done except to keep the groove tiny and shallow. But a certain depth is needed because otherwise the spring loaded ball will slip out of the groove and the standing valve will stay closed. This slippage rate contradicts the efforts with the 150mm long shaft to keep slippage as low as possible.

In the worst case if the system fails the valve stays closed and in the upstroke the pressure rises in the pump until something is going to break. Therefore, another simpler approach is the implementation of magnet operated valves, to equalize pressure, that are mounted in addition to the currently used SRABS.

3.2 Magnet Operated Secondary Valve System

Because of the difficulty of implementing a direct control mechanism an indirect one is devised with the intention of solving the issue of getting rid of gas in the pump and keeping the slippage as low as in the SRABS before and not sacrificing reliability.

The purpose of a secondary valve system inside the standard valve body of the SRABS is to establish a pressure connection between the fluid column to surface and the content of the downhole pump. It releases the force holding the valve closed and therefore resolves the problem of causing the valve to open too late because gas is in the pump. The gas can escape from the pump and is produced to surface with the fluid.

3.2.1 Operational Principle

The underlying problem is that gas which is trapped in the pump is causing the standing valve to open too late and reducing the produced volume per stroke. The magnet operated secondary valve system is an adaption of the currently used system. The valve body has a revised design with a channel added inside combined with a valve system that can open and close the channel mentioned before. At the lower dead center of the stroke the standing valve has to open and the traveling valve has to close. The ball and ring shaped check valves operate based on a pressure difference. When the pressure in flow direction is higher above the valve than below, it is held shut by the pressure difference. In case the fluid pressure is higher below, the valve opens and allows the media to flow. The magnet operated secondary valve system establishes a pressure connection at the lower dead center of the stroke to equalize this pressure difference in case there is gas accumulated in the pump during the stroke. This will allow the valve to open in case more pressure is present above the valve, because it can be equalized.

The valve operation is done via a magnet. The magnet is inside the rod that goes through the center of the pump connecting the traveling barrel. The location is at the exact position of the valve body at that point in time when the system is at its lower dead center. The length of the magnet determines how long the valve stays open. Due to the fact that the metal parts in the SRABS are magnetic, all parts in a radius of 4cm around the rod should be symmetrical to avoid additional forces resulting from the magnetism. Nearly all parts of a downhole pump are rotationally symmetrical anyway so this is not a big issue.

In the valve body itself a cylinder obstructs the path of a connection channel between above and below the standing valve. This cylinder is held in the closed position by a spring. When the magnet, which is placed in the rod, enters the valve the cylinder is pulled into the magnetic field and opens against the force of the spring. As long as the magnetic field is present the valve stays open and allows a pressure communication through the standing valve. This allows for an equilibrium of pressure and the valve can open normally during the beginning of the up stroke. Gas that starts to accumulate in the pump is vented during every stroke and cannot accumulate to higher volumes.

3.2.2 Valve Design

The adaption process of the valve starts with the normal SRABS standing valve. Two channels are drilled on one side of the valve. At first a smaller vertical channel connects the area above and below the valve and will later establish the pressure connection, which will allow fluids to travel past. Then a bigger channel is drilled perpendicular to the first and intersects it. In this channel, which does not penetrate through the whole body, the valve mechanism is implemented. A spring is entered at first and afterwards the cylinder that acts as closing mechanism is added. A threads is cut at the outside end of the bore and a screw is set in it. This screw pre-tensions the whole system.

Figure 26 shows a cut through the valve body and depicts all parts. When the magnet moves past, the cylinder moves towards the center of the valve and opens the channel to establish the connection.

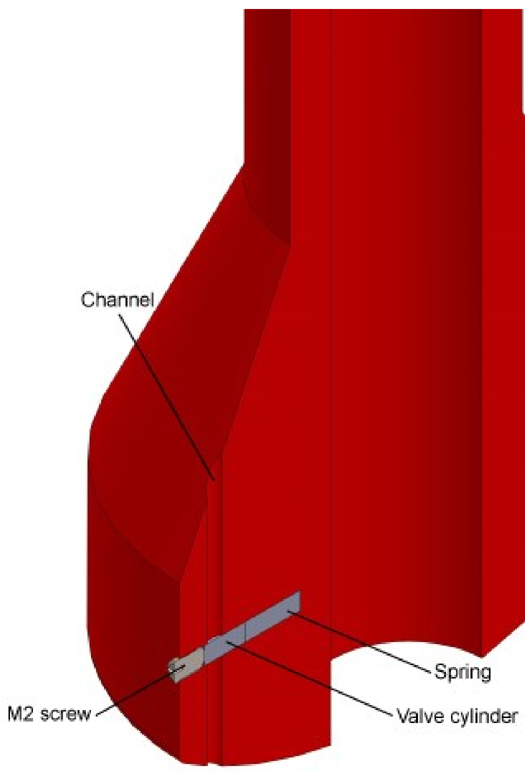


Figure 26: Cut through the valve body

To go into further detail in Figure 27 the manufacturing drawing is shown. In this document the channels in which the valve mechanism will be implemented are depicted. The vertical connection channel is 1.5mm in diameter and penetrates the whole valve body. It is located 17.5mm away from the middle axis. The horizontal bore, which is 1.8mm in diameter, is exactly at the same spot related to the first bore and intersects with it. The inside is machined to Ra 0.2µm to get good sealing capabilities and low friction during operation. The location of this vertical channel is 14mm from the bottom of the valve body and its depth is 13.5mm. There is a threading in the beginning, which is 4mm deep and a standard M2 thread. The screw sitting there has the task to tension the spring 0.5mm to ensure the system cannot move on its own. The aim is to get the mechanism as close as possible to the center of the valve body to lower the distance to the magnet as much as possible. A smaller distance to the magnet ensures that the force is sufficient to operate the valve.

