ARTIFICIAL LIFT HYDRAULIC PUMPING SYSTEM

Keith McDonald
Bosch Rexroth Industrial Hydraulics

1. DESCRIPTION & OVERVIEW

Specially designed hydraulic power systems can be optimally designed for artificial lift crude oil pumping or natural gas dewatering applications. They can be used in applications with virtually any rod load or stroke length but are not very economical in applications with rod loads above 35,000 lbs. and stroke lengths over 20 ft. Hydraulic systems can be made to be extremely simple and very inexpensive; however, the hydraulic systems discussed in this paper are of the more sophisticated variety and are most likely only economical for wells with rod loads between 15,000-35,000 lbs.

Hydraulic systems consist of a hydraulic power unit, which is driven by an electric motor or a gas engine, and a hydraulic cylinder, which is installed vertically above the well head with the cylinder rod end facing down. There are a variety of ways to mount the cylinder, which will be discussed in a later section. The prime mover of the power unit drives a hydraulic pump, which is usually a variable displacement axial piston pump. The power unit also contains an electrical control cabinet with a PLC and an operator touch pad to input control parameters to the system. Additionally, the power unit normally contains components which are used to generate and store energy on the down stroke of the cylinder. There are a couple of different ways to achieve this energy recovery, which will also be discussed in a later section. .

Hydraulic systems have many advantages over traditional mechanical beam pumping systems. These advantages stem primarily from the inherent properties of fluid power, but are also realized through the precise drive and control of the hydraulic system. Hydraulic systems have been around for years, but technology advancements have allowed hydraulic systems to operate at higher pressures, and these advancements allow them to lift larger loads without increasing their footprint size. Additionally, the controllability of hydraulics has improved and makes for better actuator control, which allows the systems to run at faster speeds than they have been able to in the past.

2. FLUID POWER

Fluid power has many inherent advantages over mechanical systems which mostly derive from Pascal’s Law which basically states that the pressure a fluid exerts will be equal in all directions. This concept has enormous power density ramifications and means that hydraulics can provide more force or torque in a smaller package than a mechanical system. Because pressure is equal in all directions, the pressure at the outlet of the pump will be the same as the pressure at the cylinder assuming there is no valving in between. If there is valving, then there will be some pressure drop over the valve. Force is a function of the surface area times the pressure, which means that if there is a small surface area, like the surface area of a piston inside a pump, then only a small amount of force will need to be exerted to move the fluid. However, on the other end, if there is a large surface area, like in the piston of a hydraulic cylinder, then a large amount of force will be able to be moved. This allows fluid power to lift large loads with smaller amounts of force than a mechanical system, which needs a direct linkage to drive a system.

In a crude oil pumping application, the lifting force exerted by the hydraulic cylinder is a function of the annulus surface area of the cylinder (piston area minus rod area) because the cylinder rod side is facing downwards, so all the work is done on the rod side of the cylinder. If the desired dynamic rod load is known, then the cylinder size can be determined by dividing the desired lifting force by the desired working system pressure. The maximum system pressure is determined by whatever the components of the hydraulic system are designed for. The maximum system pressure cannot exceed the design pressure of the hydraulic component with the lowest maximum pressure rating. Then the working pressure is set slightly lower than the maximum pressure. Working pressures can range up to 5000 psi.
Next, the hydraulic fluid flow requirement of the system must be determined. The flow is a function of the desired speed along with the size of the cylinder. The desired speed is of course determined by the desired crude oil production of the well. This desired speed is then multiplied by the annular surface area of the hydraulic cylinder piston to determine the necessary flow of the hydraulic pump. A hydraulic pump displacement is then selected based on the flow calculation, and the horsepower requirement of the prime mover is determined by multiplying the maximum flow of the pump by the working

pressure. When calculating horsepower, mechanical efficiencies of the prime mover need to be taken into consideration as well.

