Artificial Lift

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Lecture-30 SRP- Pump Performance Analysis-Part-3

We discussed surface units, subsurface units, and dynamometer cards in previous lectures. Now, we'll delve into the sucker rod string. A sucker rod string typically consists of metal rods, although non-metallic rods are also available these days. These metal rods are usually about 25 to 30 meters long and individually connected. Due to the cumulative mass, the string becomes quite heavy as you connect these rods. This weight causes elongation and introduces other issues, which we'll discuss here.

In the case of very long wellbores, tapered rods are often used. Tapered rods have varying diameters, with the upper portion more comprehensive and the lower portion narrower. The reason for this tapering is to account for the varying stresses along the length of the rod. The highest stress occurs at the top position because it bears the weight of the entire rod string, not just the pump load. Consequently, wider or larger diameter rods are used at the top, while narrower ones are used further down the string.

Typically, rod strings have three stages, each with different rod diameters. For instance, you might start with a one-inch rod (rod 88), then progress to seven-eighths of an inch (rod 76), and continue downwards, reducing the diameter by one-eighth of an inch each time. Thus, rod 88 has a one-inch diameter at the top, tapering down to six-eighths of an inch at the bottom. If you have rod 75, it involves three stages: seven-eighths, six-eighths, and five-eighths. In the case of a four-stage rod string, the rod numbers will change, such as rod 107, which includes ten-eighths, nine-eighths, eight-eighths, and seven-eighths diameter rods.

This way, you reduce the rod size to manage the weight effectively. What happens if you use the same size rod from top to bottom, let's say a ten by eight rod? The stress at the top becomes very high. This isn't a proper design. Instead, it would help to use a larger diameter at the top and gradually decrease it as you move down the rod string. By doing so, you maintain nearly equal stress levels throughout the entire rod.

Now, let's discuss stress-strain diagrams and definitions. When studying rods, it's crucial to understand the material properties. You can't buy or effectively use your rod without knowing these properties. You need to grasp basic mechanical systems, mechanical failure mechanisms, and the fundamental mechanical properties of materials. We typically begin with a stress-strain diagram in mechanical analysis involving forces or stresses.

The diagram depicts stress on the y-axis and strain on the x-axis. The diagram takes this shape, where we have levels. Up to this point, we refer to it as the proportionality limit. Beyond this, there's the fracture or rupture point. This region is known as the endurance limit. When designing a sucker rod or calculating for one, your rod should operate within the proportionality or elastic limit range.

For example, extending it to a certain level should return to its original position. The material has undergone permanent deformation if you stretch it so much that it doesn't return to the same position. In this illustration, I'm using an elastic band as an analogy, but metals behave somewhat like elastic bands when subjected to high forces. You apply a load to a certain point where the material either elongates or compresses and then returns to its original state.

If it doesn't return to its original position, that means it has undergone plastic deformation. This is called elastic deformation, where the material returns to its original shape. When you apply a load to a rod or tubing, the rod stretches but should return to its original position. Similarly, tubing will stretch and then return to its original position. However, if you overload it, let's say 100 Newtons are allowed, but you apply 150 Newtons, what happens? You exceed the proportionality limit, causing an increase in stress. You can see this in the image where the stress is indicated. The material undergoes permanent deformation with increased stress, known as plastic deformation. The material elongates but doesn't return to its original state. Molding a softer material like mud or clay won't return to its original position.

In contrast, elastic materials, as shown here, can elongate to a certain extent and return to their original position. However, if you stretch them too far, they won't recover, resulting in permanent deformation. You should understand the concepts of plastic and elastic deformation. Elastic deformation means the material returns to its original shape, while plastic deformation implies a permanent change.