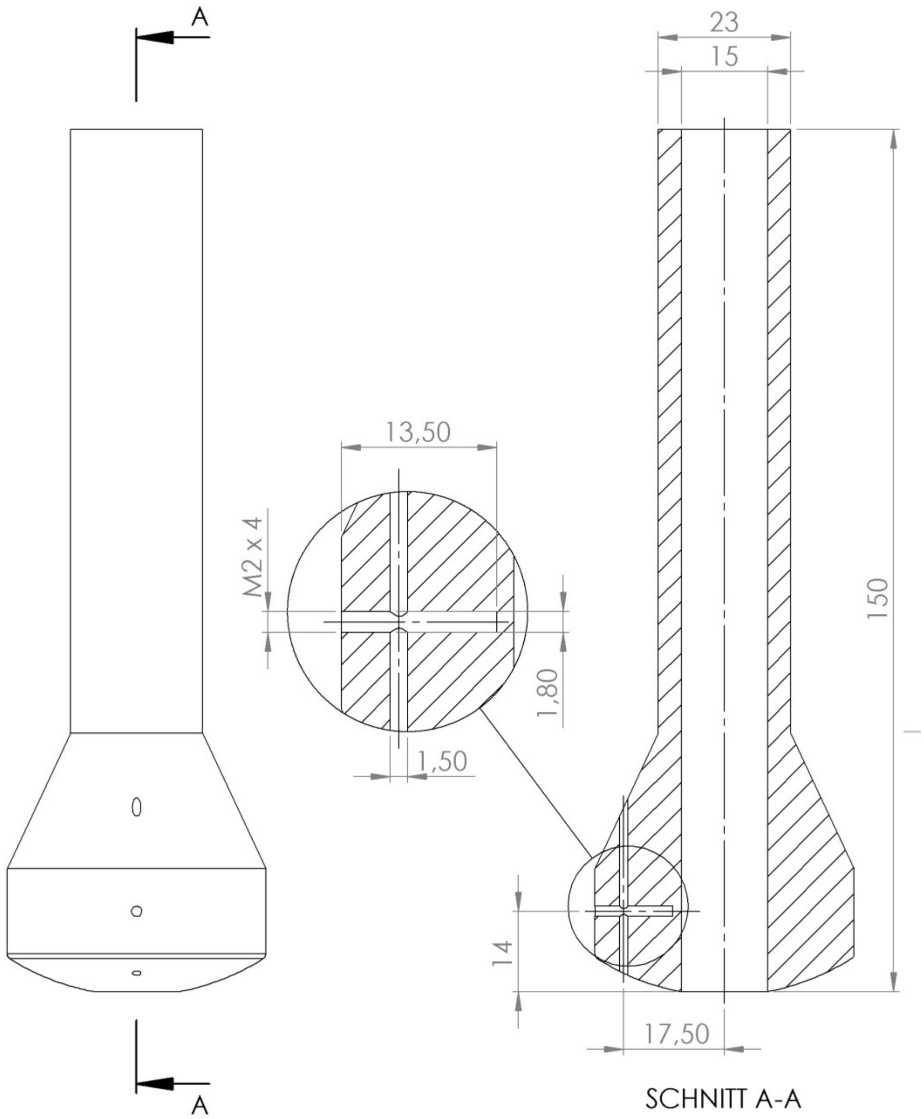


Figure 27: Plan of the adapted valve

The main detail-parts of the system are the spring and the cylinder. The spring used for this purpose is shown in Figure 28. The main dimensions at rest are 7mm in length and 1.7mm in diameter. The static force rating is 0.32N/mm and the maximum force the spring provides is 1.3N at which the spring is 4mm compressed and the windings will touch each other. The 0.18mm thick rod makes a total of 11 windings. [26]

Figure 28: Spring for secondary valve system [26]

The second detailed part is the cylinder, which is shown in Figure 28. The diameter is 1.8mm and it is 4mm long. The cylinder is made of out of the same material as the rod to ensure the same resistance against corrosion. The material is induction hardened stainless steel (42CrMo4V). The surface is machined to Ra 0.2µm to minimize friction during operation and obtain good sealing capabilities. The steel is getting magnetized when it enters a magnetic field and is drawn into it.

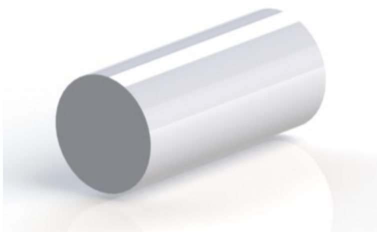


Figure 29: Valve cylinder

3.2.3 Rod Design

The rod design as it currently is, is based on a hydraulic cylinder from the company "chromsteel", which is located in Romania. Unfortunately, there is no hollow pneumatic cylinder with the same outside diameter as used in the current SRABS system of 15mm in their product portfolio. However, they offer a 16mm outside diameter version with an inside diameter of 7mm. After consultation with the Montanuniversität Leoben, where the SRABS test stand is located, it came to knowledge that there is a second SRABS test system with a 16mm diameter rod with all the belonging equipment, too. This information gives the option to work with a 15 or 16mm outside diameter rod in the planning. Because the previous valve design is based on 15mm inside diameter the following rod is also continued to be based on 15mm outside diameter.

There is the general possibility to take the cylinder that is currently used and drill out the inside until the required depth is reached or to order a hollow 16mm rod. The first choice would mean one meter has to be drilled into the rod from the upper side. With the equipment located at the University for test-purposes it would be easier to take one of the existing rods and drill out the inside. This prevents the costly order of a hydraulic rod and also saves time because it takes much less time to drill out the rod than waiting for the delivery of the ordered rod.

The channel drilled into the rod accommodates the magnet, which needs to be placed 800mm away from the upper end of the rod to be at the right position to actuate the valve. The magnet should be about 200mm high to ensure a sufficient opening time of the valve. Due to the fact that metals are drawn to the poles of a magnet the valve will close shortly when the valve is at the middle of the magnet. Magnets in this length need to be specially produced for this purpose, therefore a shorter magnet with the same properties can be used for a trial run of the system to proof the working principle. The magnet required is a neodymium magnet, which is strong and readily available on the market. In Table 2 the detailed data of the magnet properties is shown.

Table 2: Data sheet of the properties of the S-06-25-N magnet [27]

Position	Type
ID	S-06-25-N
Material	NdFeB
Type	Stick
Diameter	6.35mm
Height	25.4mm
Tolerance	+/- 0.1mm
Direction of magnetism	axial
Coating	nickel-plated
Production	sintered
Magnetizing	N42
Holding force	15.7N
Max. temperature	80°C
Weight	6.1134g
Curie temperature	310°C
Remanence	1.29-1.32T
Energy product	318-334kJ/m³

Figure 30: Picture of the S-06-25-N magnet [27]

3.2.4 Calculation

The different forces acting on the valve system are forces provided by the spring that holds the valve cylinder in the closed position on the one hand and the fluid column that sits on top of the valve on the other one. These forces have to be overcome by the magnetic force applied to open the channel.

3.2.4.1 Force of the Spring

The force of the spring is working against the direction of elastic deformation of the spring because it has the tendency to go back in its original shape. The calculation is fairly simple because the spring rate is linear and therefore it is just the multiplication of spring rate and the compression length. F_S stands for the spring force and k is the constant of the spring, which reflects the exact force per distance compressed the spring can provide. x is the distance the spring is compressed. The minus sign in the equation is due to the fact the spring is providing force against the direction of compression.

$$F_S = -k * x$$

Table 3: Calculation of the spring force

F_S [N]	k [N/mm]	x [mm]
-0,96	0,32	3

In the calculation above the maximum force the magnet has to pull in the end position is shown. At the beginning the force is 0N and with every millimeter the valve is pulled the force raises by 0.32N. This is important because it means the magnet does not need to pull the whole force at the furthest distance. Only each incremental force has to be pulled at each distance. The magnetic force declines with distance. That means if the magnet can grab the valve it does not need to pull the whole force from the very beginning to work. Figure 31 shows the force at each distance the spring is pulled.

At the idle position of the spring when the valve is closed, at 0.5mm compression, the force the magnet needs to pull is about 0.2N.

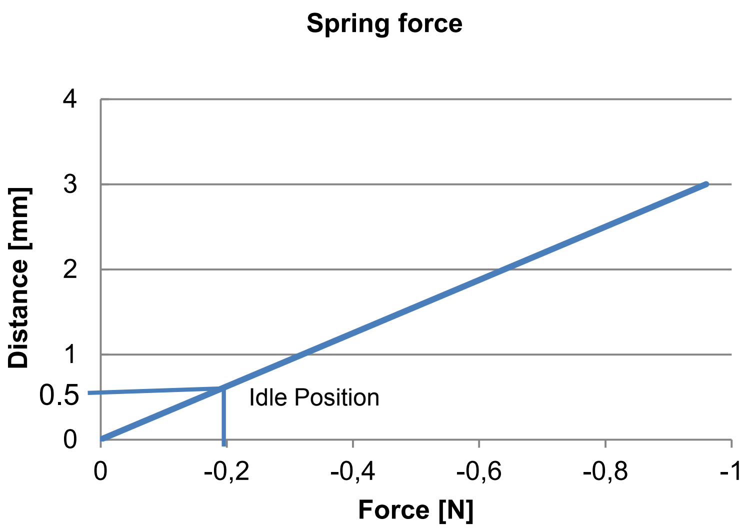


Figure 31: Spring force depending on distance compressed

3.2.4.2 Hydraulic Force

When the piston is in its closed position, the pressure difference resting on it exerts a force. This force combined with friction in its track gives an additional force working against the movement of the little piston.

The pressure from the fluid, in this case 70bar ($7*10^6$Pa or 7N/mm²) difference have been chosen, exceeds a force on a certain area. This 70bar are the worst case when there is the pump filled with gas and the fluid load from surface is only supported by the valve. Normally, when the system is working, gas should never accumulate in the first place because it is vented every single stroke of the sucker rod pump. Therefore, the little amount of gas is compressed and lowers the pressure difference on the valve cylinder. This lowers the force acting.