3. OPERATION

The hydraulic power unit portion of the drive system has a prime mover driving a variable displacement axial piston hydraulic pump. The outlet of the pump is then piped directly to the bottom (rod) side of the cylinder. The top side of the cylinder has a direct connection to the hydraulic reservoir on the power unit, so the pressure on that side of the cylinder remains around atmospheric pressure throughout the cycle by sucking oil out of the hydraulic reservoir during lowering and pushing it back into the reservoir during lifting. The speed of the cylinder is controlled by the displacement of the pump. Pump displacement is controlled by an internal control piston that controls the angle of a swash plate inside the pump. The swash plate angle determines the horizontal in and out movement of the pistons in the pump. The horizontal stroke distance of the pistons multiplied by the speed of the prime mover determines the pump displacement, which can by infinitely varied between +100% and -100% of maximum flow. The internal control piston is controlled hydraulically by a proportional valve mounted directly on the pump. This proportional valve can vary the force on the control piston, which varies the swash plate angle over its full range of motion. The proportional valve gets its signal from the PLC, which is reading feedback devices in the hydraulic system and making adjustments according to the difference between the desired set points and actual values. The feedback devices include a pressure transducer on the bottom side of the hydraulic cylinder, which measure hydraulic system pressure. This pressure is used to calculate the load on the cylinder at any given moment in time. The other feedback device is either a linear position transducer in the hydraulic cylinder or limit switches at each end of the hydraulic cylinder. The position transducer can measure where the piston is at all times down to the micron, and by using this transducer, the stroke length of the cylinder can be varied infinitely from zero to full stroke. If limit switches are used instead of a transducer, the system will only know when the cylinder has reached the end of its stroke on each end. In order to change the stroke length of the cylinder with limit switches, the switches need to be physically moved to their desired location. Dynograms can be generated with either type of cylinder position feedback; however, a linear transducer is more accurate because it measures the actual position at all times while only can estimate of position can be used with position switches. A linear transducer is always preferable; however, there are limits to the length of a linear transducer, and it is also more expensive than a position switch.

In order to lift the hydraulic cylinder and polished rod assembly, the pump displaces fluid to the bottom side of the cylinder lifting it upwards; however, on the down stroke, the cylinder is gravity lowered by the weight of the rod string. The flow then goes back through the pump, which actually turns itself into a motor by making the swash plate go over center to a negative displacement operation. This means the pump, which is now acting as a motor, reverses the flow and allows the cylinder to lower. In fact the high pressure in the bottom side of the cylinder actually drives the motor. Because the swash plate can swivel over center, the direction of rotation of the prime mover shaft does not need to change in order to change the direction of flow.

In most hydraulic systems, there is some type energy recovery system. This can be done in a variety of ways with an accumulator system being the most common. The high pressure fluid on the bottom side of the cylinder either drives a motor like previously discussed and the motor then drives a second pump which pumps fluid into an accumulator, or the fluid bypasses the motor altogether and is redirected by a directional valve and fills the accumulator. This high pressure fluid stored in the accumulator is then used on the upstroke to drive the cylinder with the pump and prime mover making up the difference. Another recovery option for an electric motor driven power unit is via a flywheel which is attached on the back side of the electric motor. In this case the hydraulic cylinder drives the hydraulic pump/motor as previously discussed, but then the motor exerts a torque on the shaft which spins the flywheel and stores the energy as rotational inertia. This rotational inertia is then used to spin the pump/motor on the upstroke when the swash plate goes back to a positive displacement position and acts again like a pump. No energy recover system can recovery 100% of the energy due to friction and other losses, but enough can be recovered to reduce the installed power of the power unit as well as peak loads during the cycle.

Along with the main variable displacement axial piston pump, there can also be two other small fixed displacement pumps mounted to the back of the main pump running off of the same through drive shaft. One of the small pumps is used for a filter/cooler loop, which continuously filters the oil in the reservoir and cools it so that the oil maintains a temperature which is satisfactory for the hydraulic system operation. The other pump is used as a control pump to control the proportional valve on the pump which controls the swash plate angle and pump displacement.

