Artificial Lift

Prof.Abdus Samad

Department of Ocean Engineering

Indian Institute of Technology Madras, Chennai

Lecture-38 Electrical Submersible Pump-Part-2

In previous lectures, we've covered various types of pumps, but here I've excluded all the additional pumps and focused only on those used in the oil industry. The oil industry primarily employs positive displacement and centrifugal pumps, with a few others like gas lift systems and jet pumps. I'm excluding everything else to concentrate on positive displacement (kinetic) and centrifugal pumps. We've already discussed reciprocating positive displacement pumps, and we'll delve into screw pumps (specifically, Progressive Cavity Pumps or PCPs) later. For now, let's focus on centrifugal pumps.

Centrifugal pumps come in different types, which we'll explore later. There are axial flow pumps, mixed flow pumps, and radial flow pumps. Axial flow pumps have high flow velocities and low head, while mixed flow pumps fall in between with moderate flow rates and head. Some engineers and scientists have even designed mixed flow pumps to balance higher head and flow rate.

I recommend watching YouTube videos on how pumps work for more detailed information. Now, let's look at some pictures. Before I show the pictures, let me explain. This is an impeller, similar to the one we've tested in our laboratory. However, we cannot see what's inside the impeller. To illustrate, I've brought this model. Inside the impeller, there are flow channels or passages. These flow channels guide the fluid's path. Fluid enters through these channels, then goes here, exits there, enters again, and exits again. These are known as flow channels or flow passages.

Here, you can see the impeller's eye, and this area is called the impeller eye. In this image, you can also see the blades; these are the blades. This region, which I've marked as 'eye,' corresponds to the impeller eye. However, in the first picture, we couldn't see it because there's already one plate covering it. The impeller consists of a front plate and a back plate. In this picture, the back plate is visible. It looks like this, but if I remove the front part, I can show you the impeller like this.

This impeller is the same; actually, both are almost the same. I've removed the front plate to show you the blades. This part is the impeller eye, and these are the blades. The blades have this path, which you can see as the blade path.

The impeller has a higher height on the inlet eye side, while the impeller height is lower at the exit. So, the height is higher at the impeller eye and lower at the exit. Fluid enters here axially, and then it goes through this passage. Observe how the axial flow becomes radial. Fluid comes in from here, enters, and then encounters the back plate. This plate is the back plate. The fluid can't go directly; it comes in axially and then turns radially, perpendicular to the axis. This is what we call a radial flow impeller. This is my radial flow impeller, and a radial flow impeller will have a front plate.

In the picture, I'll label it. I think in the next picture, I should have this. This is the back plate, and this is the front plate. As you can see, the back and front plates create a passage or channel. There's a hole here, and the fluid enters through this hole, goes through this channel, and exits. This is called an impeller. Why impeller? Impeller means fluid impeller; it will be rotating at a very high speed in this direction. It would help if you remembered this direction of rotation. This is the direction, not like this. If this is the direction of rotation, the fluid will be entering from the exit and coming to the eye. So, the fluid rotates in this way.

So, fluid will be entering; it will come to the eye. Actually, the centrifugal pump will not pump; maybe it will be sucking. So, the actual pump action will be rotation like this. Fluid will be entering and going out. Here, I will mark the flow direction. The impeller's rotation will be like this.

Here also, rotation will be like this, with the impeller rotating in this direction. Fluid is going out as the impeller rotates. So, when the impeller is rotating, fluid will be entering, and it will be going. Why should it enter? First, you have to fill the impeller properly; when you are filling, that is called priming. The term I already explained in some other lecture, priming. Priming is filling the impeller completely; then you get very high rotation. I think the rotation speed will be 1400, 3000, not less than 700. So, the normal ESP speed will be 3600.

ESP speed can be based on electrical frequency, normally 3000 or 3600 rpm. In the US, it's normally 3600; in India, it's 3000. Or they can change the frequency using a variable frequency drive, and they can change the ESP speed. So, it doesn't matter whether it's in India or the US because VFDs are available these days. Now, it will be rotating at a very high speed. When it's rotating at a very high speed, if some fluid is taken here, the fluid will try to go out of this impeller because of the very high rotation.

What is it trying to do? Trying to go out, so that area will be vacated. Let's say I have this impeller with one passage or channels like this, and it's rotating like this. Now, some fluid particle is here, and you give it a very high speed. So, the fluid particle will try to move here, here, here. The particle will try to move; when one particle you take, it's trying to move towards the exit. What will happen? This area vacated; low pressure will be created.

A low-pressure created means some pipe is connected to this; it will suck more fluid and fill the cavity, the void area. So, that means fluid is sucked; some fluid came in. Again, continuous rotation is going on, so that fluid also tries to move. So, one particle is moving here; another particle is coming here, and another particle is coming here. So, slowly all the particles will move; they will try to exit because of centrifugal force. How centrifugal force works, let's say if I have this one, if I rotate it, you'll see this.