The area is from the connection channel, where the pressure exceeds its force. This force is the direct acting force on the piston in direction of the pressure gradient from the higher pressure to the lower pressure. The force acting on the valve is the normal force F_N. p is the pressure provided from the fluid and A is the area the pressure is affecting so the equation is resulting in:

$$F_N = p * A$$

The projected area needed for the calculation of the normal force F_N is the area of the connection channel that works on the valve body. It is defined by the diameter d of the channel giving:

$$A = \frac{d^2 * \pi}{4}$$

To get the force in direction of the movement the friction factor needs to be included into the equation. The normal force times the friction factor results in the friction force which works against the direction of movement. The friction coefficient is assumed to be 0.12 in this case of steel on steel friction. [28]

F_F is the friction force opposing the direction of movement and it consists of the friction factor μ and the normal force F_N:

$$F_F = \mu * F_N$$

Table 4: Normal and friction force acting on the valve cylinder

F_R [N]	F_N [N]	A [mm²]	p [N/mm²]	d [mm]	μ [ ]
1,48	12,37	1,77	7	1,5	0,12

3.2.4.3 Combined Force

The combined force needed is found by adding up the maximum force of the spring (0.96N) and the force the friction opposes to the movement (1.48N) of the valve cylinder. 2.44N are necessary to move the cylinder to its completely opened position.

3.2.4.4 Magnetic Force

There are many difficulties in this part of the calculation. It is very hard, if not impossible, to calculate with basic formulas how the magnetic field will distribute itself in the downhole pump. The reason for that is that there is not only one media present. Most components are made from stainless steel with the consequence that it transmits the magnetic field much better than air, vacuum or composites for example. There are gas and liquids there as well with very different magnetic properties resulting in a very complex magnetic field distribution.

“Thyssen-Krupp” has a magnetic force calculator that was used in this case as a basic calculation. It is calibrated for pure air. This was done to get an insight for how far a magnetic force can reach from the surface of the magnet. Figure 32 shows the force of the magnet compared to the distance to its surface. [29]

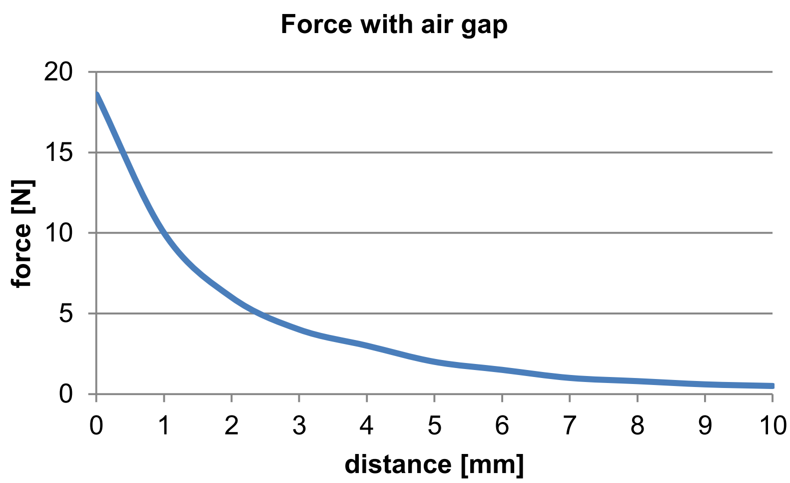


Figure 32: Magnetic force over an air gap [29]

It can be seen that at a distance of 7 to 8mm the magnet struggles to overcome the friction force of the valve. The magnet is placed in a stainless steel tube and the valve cylinder in a stainless steel body as well. The uncertainty is how much further a magnetic field will develop in this environment and how much stronger the field will be. There’s an experiment needed to answer these important questions. In the base plan (Figure 27) the valve cylinder is 7.5mm away from the magnet.

3.2.5 Conclusion and Improvement

There is the need to test the system in real life to see if the magnetic operation works as intended. The forces needed to actuate the valve are quite low in general. In case the magnet in the rod is too weak there is the possibility to use a neodymium magnet as valve cylinder as well. The problem in this case is that the magnet now is not in the center of the system any more. This has the consequence that the valve cylinder might not travel undisturbed in the channel and might stick to the screw. Therefore, the screw has to be a non-magnetic material to avoid problems and interference in the axis of the travel direction of the valve. Additionally, the friction in the channel will rise due to the fact that the valve cylinder will try to stick to the sidewall of the channel.

Another very important point is that the magnets in the string need to be double the length because of the polarity of two magnets to each other.

There are neodym magnets available in the size nearly the same the original cylinder has been. To use this magnet the bore needs to be 2mm instead of 1.8mm in diameter and the tread needs to change to M2.5 or M3. Table 5 shows the details of the required magnet.

Table 5: Data sheet of the properties of the S-02-04-N magnet [27]

Position	**Type**
ID	S-02-04-N
Material	NdFeB
Type	Stick
Diameter	2mm
Height	4mm
Tolerance	+/- 0.1mm
Direction of magnetism	axial
Coating	nickel-plated
Production	sintered
Magnetizing	N45
Holding force	1.57N
Max. temperature	80°C
Weight	0.0955g
Curie temperature	310°C
Remanence	1.32-1.37T
Energy product	342-358kJ/m³

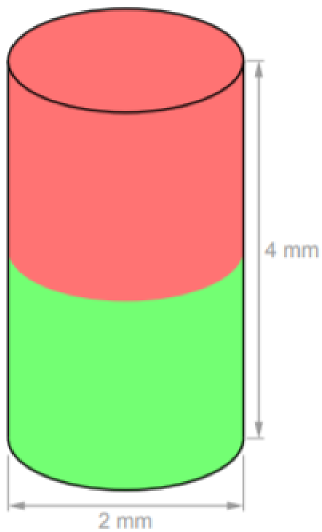


Figure 33: Picture of the S-02-04-N magnet [27]

Another possibility would be to locate magnets on the surface of the rod. This approach is explored in the following chapter.

3.3 Adapted Magnet Operated Secondary Valve System

If the magnets are not strong enough to operate the valve system a possible solution is to move them closer together or use a magnet as valve cylinder as well. To get the distance between the magnets down the magnets can be mounted on the surface of the sucker rod string. Therefore, a normal 15mm diameter full rod is used and the magnets are countersunk and glued in place in pre-milled holes. Using this technique, the distance between valve cylinder and magnet can be reduced to about 4 to 5mm.

In this case the magnet in the rod has to be aligned with the secondary valve system in the valve body.

3.3.1 Valve Design

The valve design of the ring valve is identical to the chapter before with the option to use a steel cylinder as valve and the option to use a magnet as valve cylinder.

3.3.2 Rod Design

The rod is based as well as the previous approach on the 15mm rod used now in the SRABS system. Now cuboid magnets are used which are 10mm long, 5mm wide and have a depth of 3mm. They are glued in milled holes on the surface of the rod and face in the direction of the secondary valve system. 20 magnets are needed to cover the 200mm of length in the rod. When the magnets are on the surface of the rod one pole directly faces the valve and this means that there is no weak transition in the middle between the poles. In Table 6 all the details regarding the cuboid magnet are listed.

Table 6: Data sheet of the properties of the Q-10-05-04-N magnet [27]

Position	Type
ID	Q-10-05-03-N
Material	NdFeB
Type	cuboid
Base	10x5mm
Height	3mm
Tolerance	+/- 0.1mm
Direction of magnetism	axial to 3mm
Coating	nickel-plated
Production	sintered
Magnetizing	N45
Holding force	14.7N
Max. temperature	80°C
Weight	1.1400g
Curie temperature	310°C
Remanence	1.32-1.37T
Energy product	342-358kJ/m³

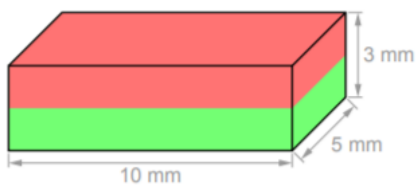


Figure 34: Picture of the Q-10-05-03-N magnet [27]

The design of the rod changes as well to accommodate the magnets. A 200mm long, 5mm wide and 3mm deep groove is necessary to place them in the string. Below in Figure 35 the manufacturing drawing is shown. The details of the rod design are depicted there.