4. HYDRAULIC CYLINDER MOUNTING OPTIONS

There are a few different ways to mount the hydraulic cylinder above the well. Assuming there is not some sort of mechanical linkage or contraption mounted to the cylinder, the vertical centerline of the cylinder needs to be mounted directly above the centerline of the well head. Then it can be coupled to the polished rod. The only variable is what does the cylinder actually mount to and at what height above the well head. The cylinder can either be attached directly to the top of the well head, slightly above the top of the well head, or at least a stroke length's distance above the well head. If it is mounted directly on the well head, then the cylinder rod acts as the polished rod and no stuffing box is required. This saves space and parts, but it makes it more difficult to detach the cylinder from the rod string when needed and all the loads of the rod are transferred through the well head. Because the cylinder is mounted directly to the wellhead, the cylinder rod gets immersed in the crude oil. This could create a problem for the cylinder rod coating depending on the corrosive properties of the crude oil. To alleviate the difficulty of removing the cylinder from the rod string in a maintenance situation, the cylinder can be mounted a few feet above the well head, so that there is a big enough gap to get access the coupling between the hydraulic cylinder rod end and the rod string. In this situation, the cylinder rod would act as the polished rod, but a stuffing box would be required and a platform would need to be built to mount the hydraulic cylinder. The platform could either be attached to the well head, which would still transfer the rod string load through the well head or secured to the ground. This alternative still has the potential to create corrosion problems on the cylinder rod depending on the crude oil properties. The third alternative is to build a taller platform that is secured to the ground and allows the cylinder to be at least one stroke length above the wellhead. This gets the hydraulic cylinder rod completely out of the crude oil, but a polished rod and stuffing box are required. If the cylinder is not at least a stroke length higher than the wellhead, then it will hit the stuffing box before being able to complete a full stroke. The platform also has to be high enough so that when the cylinder is fully extended, there is enough clearance to the cylinder rod and polished rod connection point.

5. VELOCITY PROFILE ADJUSTIBILITY FOR INCREASED SPEED

One of the main advantages of a hydraulic system is the ability to manipulate the velocity profile of the rod string to whatever is desired. With a mechanical system, the velocity profile is fixed as a sinusoidal wave. The period (stroke time) of the wave can be modified by changing the amplitude (speed); however, the profile will always stay in the form of a sinusoidal wave. On the other hand, because a hydraulic system is not rotating like a mechanical system, it is just moving up and down in one dimension of movement, the profile can easily be modified. Figure 1 at the end of this paper illustrates this concept. A hydraulic system can ramp up to the desired speed immediately, while the mechanical system must slowly accelerate to a peak speed because of the sinusoidal wave properties. Additionally, a hydraulic system can maintain that desired velocity over virtually the entire stroke of the cylinder; whereas, a mechanical system only momentarily reaches its peak velocity before it has to decelerate again. Consequently, the hydraulic system can complete the stroke in less time than the mechanical system which increases the rod string assembly stroke rate. This can be accomplished even with the rod string actually travelling at a lower maximum velocity than the peak velocity of a mechanical system.

If an increase in speed does not have any value for a particular well, the velocity profile can be configured in such a way that either the lifting or lowering speeds are decreased while still being able to maintain the same strokes per minute. For example, if a slower lowering speed is desired without sacrificing the overall strokes per minute, then the velocity profile can be adjusted to increase the lifting speed and decrease the lowering speed as depicted in the Figure 1. Velocities and strokes are easily adjusted on a hydraulic system just by changing the speed or stroke parameter via the key pad. Nothing on the system needs to be physically moved and the system does not even have to shut down to make the change, unless the system uses limit switches, which would need to be moved to adjust the stroke length.