There are more terms to consider, such as fatigue. Fatigue occurs when continuous tensile and compressive forces are applied to an elastic material. This creates stress cycles, numbered as 1, 2, 3, 4, and so on, going up to large values. Machine components, including those used in aircraft engines or other machinery, are designed and tested based on stress cycles. They check whether the material can withstand several cycles under specific stress conditions. For example, if applying a 10 kg load results in 1 million stress cycles without breaking, it is considered safe and free from fatigue. However, increasing the load to 100 kg while keeping the same number of stress cycles, subjecting the material to a higher load, may cause fatigue.

Let's say initially you apply 1 million cycles with a 10 kg load. Apply the same 1 million cycles with a 20 or 100-kg load. What will happen? The material will fail. When you apply a static load, there is no dynamic change; the material remains safe. However, when you subject the material to continuous dynamic changes involving elongation and compression, fatigue can damage it. Just like a person who works hard in the morning may become tired by evening, materials can also experience fatigue when exposed to excessive forces.

So, if you apply too much force or change the load frequently, the material may become tired and unable to perform at the same level. Similar to how physical and mental fatigue affects a person's ability to work, materials can also tire out if subjected to excessive stress. For example, if you increase the load or apply the same load repeatedly, the material can become fatigued and may fail. Fatigue loading considers both the magnitude of the load and the number of cycles applied.

Many machine elements are designed to withstand various fatigue scenarios, ensuring they won't fail even under many fatigue cycles. Engineers use an S-N curve to calculate fatigue, where 'S' represents stress and 'N' represents the number of cycles.

So, a curve is drawn for fatigue calculations, indicating the stress cycles applied. For instance, if you continuously apply a load to a rod, you can count the cycles—once, twice, thrice, and so on. You can plot the cycle-stress relationship by determining the force applied and the point at which the machine fails. As you increase the load, you'll notice that the number of cycles decreases. Higher 'S' values represent higher stress levels under pressure for the same cross-sectional area.

So, that's the stress. If you increase the force or pressure, the number of cycles reduces. This curve shows that the number of cycles decreases as force increases. After a certain point, you'll notice that the number of cycles below a certain stress level becomes infinite. Engineers design machine elements in a way that they can withstand any number of cycles. However, some machine elements may not account for infinite cycles.

For example, if you're designing a system that experiences continuous stress and relief in rod pumping applications, you might think, 'Instead of using a 1-inch diameter rod, I'll go for a 2-inch diameter rod to eliminate fatigue and extend its lifespan.' The issue here is that by increasing the rod's diameter, you're also increasing its weight. As I mentioned earlier, the top section bears a significantly higher load when the rod becomes heavier. So, while you reduce stress by increasing the rod's cross-sectional area, you also increase the load.

When you increase the load, the dynamics and momentum of the entire system change. This affects your gearbox and other components. Ideally, you want to keep the rod as lightweight as possible. You can't simply reduce or increase the rod's size without consequences. Reducing the size changes the force-to-area ratio, resulting in higher stress and fewer cycles. Conversely, if you increase the diameter significantly, the top section will experience higher stress, leading to a lower number of cycles. This highlights the need to find the optimal rod size, neither too large nor too small.

Now, let's discuss how the initiation and propagation of fatigue affect material failure. Imagine you have a single rod or pen and continuously apply vertical loads to it. Initially, you'll notice that surface cracks begin to form due to various reasons.

Cracks can form for various reasons, such as corrosion, fittings, or wear and tear. These cracks may also result from microstructure fractures on the surface. When continuous alternating stress is applied to an object, like this rod, it experiences both positive and negative stresses. As a result, small cracks can develop and propagate, gradually increasing in size.

Consider the stress formula: stress equals force divided by area (stress = force/area). When a small crack forms due to various factors, it reduces the effective area. If we compare area 1 and area 2, where area 2 is smaller due to the crack, the stress (F / area) increases. Increased stress levels can lead to failure, particularly when you have alternating stress conditions.

Now, let's discuss two more definitions: brittleness and ductility. Brittleness refers to materials that tend to break rather than elongate when subjected to force. For example, dry mud or stones will easily break when you try to snap them. On the other hand, ductile materials are known for their ability to deform extensively under stress. When you pull a ductile material, it forms a thin, elongated shape. Gold jewelry is a prime example of ductile materials, as they can be crafted into intricate designs.