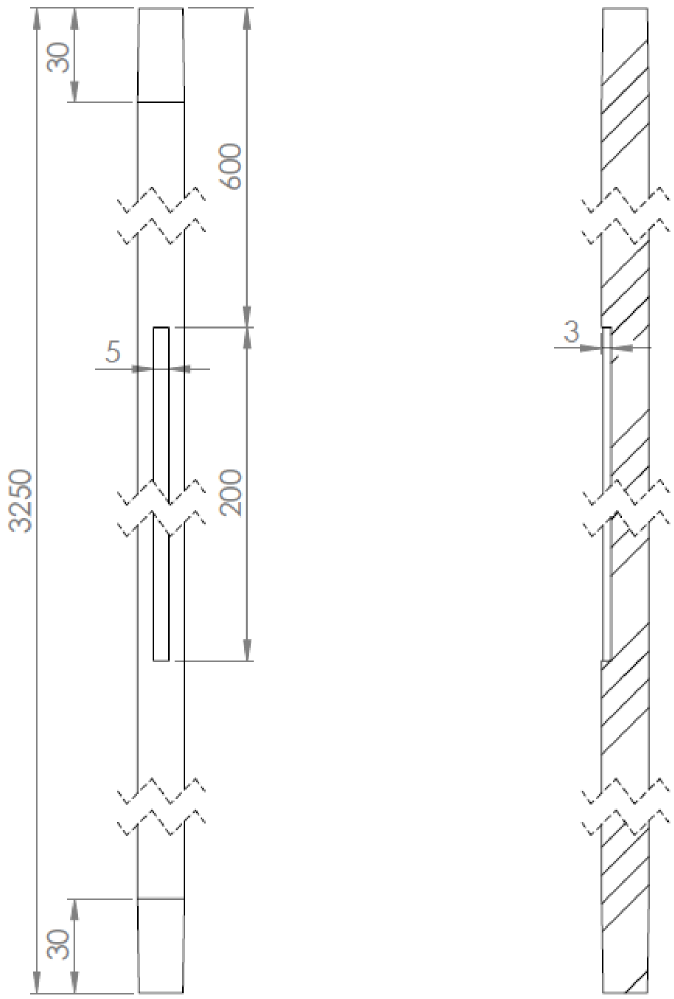


Figure 35: Detailed drawing of the rod prepared for surface mounted magnets

3.3.3 Conclusion

Very important in this instance is the alignment of the magnets to the secondary valve in the valve body.

Some problems that were present in the groove system occur here as well. For example, the rod cannot be rotated in this design which raises reliability issues considering the life span of the rod. If rod rotation should be possible these magnets have to be around the whole circumference of the rod. Maintaining the same outside diameter would not be possible because the rod would be weakened considerably. A bigger rod would be necessary and this would change the whole design. The surface of the magnet is flat meaning that after mounting them to the rod a flat spot on the surface introduces a slippage path. This again cuts into the productivity of this approach.

This system can be used with a stainless steel valve body or with a neodymium magnet valve body. In case of the usage of the magnet it is important to be aware of the poles. The magnet-magnet setup has the benefit of the highest force applied and a good opening of the valve. Beneficiary here is that both magnets, if used, are perfectly aligned to each other.

3.4 Channel

The idea is to achieve a connection at the lower dead center between the fluid above and below the standing valve. Another option of doing this is by making a channel in the sucker rod at the lower dead center. This ensures a connection where gas can migrate and the pressures can equalize. The big benefit of this solution is that it is very easy to implement and has no influence on the reliability of the pump.

The channel is inside the rod and is connected with two holes with the area above and below the valve. This system as well as the secondary valve system will reduce the net stroke length by a bit. When the system is active a pressure connection is established between the traveling valve and surface forcing it to close a little bit premature to the lower dead center.

3.4.1 Rod Design

The rod needs to have a channel inside to connect the parts above and below the valve body of the standing valve at the lower dead center position of the system. This can be achieved by using the existing rod in the SRABS system and drilling one central hole 800mm deep and then two connection bores 200mm apart. The width is not that important for this case but 7mm diameter would provide the benefit of interchangeability with the magnet operated secondary valve system for trial runs. The other option, as before, is to use a hollow rod and only drill the two connection holes.

The detailed manufacturing drawing can be seen in Figure 36. The starting point is the standard rod as in the normal SRABS system. From the top a 800mm long hole is drilled in the center of the rod. From the side two holes, 3mm in diameter, are drilled to connect to the center bore. These holes are 200mm apart, one set at 750mm and one set at 550mm.

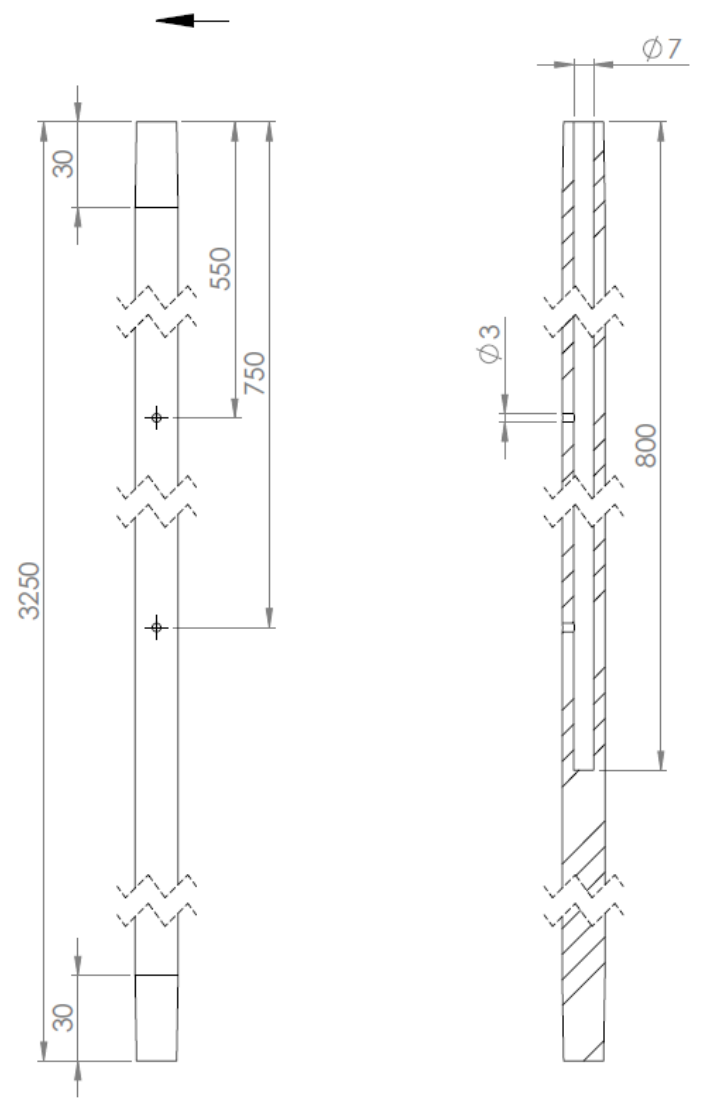


Figure 36: drawing of the rod with channel

3.4.2 Conclusion

The channel in the rod is much simpler than all other systems mentioned in this thesis so far. It has no moving parts added to the existing system. The valve itself is not altered altogether and compared to the existing SRABS only the rod needs to be changed out. Rod rotation is no problem to be added, too. This results in the same reliability as the present SRABS.

3.5 Summary

After devising several different approaches all of them have their advantages and disadvantages. The ideas can be separated into three basic concepts. The first one is to achieve direct control over the valve resulting in a very precise mode of operation. It can operate independently from environmental influences like gas entering the pump. The drawback is that this precision is bought with problems arising in other places. For example, the control of the valve is difficult and to achieve this, a slippage path through the guiding groove is introduced. Another example would be the exclusion of rod rotators which brings down the MTBF for the sucker rods considerably.