6. OVERLOAD PROTECTION & CONDITION MONITORING

Another advantage of a hydraulic system is in an overload situation. If the rod string gets stuck during either the lifting or lowering phase, the hydraulic system will immediately recognize that the cylinder is not moving. The hydraulic system will only allow the pressure to build to a maximum set point, making sure that the rod string is never over loaded. With a mechanical system, the system would continue to try to rotate until the weakest point of the system failed or an overload switch was tripped. However, once the overload switch is tripped, there is still mechanical inertia which can exert adverse loads on the rod string assembly. Once the hydraulic system recognizes that the movement has slowed or stopped, it will wait for a short amount of time and the change the direction of the movement. The cylinder will go back to its starting position and attempt to complete the stroke again assuming it is still possible to move the rod string at that point. If it is possible to move the rod string back to its starting position, that means that the hydraulic system will be able to continue to pump crude oil, albeit over a shorter stoke, even when there is something preventing the rod string from completing an entire stroke. At best the mechanical system would shut down for a period of time. At worst, it would break something. If the overload situation continues to occur then an error message is generated and the operator can decide if something needs to be done downhole.

There is also a built in pressure relief valve in the hydraulic system, which would be set at the desired maximum pressure set point. Should pressure in the cylinder build to that set point or pressure spikes in the system occur, the additional hydraulic fluid would then be relieved over that valve making sure that the pressure in the system never goes over the maximum set point. Additionally, it is imperative that the polished rod and string assembly be designed to handle the force exerted by the cylinder when maximum system pressure is reached.

In addition to the velocity profile and overload protection advantages, the hydraulic system is able to do condition monitoring as well. With the pressure and linear transducers, the system knows exactly what the force on the rod string is at any given stroke position. Therefore, it is easy for the system to produce to data necessary for a dynometer graph. This data can then be sent to an external visualization system, either locally or remotely, in order to produce a viewable graph. For remote visualization, the data is sent over the web sing an OPC server located in the electrical cabinet of the power unit. In addition to monitoring data, control parameters can be inputted and transferred remotely over the web as well. Therefore, a person can change speeds, change stroke lengths, monitor hydraulic system pressure and load, and view dynometer graphs from the comfort of their office. All they would need is a software visualization package to do so.

7. FOOTPRINT & INSTALLATION

The picture of the hydraulic unit in Figure 1 depicts a typical hydraulic system. As illustrated the system is a very compact design with a much smaller footprint than a mechanical beam pump. The power unit is quite compact and only needs two hydraulic connections from it to the hydraulic cylinder and one electric connection. One hydraulic connection goes from the pressure port of the manifold to the bottom side of the cylinder, and the other hydraulic connection goes from the top side of the cylinder to the tank port. Hard pipe is preferred, but hoses can be used as well. The electric connection would be from the linear transducer or limit switch to the control cabinet. Overall, installation is quick and easy, and in fact, the system can be easily transported from one location to another. Besides the piping, the cylinder must be secured to the well head or platform, and if there is a platform a small concrete pad should be poured in order to secure the platform to the ground. The power unit can simply be set on level ground, but securing it to the ground in some manner is preferred. Finally, power would need to be run to the hydraulic power unit if the prime mover is an electric motor. If the prime mover is a combustion engine, then a fuel source would need to be supplied. In fact, because it has such a small footprint, hydraulic systems has been installed in offshore applications where it otherwise would not have been economical to build a platform for a different type of pumping system.

8. SUMMARY

All in all, the hydraulic drive systems offer numerous advantages for crude oil pumping or gas well deliquification. Their compact design allows for easy installation and transportation, and they can significantly increase production by achieving more strokes per minute than a beam pump by virtue of manipulating the velocity profile, which is neither fixed nor sinusoidal. Regarding gas production, they can efficiently and effectively remove liquids from gas wells because the depths and rod loads can be so high in certain dewatering applications and the speeds required can be so slow that it might not be practical to use a mechanical type solution. This is the perfect application for a hydraulic solution because hydraulics can deliver a high force or torque very efficiently at low speeds. In fact, in hydraulics, force and speed are essentially independent functions. It is just as easy for a hydraulic system to operate at low speeds as it is to operate at high speeds, and the same is true regarding pressure.