Ductile materials, like gold, silver, and iron, can be drawn into very thin wear or elongated without breaking. These materials exhibit plastic deformation, meaning they change shape plastically, and this deformation is permanent. In contrast, brittle materials like concrete or bricks tend to break rather than elongate when subjected to force. They have low plastic deformation and minimal elongation; instead, cracks propagate quickly, causing sudden separation.

Strength refers to a material's ability to withstand high-stress levels, characterized as high-strength material. Resilience measures how much energy a material absorbs before undergoing plastic deformation. Like those used in sucker rods, ductile materials are particularly suited for tensile stress situations. Iron, for example, is a ductile material.

However, if a ductile material's properties are altered, it can become brittle. In contrast, brittle materials are well-suited for compressive strength applications. For instance, buildings are constructed using brittle materials because they primarily experience compressive loads, not tensile stresses.

Compressive stress is applied in building construction as each layer is constructed, rather than applying tensile stress by pulling the structure from top to bottom, as seen in the construction of the Burj Khalifa. Therefore, brittle materials excel in compressive strength applications. On the other hand, ductile materials are used for creating wear components, long rods, and pipes.

Ductile materials are advantageous. Next, stress concentration, as I previously mentioned, is a crucial consideration when designing mechanical machine elements. We always identify the weakest point on the machine's surface. Typically, the joints become the weakest points in a rod like this. Nut or bolt locations, as well as any microcracks, represent these critical weak points. Initially, these weak points cause stress concentration. How does it occur? Let's consider an example: I have one rod like this. Stress concentration occurs in the narrowest section. If there is pitting or a hole for a nut, this creates an area of stress concentration. Likewise, if there is a bend in the rod and you apply a pulling force, that area becomes a stress concentration zone.

Having a completely smooth and meticulously checked surface with no microcracks will extend the component's lifespan. However, internal cracks may exist, potentially causing problems and further increasing stress concentration. For example, when we bend a rod, we decrease the actual surface area. If we pull it in the A, B, and C directions, the C section experiences more stress because the entire surface begins straightening. This section attempts to withstand more force and may develop propagating microcracks, leading to breakage.

When designing any machine element, you must incorporate a factor of safety. The safety factor implies that the machine can handle a 10 kg load, but you advise the customer to use only 5 kg or 8 kg loads. It's essential not to inform the customer that the material can withstand a 10 kg load, as they might occasionally exceed this limit, leading to material failure.

The company or manufacturer will recommend using a 6 kg or 7 kg load, not 10 kg. They will not specify anything beyond 10 kg and claim to have a safety factor greater than 1.5. This is because if there are any microcracks or imperfections, applying a lower load prevents the cracks from propagating. However, using a higher load may cause the cracks to spread slowly. Therefore, machine elements are designed to ensure that small microcracks caused by imperfections in the design are not affected by repeated stress or stress cycles; since it's impossible to visually inspect all the rods during mass production for tiny spots, a factor of safety is used.

All machine elements are designed based on the weakest point. In the case of a sucker rod pump, the sucker rod typically consists of a tongue, a rectangular range section, a threading section, and a threaded section. The weakest point is usually the neck or potentially problematic region. To mitigate stress concentration in these areas, designers increase the diameter. By doing this, they acknowledge that the neck is the weakest point and aim to provide a slightly larger area. This increase in area reduces stress since stress is the force divided by the area. Remember the distinction between force and stress: force is what you apply, and stress is what the material experiences. To minimize stress on the material, you increase the diameter, thereby reducing stress in that specific location. The neck area and other connecting regions are usually given a slightly larger area to ensure stress reduction, eliminating stress concentration. Now, the material can fail anywhere, whether it's in the rod body, the range area, or the thread area, as designers have considered stress concentration areas and adjusted dimensions accordingly.