The second idea is to work with a completely isolated secondary system that only establishes a pressure connection to get rid of the pressure holding the valve shut during gas interference problems. The system is magnetically operated and allows for a defined opening point of the secondary system during the stroke. This eliminates gas interference and gas lock problems. Due to the complex magnetic interferences it has to be tested in a trial run and evaluated. Rod rotation and all the other benefits of the previous SRABS system will continue to work as well. It is designed so that it can be implemented in the system without a lot of modifications. The only changes refer to the valve body of the standing valve and the rod that goes through the downhole pump.

If this approach fails there is the possibility to relocate the magnets. Therefore, the magnets are closer together and better oriented to each other. The drawback is that the magnetic field is now oriented to one side and as a result the valve system and the rod has to be aligned. This means the use of rod rotators does not apply any more. The slippage is raised in this case as well due to the flat spot the magnets introduce.

The last approach is to implement a channel into the rod near the lower dead center of the system. This channel simply connects the upper and lower part of the standing valve. This equalizes pressure and allows the valve to open. This system is the simplest one and also has the least moving parts. It works with rotating rods as well.

In my opinion the most promising concept is to start a trial with the “rod with a channel” system. This system is the easiest to build and implement. It also looks the most auspicious and reliable. The drawings in this thesis are designed in a way that the “rod with a channel” can be adopted and used for a trial run for the “magnet operated secondary valve system”, too. I would not recommend to try out the axial valve system that is groove operated. In comparison to the other systems it is the most complex and also the one, which has the most drawbacks and is the most unreliable.

4 Downhole Electricity

Industry 4.0 is approaching and a major part of this is to acquire data from processes and equipment. The aim is to use these data in automation or improvement. Difficulties in this sector are the implementation of these systems in existing equipment and processes without cost intensive re-design.

As an example in the field of drilling engineering the digital rig can be mentioned. The number of sensors on the rig is always rising and goes from classic load sensors to determine the hook load or revolutions per minute (RPM) to more advanced sensors that measure vibrations for instance. The aim for drilling is to work more efficiently and avoid running into problems or at least catch them early.

In production engineering the close monitoring of pumps and other equipment like valves can give vital insights into the components health and estimate wear for example. This can tell the operator of the equipment when to change critical parts and prevents unexpected failing of the equipment. The maintenance intervals of equipment can be made flexible and longer, too. In regard to this thesis the focus is on sucker rod pumping systems. The most used system to monitor the pumping process and the health of the pump is the dynamometer card. The measurement of the card is done on surface at the polished rod. The reasons for that are mainly the easy access to the polished rod, the available space and connection to a power source. Another benefit to mention is that the data can be easily transmitted from the pump jack location to wherever needed to be interpreted. A major downside of this measurement is that it reflects the behavior of the pump several hundred meters below and does not measuring it directly. That means it includes unwanted interferences of the tubing and the string in between as well as potential vibrations. A more precise way to measure the acting forces downhole is to take measurements directly at the pump plunger.

Measuring downhole obviously is a lot more complicated than measuring on surface. The reasons are the limitations in space, the higher temperature, the presence of high pressure, fluids and gases, as well as the need for an energy supply. The temperature, fluid and gas environment, and pressure issues are solvable simply by purchasing equipment suitable for the job. Thermocouples, pressure-sensors and strain gauges are available in types suitable for this application. The energy supply is the main problem. While it is technically possible to establish a connection to surface it is expensive and complicated to put into the well in combination with a moving sucker rod string.

The solution for this problem might be to produce the needed electricity directly downhole. Most sensors have a very low power consumption therefore a small generator would suffice. Measurements can be taken and stored downhole by the generated electricity to be evaluated later after a workover is done. This has the downside that no real time data is provided but a thorough evaluation afterwards can be done to optimize the system for future applications. In further development stages the technique of intelligent drill pipes can be adopted for sucker rods to provide real time downhole data. [30]

4.1 Generator

To provide energy downhole a generator of some sort is needed. The premise downhole is mainly space as discussed in previous chapters regarding valves.

4.1.1 Working Principle

The working principle of a generator is based on the Lorentz force that describes the force a point charge experiences in a magnetic or electric field. Generators use a moving magnetic field that forces charges in a conductive material to one side and give it a potential. This potential is the voltage that can be picked up. A generator uses this process periodically to produce a usable current. Most common are generators that have a magnet as rotor inside and conductive coils placed around on a ring. A constant rotation changes the potential cyclically and the output is alternating current. Generators like this are used in water power plants connected to a water turbine and also in gas power plants connected to a gas turbine. In Figure 37 a basic sketch of the working principle related to a generator is shown.

A lot of equipment that is powered by electricity on the other hand needs direct current as input. Therefore, a rectifier is needed in most applications. Its job is to change the sinusoidal alternating signal into a constant one. This is achieved by a rectifier with a set of p-n junction diodes which conduct current only in one direction. [31, pp. 2-1] [32]

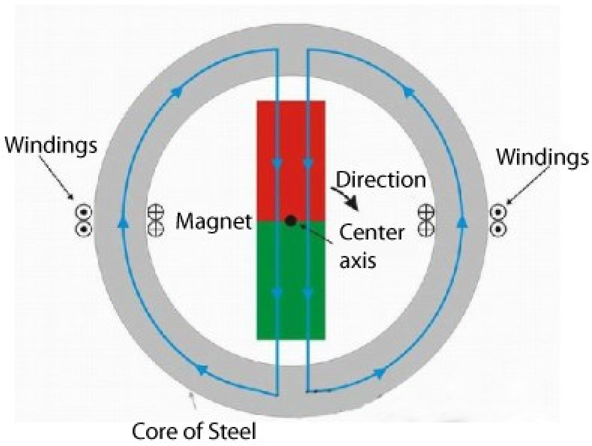


Figure 37: Rotational Generator [32]

Another, more seldom, used way to generate electricity is the linear generator. In contrast to the above described model this utilizes a magnet that travels in a linear motion back and forth through a coil. This method is as old as the rotational one but never was used in many applications because it was unreliable and difficult to operate most of the time.

4.1.2 Linear generator

The idea for example works very well with piston engines but never led to commercial success because the efficiency and reliability of the linear generator is an issue compared to other power sources.

A piston engine converts the up and down motion into a rotational one through the crankshaft. A diesel power generator for example uses this rotational energy and feeds a generator. With a linear generator it is possible to use the up and down motion of the piston directly to move a magnet back and forth in a coil winding. Below in Figure 38 the generator part that produces the electricity is shown. [33]

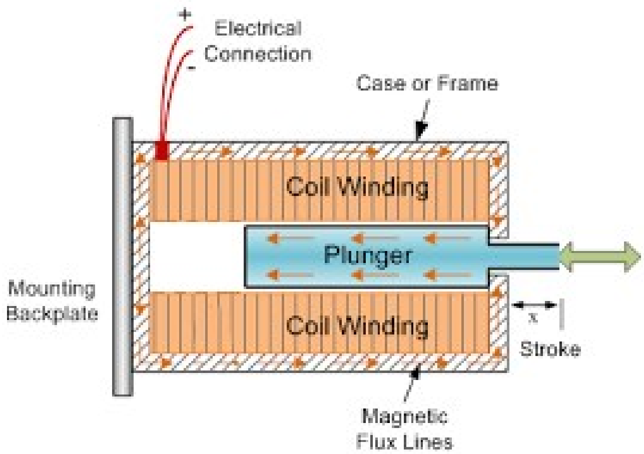


Figure 38: Working principle of a linear generator [33]

So electricity can be produced with much less parts involved which minimizes losses due to friction. A smaller footprint for the generators is also possible which is used today in more and more popular electric cars. The batteries in most of the cars today do not provide a sufficient range and charging takes a long time. The solution currently is to use so called range extenders. They are small petrol engines hooked up to a generator to charge the batteries on the move. To use a conventional petrol engine with a generator takes up quite some space and is heavy as well. Linear generators are a usable solution because they are small enough to be implemented in the floor of a vehicle and are a lot lighter than conventional engines. [34]

Below in Figure 39 a linear generator prototype produced in Germany is shown. The generator consists of a combustion unit and two generating units. The combustion unit is set up in the middle by two opposing cylinders that form the combustion chamber. During the power stroke both cylinders are forced outwards, moving the magnets through the coils on each side. The area between the piston and the generator is filled with gas forming a gas spring. This forces the piston back in their original position and compresses the new air fuel mixture for the next power stroke. The whole system is not much higher than the piston itself and has about 1.5m in length.