These production advantages, combined with their increased adjustability and flexibility, their increased safety, decreased installation costs, and decreased rod string failures make hydraulics a very attractive solution for many different wells. With all of these advantages, the next generation in artificial lift has arrived.

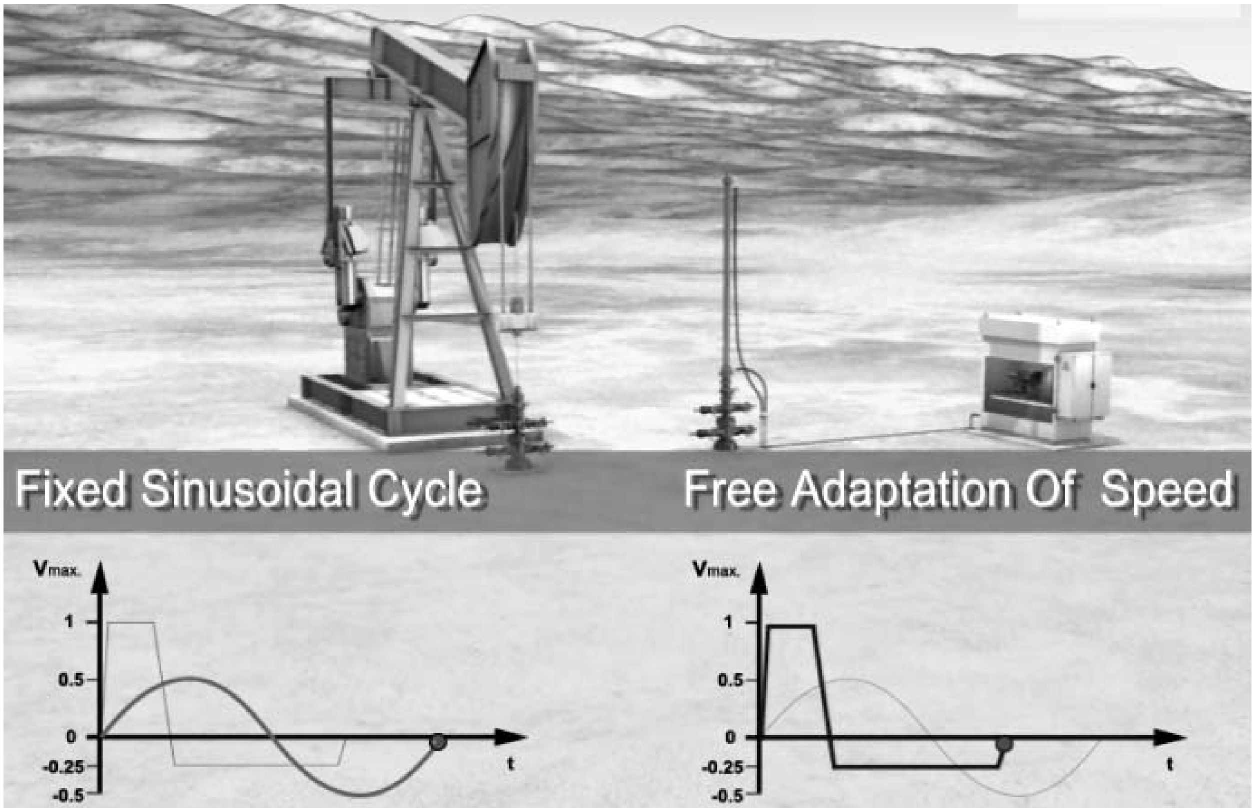

Figure 1 - Velocity Profile Comparison