Failure modes: As I mentioned earlier, any microcrack present can propagate and lead to failure when subjected to repeated or reversed forces. Now, let's consider a sample rod. You may have conducted experiments like this if you've studied mechanical or civil engineering. Take a rod and apply a very high tensile load to it. When using this tensile load, the rod elongates slightly, similar to how an elastic material stretches when you apply force. However, to achieve this elongation, you need to apply a substantial load, possibly in the mega Newton range.

Now, here's what occurs: as the rod elongates, certain sections of it will narrow down while others expand. The total volume of material remains the same, but it gets redistributed. Consequently, areas such as A2 experience a reduction in cross-sectional area, leading to higher stress. These high-stress areas become problematic as they are prone to material failure. As you apply force, these areas elongate further until the material eventually fails. This type of failure is characteristic of ductile materials.

Ductile materials tend to exhibit elongation and necking down before failure. On the other hand, brittle materials do not provide such warning signs. If you take a brittle material, like a brick, and attempt to pull it, a crack may suddenly initiate, leading to rapid failure without prior indication. This is why many machine elements avoid using brittle materials. However, I've heard that some Chinese manufacturers have started using brittle materials in specific machine components, which can be unsafe since they do not provide any warning signs before failure. Using ductile or softer materials is generally safer because they may bend or show some signals before breaking.

While brittle materials may be more cost-effective, they can be unreliable. However, for buildings and structures, ductile materials are not suitable. Brittle materials are better suited for handling compressive loads. Another failure mode to consider is buckling, especially in long, slender rods.

When dealing with a slender rod of significant length and applying compressive force, it won't break. Instead, it will form a wavy shape, and the specific condition of the wave depends on the material properties. This phenomenon is called buckling and is a brittle failure mode. For instance, in a sucker rod pump scenario, if the plunger becomes stuck and you apply force, causing the entire rod to move downward rapidly, the rod will buckle, creating a wavy shape. This can lead to the rod rubbing against the tubing and potential joint failures. Therefore, in sucker rod pumps, a mixture of these failure modes or variations thereof may occur.

However, it's worth noting that both compression and tension may not be simultaneously possible. These forces are opposite, and if the sucker rod pump is experiencing compression, the described failure modes may not apply, as the pump typically operates under tension. Therefore, maintaining a certain level of tension is essential to keep the system integrated and enable continuous motion. The nodding donkey moves up and down, and simultaneously, the sucker rod and plunger also move up and down, possibly with some phase difference, but they generally move together.

Regarding materials, if we consider ductile materials, they tend to exhibit significant plastic deformation before failing. In contrast, brittle materials fail directly without much deformation. Stress, denoted as force divided by area (F/A), is a key concept to remember. Strain, symbolized as 'e' or 'epsilon,' represents how much extension occurs under a certain load. For example, if a 1-kilometer rod extends by 5 centimeters, the strain would be 5 divided by 1 kilometer. Stress divided by strain leads to Young's modulus, a material property that characterizes its elasticity.

The sucker rod pump utilizes rods made from various materials, with iron being the most common choice. Pure iron is seldom used; instead, it is typically mixed with a certain percentage of carbon to create steel. Steel can vary in carbon content, ranging from 0.15 percent to possibly 2 percent or more. Higher carbon percentages tend to increase brittleness, while lower carbon percentages result in a milder, softer material.

Mild steel is often preferred, as it can be easily melted and shaped into various forms, such as knives. On the other hand, cast iron is a brittle alloy of iron and carbon containing about 2 percent or more carbon, making it stronger and harder but also more brittle. Sometimes, instead of using excessive carbon, other materials like nickel, chromium, or magnesium are introduced to modify iron's properties. For example, a small percentage of nickel can enhance corrosion resistance when mixed with iron. Chromium is another element that provides corrosion resistance, and magnesium and other materials can be used to enhance properties such as corrosion resistance, wear resistance, and surface hardening.