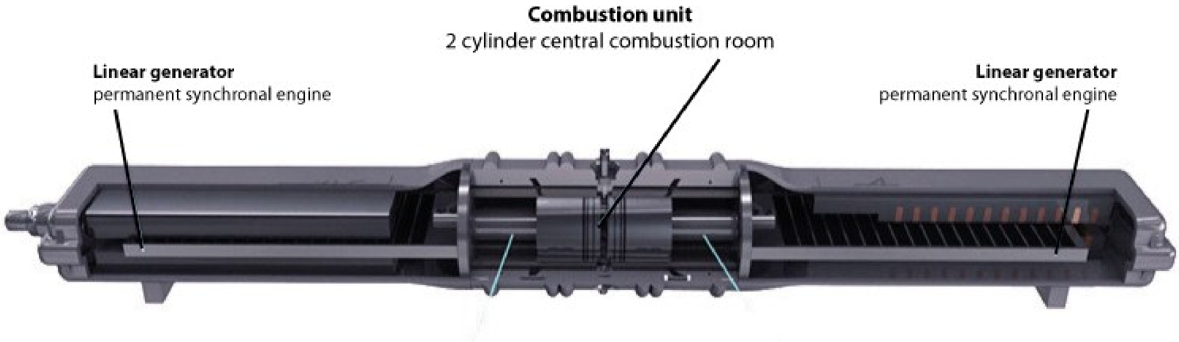


Figure 39: Prototype of a combustion powered linear generator [35]

This system has a rapid movement and can produce 35kW. For the purpose of using the motion of the sucker rod string a much slower approach is needed. [35]

However, there is a system of linear generators that use the same working principle but the energy of ocean waves is utilized. This is shown in Figure 40. A big buoy floats on the surface of the ocean and is connected via a line to the generator. The generator housing is fixed to the sea floor and contains a set of springs and the generator itself. The movement of the waves is translated to the generator and is slowly pulled up and down.

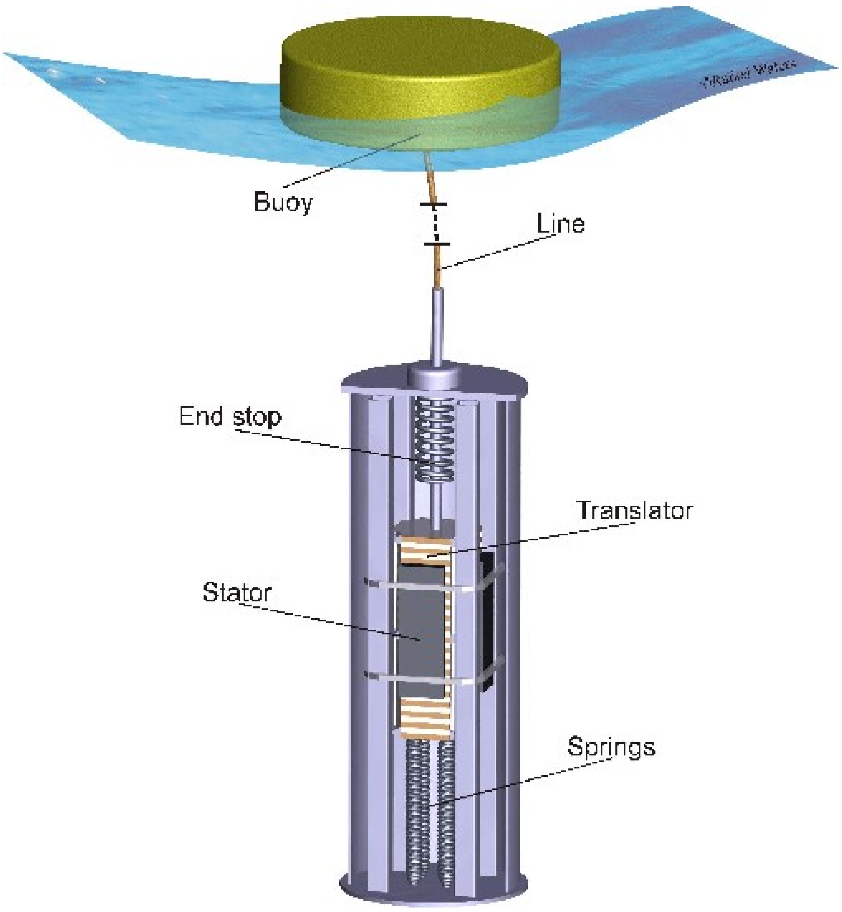


Figure 40: Linear generator for extracting wave energy [36]

This system is much more comparable with the speed and oscillation time of a sucker rod string but much larger. In the next chapter it is focused on how to implement the technology of linear generators into the downhole environment of a bore hole. [36]

For the purpose of downhole energy generation a linear generator seems to be the best way. It has the benefit of a small foot print compared to a rotational generator and it works with an oscillating motion of a magnet. This can be combined very well with the motion of the sucker rod string.

In this case no constant energy production is possible because the sucker rod string moves with a quite low velocity and slowly stopes twice a stroke. A decent velocity can be achieved mid-stroke and this is the part which has potential for the implementation of the generator. The main idea is that mid stroke mounted magnets move through standing coils mounted to the tubing.

Figure 41 shows the working principle of such a linear generator on the example of a simple commercially available torch. [37] By shaking the torch the magnet moves through the coil and induces a current. This energy is stored in an electrical storage device, which is a capacitor in this case. In between the coil and the capacitor a rectifier is needed to charge the capacitor always from the same side. The capacitor provides the power through a resistor to run the LED. With 30 minutes of shaking the lamp can be powered for 2 minutes.

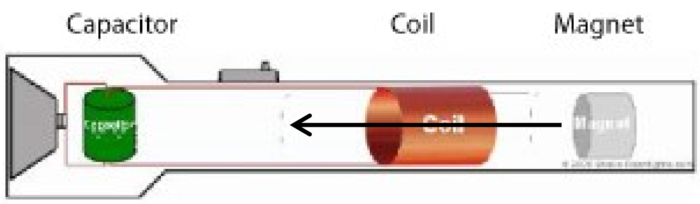


Figure 41: Linear Generator of a LED-torch [37]

For downhole usage this system is a very good basis because all the necessary components of the torch can be used and scaled for the downhole implementation. The power consumption of a diode this size is about 0.1W. [38] The consumption of low energy micro-electronics like temperature sensors and load sensors are in the low mW range. The magnet in the torch has a comparable size to the magnet used in the string and the used coil is smaller because it does not need to accommodate the sucker rod. The production of electricity downhole is intermittent and interrupted each stroke when the string slows down and comes to a hold. This time has to be bridged by an energy storage. When the pump is stationary the generator does not produce electricity anymore which means that during maintenance or during a workover an energy supply has to be ensured. For this reason it makes sense to oversize the capacitor to support the system during downtimes. Extra capacity is given by the oversizing to ensure the data can be recovered and interpreted. To determine how long the system can work independently the equipment used has to be known. The number and type of capacitors is important as well. In chapter 4.3 it is estimated how long one temperature element can last with one fully charged capacitor.

4.2 Super capacitor

Super capacitors can hold a lot of energy and work as puffer to have a constant DC energy supply. They are industrial products and are passive electrical elements which stay between capacitors and accumulators. 10,000F at 1.2V is the top of the range and this is 10,000 times the amount a normal capacitor can provide. This supply of energy is used for powering measurement and storage equipment. Super capacitors are commonly used in digital storages as float voltage to ensure the data stays saved. This is one of the main applications needed downhole. Another one is to measure data. [39]

Super capacitors are, as mentioned before, used to store electricity. Compared to batteries they work better in high temperature environments and do not have the downside of limited charging cycles, too. Additionally, batteries are quite inert and have relatively long charging and discharging times. For capacitors there are much higher limits as temperature and charging cycles. They are much more stable in performance and can be charged and discharged much faster and more often than batteries, too. They are charged by the linear generators and provide power to the measurement tools downhole and the data storage facilities.

They can operate as long as the sucker rod pump and during a workover the data can be collected and evaluated from the storage system. [40]

4.3 Consumer

Parts like a temperature element are tiny consumers. For example it takes only 30µA at 1,8V to operate such an element. Using a Super capacitor with 1F it would last about 32 hours. This means that one of these super capacitors is easily capable of sourcing a view measurement tools and a processing unit to store the data. [41]

4.4 Experiment

The principle of induction is well known and this experiment should provide answers to the question if a magnet inside a given sucker rod is strong enough to move electrons in the coil around the tube and provide electric energy. The construction resembles a short part of the sucker rod string mid stroke to look at the effects as isolated as possible.

4.4.1 Construction

The sucker rod used here has a diameter of 16mm and a bore in the center of 7mm. Inside of the bore a magnet is located which is 25.4mm long and 6.35mm in diameter. Around the sucker rod an enameled copper wire coil is positioned, which has a wire diameter of 0.15mm and ~3500 windings. The rod passes through the coil at two defined speeds which represent common speeds in sucker rod pumping applications and the induced voltage and current are measured.

The main goal is to minimize interference with the magnetic field. Therefore, the construction is made of wood and cardboard. The frame is made of 7cm wide and 2cm thick boards in general. The standing frame is L-shaped and 1m high. On this “L” the guiding pipe is mounted and at 60cm from bottom the coil is set. It is wired to the top of the frame to have easier access to the measuring poles. From there the voltage and the current is measured simultaneously with two digital mulitimeters (eumig M3900). At the top the control panel, where the input voltage (9V DC) can be regulated and the system can be powered on and off, is mounted. This panel feeds the electric motor of the winch and regulates the speed the rope is wound up. The winch is placed directly above the guiding pipe. Pictures of the experiment assembly are depicted in “Appendix B – Pictures of the Experiment”.

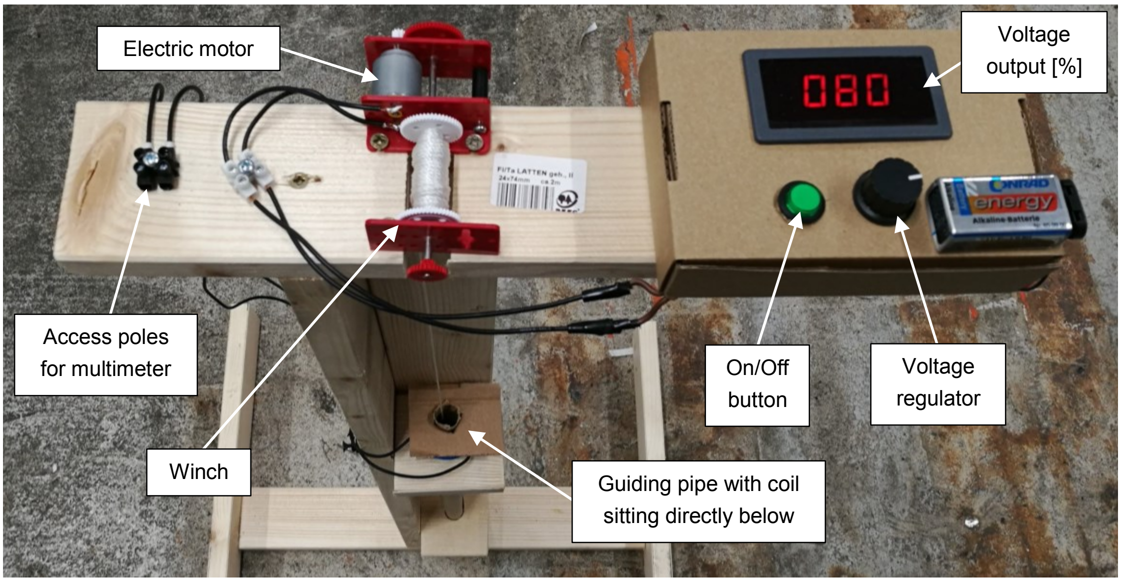


Figure 42: Top view of the experiment.

4.4.2 Calibration Run

To link the speed of the rod to voltage a calibration of the system is needed. This is done via a video time measurement. On the frame there are markings at defined distances and the rod is pulled 5 times at each voltage increment (1V increments). Then the time it takes the rod to move past each marking is measured. The distinction between the part where the rod accelerates and where it travels with a constant velocity is one result. Another one is that the position of the rod can be determined 60 times a second by the video played frame by frame. With the position of the rod (exact determination when the top of the rod passes a marking) and the passed time between two markings (counting of the frames) the speed can be calculated.

The result of this run is that up to 40cm the acceleration takes place. Therefore the coil was set at 60cm height to ensure a constant velocity of the passing rod. Another conclusion is that below 3V the motor struggles to lift the weight of the rod and therefore a cutoff was made. The curve is depicted in Figure 43. Below there is a table of common sucker rod speeds mid stroke where the investigation should take place. Table 7 breaks down the speed and the corresponding strokes per minute as well as the stroke lengths.

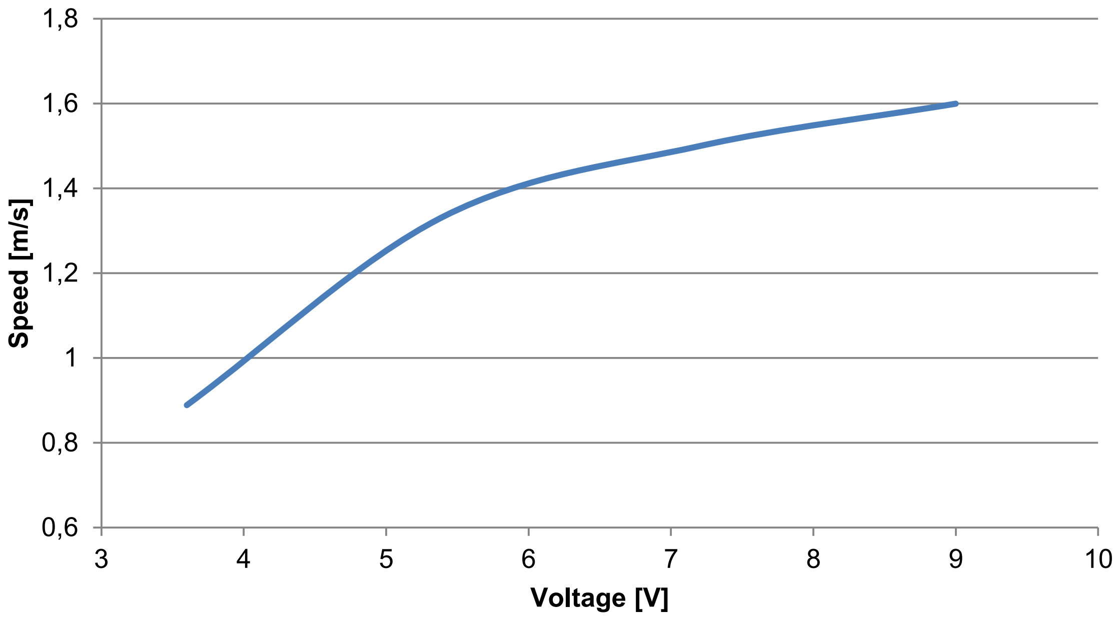


Figure 43: Speed of the sucker rod in relation to the input voltage

Table 7: Correspondence of strokes per minute, stroke length and mid stroke speed.

No.	SPM	Stroke length		Speed for Test
	[-]	[in]	m	m/s
1	12	112	2,8448	0,9
2	12	184	4,6736	1,5

The stroke speed is following a sinusoidal function which means the maximum speed can be calculated from the average speed by using the factor 0.637.

The speeds to investigate of 0.9m/s and 1.5m/s are corresponding to 3.7V and 7.2V. These two are the inputs for the test run. These speeds are chosen because they resemble realistic values of the moving sucker rod as well as not using the last 10% of the range the setup can provide.