Various techniques may be applied when manufacturing rods, including surface hardening methods like quenching. While iron remains the most common material, modern alternatives such as Fiber Reinforced Plastic (FRP) rods have gained popularity.

FRP rods are lightweight and offer good strength. Their low weight reduces the load on the polished rod. However, it's worth noting that FRP is a relatively soft material.

Corrosion can be prevented by applying a very high additional load that the rod cannot handle. If you aim to reduce rod weight, then Fiber Reinforced Plastic (FRP) is an excellent choice. Numerous companies manufacture FRP rods made from protruded fiberglass and standardized by API Spec 11B. Factors like temperature, load reversal, and fatigue have a more significant impact than corrosion. It can be challenging to handle compressive forces due to the softer nature of FRP.

Now, let's discuss the polished rod. As mentioned earlier, the polished rod transfers loads and seals with the stuffing box. Its diameter should be about 1/4 inch larger than the top rod section. Any abrasive action or corrosion damage is prohibited, as it can lead to fluid leakage. Therefore, the surface finish of the polished rod should be of high quality. The standard length of a polished rod typically ranges from 8 to 36 feet, with the proper length determined by factors like the maximum stroke length, extra length needed to accommodate the polished rod clamp, and additional length below the stuffing box to allow for overtravel.

Moving on to joints and lengths, a sucker rod pump consists of joints that connect the rods. These joints play a crucial role in ensuring the rods are securely connected. Generally, stress concentration sections should have a larger area, followed by the range area where rings are placed to secure two rods together. There will be extra areas before and after the threads of the rods. To connect these sections, a coupling is used, which also contains threads.

The coupling is typically around 4 inches long. It's important to note that the areas near the coupling should be slightly larger to avoid stress concentration. However, in cases involving slim hole tubing with a diameter of 2 and 3/8 inches (a very narrow tubing), coupling size and diameter need to be adjusted accordingly to avoid stress concentration, making it a potential problem area.

API specifications can be found in any API table, including API 11B. API 11B provides specifications such as API grade K, API grade C, API grade D, and more. When encountering a rod with API grade K, use the data specified in the API table 11B.

Sucker rod pump failures can occur due to corrosion. Corrosion can result from various factors, such as H_2S gas or CO_2 or even small amounts of oxygen. However, H_2S is often considered the most significant threat to the oil and gas industry. When H_2S reacts with iron, it forms ferrous sulfide (Fe_2S), which is softer than pure iron. This can lead to the creation of small cracks on the rod's surface, which may propagate due to alternating stress from fatigue loading, eventually leading to pump failure. H_2S can also create acid, which further reacts with iron, causing the formation of iron sulfate salt. This softer material can erode from the rod's surface over time, leading to corrosion-related failures.

Failures in sucker rod pumps can also result from stress cycles, joint failures, overloading, and issues such as sticking rods during operation. Therefore, when using a sucker rod pump, it's crucial to consider these factors.

Throughout these lectures on sucker rod pumps, we've explored surface pumping units, subsurface pumping units, and the components involved. To understand the entire flow mechanism and dynamics comprehensively, you need to familiarize yourself with the dynamometer curve or card and the pump card. The pump card is calculated from data recorded by the dynamometer card at the surface. It provides valuable information about fluid fillage, rod sticking, tubing, barrel, TV, and SV issues. By understanding these problems, you can address them effectively, whether through pump control or gas lock mechanisms.

To grasp how power is transferred from the motor to the V-belt, gearbox, pitman arm, working beam, horse head, and ultimately to the polished rod, along with how leakage is prevented in the stuffing box, you gain insights into the operation of the sucker rod pump and its impact on production rates. This knowledge is crucial for those involved in buying, installing, designing, or working as production engineers.

In conclusion, a comprehensive understanding of the entire system is essential for optimizing sucker rod pump performance. Thank you very much for attending this lecture on sucker rod pumping.