4.4.3 Test Run

With the speeds from Table 7 the test runs are performed. Two multimeters, one for voltage and one for current measurements, are attached to the coil. One is set to mV and DC where the other is set to µA and DC. This is the expected range from a test where a multimeter has been attached to the torch described in Figure 41. The data from this test will be in the table with the data from the test stand for comparison. (The data from the torch are not representative because they were acquired while shaking the torch which is not a reproductive process. They are just for information and comparison purposes)

For each test run the rod is lowered in the guiding tube and then the rope is tensioned by hand via the winch. The voltage is set afterwards and the system is powered on. While the rod passes through the coil voltage and current is read from the multimeters. The data of the test runs can be seen in Table 8.

Table 8: Results of the test runs with 3.7V and 7.2V as well as the results from the torch as comparison

Voltage setting	41% (3,7V)		80% (7,2V)		Torch	
	Voltage	Ampere	Voltage	Ampere	Voltage	Ampere
Run No.	[mV]	[µA]	[mV]	[µA]	[mV]	[µA]
1	4,5	2,1	11,6	4,7	52	834
2	5,3	4,8	4,1	3,8	61	724
3	6,4	1,5	7,8	6,9	120	924
4	7,1	2,7	8,3	12,1	50	624
5	7,6	1,8	7,8	4,0	75	687

4.4.4 Discussion of the results

The main question is if the induction provided by the magnet is sufficient and what the influencing factors to the output are. One influencing factor is the speed of the rod. This can be seen clearly in Table 9 below. 1/3 more speed means the power output rises by 2/3.

Table 9: Comparison of the influence of the rod speed

Voltage setting	41% (3,7V)		80% (7,2V)	
Run No.	Voltage	Ampere	Voltage	Ampere
Unit	mV	µA	mV	µA
Average	6,18	2,58	7,92	6,3
Difference	78,03%	40,95%		
* Power Difference	31,96%			

* Power is the multiplication of voltage and current

Another influencing factor is the distance between magnet and coil. The closer both come together the higher is the output of the coil because the change in the magnetic field is higher. This is the main reason why the torch has a much bigger output. When connecting the LED directly to the coil of the torch it flashes when the magnet passes through the coil. This shows that the induction each passing is high enough to power the LED. While the torch has a ~1000 higher output as the experiment the LED also has the same order of magnitude more energy consummation than low energy micro-electronics. The test stand with a relatively small coil has, as it is now, an output that is already nearly sufficient for the intended use downhole.

All testing was done with one magnet in the rod. Putting a second one behind the first gives the same induction in the coil a second time.

4.5 Conclusion

Taking what was observed during the experiment leads to the following conclusions. At first it can be stated that the magnet inside the rod is strong enough to provide a magnetic field change in the coil. The consequence is that electricity is induced. To power low energy micro-electronic devices like temperature elements or pressure elements the necessary input energy can be met by scaling up the experimental setting. One coil as used in the experiment is 2cm high and this means that either a bigger coil or several coils after each other are a valid option. Putting magnets over the whole length the rod moves past gives a more constant input. This input is declining towards the ends of the stroke but nevertheless it is feeding energy in the system. Coils after one another mean that the high mid stroke speed can be used better through more coils, too. Between the coils and the consumers some kind of energy storage is needed and this storage needs to be oversized as big as possible so that excess energy that is produced is available when the pump is stationary or during the workover to ensure the data stays saved. Also separate independent energy storages are advisable for measuring and storage equipment so that during longer hold periods the measuring stops at some point in time and the data stays stored. The reason for this is that measuring is more energy intensive than the float voltage needed to keep data stored. To show the possibilities and needs of different measuring devices a follow up investigation is needed. But as conclusion of this investigation it can be said that the system in general is working and with upscaling it can provide the necessary energy for low energy micro-electronics downhole.

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Appendices

Appendix A – Formulas

F	Force
F_N	Normal force
F_F	Friction force
T_R	Rotational Torque
p	Pressure
A	Area
μ	Friction coefficient
k	Spring rate coefficient
x	Distance a spring is compressed
d	Diameter

Appendix B – Pictures of the Experiment

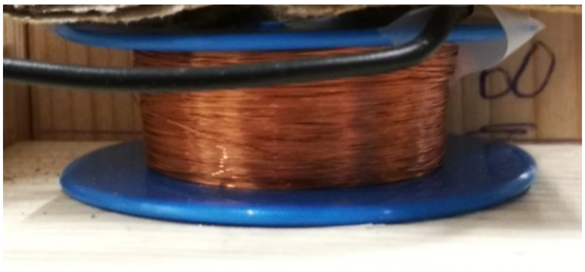

Figure 44: Enameled copper wire coil

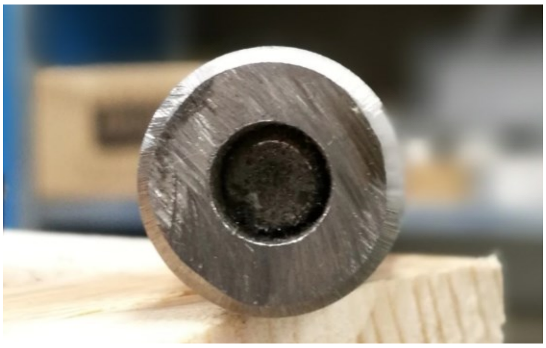

Figure 45: Placement of the magnets inside the sucker rod segment

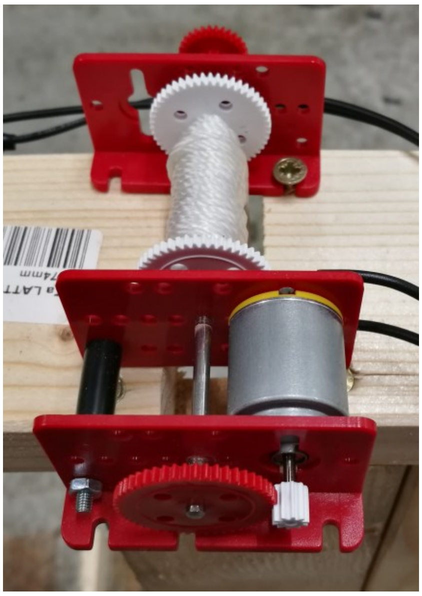

Figure 46: Electromotor, gearing and winch used for the motion of the sucker rod segment

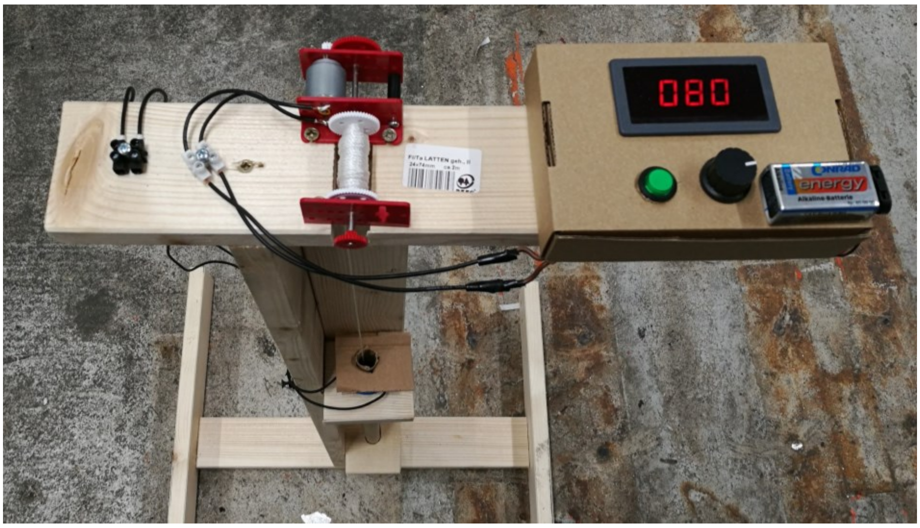

Figure 47: Top view over the experiment. On the top right the control panel can be seen and is set to 80%. On the left the black terminal strip is the point the measurements are taken. Further down the rope enters the rod guiding pipe.