It will try to move away from my hand at very high speed. So, a similar thing is happening here because of centrifugal action. If you give it a very high speed, some particle is here, and that particle will try to move away from the impeller due to the centrifugal force. From which side will they go? Backplate is there, and a front plate is there; it will try to go through this flow path, whatever path is there, it will follow. A smooth path is given, and through this smooth path, fluid will be moving. So, what is happening is, you take certain fluid here, fill the hole in the impeller; all particles are here. Because of centrifugal action, these particles move away. This area will be vacated, so in this area, fluid will try to fill the gap. New fluid will come in, filling the vacated area.

So, you are creating low pressure; low pressure will be sucking other fluid. Actually, I am saying vacated. So, there is no cavitation or anything. I am saying, like, low pressure is created because some fluid particles have moved from here, creating low pressure. So, low pressure will suck in more fluid. All fluid lines will rally together, and fluid will be continuously moving out of the impeller.

How is the impeller assisting the fluid in going out with very high velocity? You are creating very high velocity using your impeller. So, here I will write that the particles will be moving like this, then they will be going like this. These are blades; this is a blade, a blade, a blade, and so on. I am putting lines on the blades. Between two blades is a channel or path; there is a passage, a flow passage. From this flow passage, the fluid is going out.

When the fluid is going out, it will be directed inside a chamber, casing, or volute. The fluid will be collected here and then go out. If you see figures A, B, C, I've labeled them for better understanding. In figure B, if you observe, the fluid is getting collected in the volute casing. The volute casing is where the fluid, whatever it is, should be directed into one chamber.

The chamber will collect all this high-velocity fluid and deliver it to the discharge area or delivery pipe. Through the delivery pipe, the fluid will exit. I will draw one more picture to show this, not this one, the next one. So, if you see this impeller, it's the same impeller we tested in our laboratory at IIT Madras. I labeled it as A; this is A, and I will label the others as B, C, D. The fourth picture I have is from my laboratory. This is your pump section and the motor, and this impeller is inside. The impeller goes inside that cavity-like thing, which is the volute. The volute collects the fluid and delivers it to the top. If I look at this, there's a suction pipe, then it goes to the impeller, and then it's delivering the fluid, the discharge. If I match it with my experimental complete setup.

So, there's a suction pipe here, and this is the pump, the delivery, and the motor. One thing to notice here is this white portion, something is there, something is here, I think this white portion. This is actually a gear section; there's high-speed machinery. To protect the area, we put this white section. If you don't protect high-speed machinery, if any nut breaks, it can hit your head or anything. This is the suction pipe, and this is your water tank. It's connected to the water tank. Actually, the whole picture is not here, but this is the water tank, and this is the delivery pipe going through this, and the water will flow, and then the water will fall here. The whole loop will continue. There are some pressure gauges and a flow meter, and there is a flow meter and a pressure gauge, and there will be a speed sensor and some speed sensor tachometer. When you are running your experimental setup, it will be running at a very high speed with a centrifugal pump. So, the motor speed will be something. This speed will not be the same because if there is no load, fluid load, or any other load, the motor will rotate at a synchronous or very high speed. But if you apply a load, the motor will have some slip. Because of the slip, if it's supposed to have 3600 rpm, it will be about 3500 rpm. It's not fixed because the speed will change based on the load. But the motor speed is almost fixed, which is 3600 rpm. But because of slip, the speed will be reduced. And if you have a load, then again the motor will give a lower rpm, so that rpm also has to be sensed.

So, how to sense it? You have one tachometer, a small device. On this shaft, there will be a marker or reflector, a mirror-type reflector, and the tachometer will shine some light on this reflector. Based on how many times the reflector gives reflections to the tachometer, the tachometer will count the number of revolutions done by the shaft. The flow meter will measure the flow, and the pressure gauge will measure the pressure, indicating how much pressure you have in your suction pipe or delivery pipe. The suction pipe will be connected to your tank.

In the tank, there is another pressure gauge: the impeller. So, one should remember the terms: impeller; this is the impeller eye, as I already mentioned; and this is the volute casing. The volute has already been mentioned. Fluid will be collected here, entering this and then exiting as discharge. This hole is for the shaft. This is the shaft. Why is the shaft required? The motor will be rotating at a very high speed, and the impeller also needs to rotate. So, one metallic cylindrical element will provide the torque to the impeller, causing it to rotate. The volute itself doesn't rotate; only the impeller rotates. Fluid enters from the impeller eye and exits from this exit.

Regarding the exit angle, this is what it's called. When studying ESP, you should start with the basics: impeller, impeller eye, shaft, impeller blade, back plate, and front plate. This is a radial flow design. The impeller design will be slightly different if you have an axial flow. Here, I'm showing you the radial flow impeller. How does fluid get delivered? Centrifugal force moves it away, and centripetal force moves it through the flow passage. The centripetal force pushes the fluid from the impeller to the exit of the blade. When the fluid reaches the inside wall of the volute, its velocity decreases. What's happening here is this is the volute, and it's gradually enlarging in size, as you can see; the area is enlarging.

An enlarging area means it's collecting more fluid, and when the fluid area enlarges, it reduces velocity and increases pressure. You can remember the Bernoulli equation here: velocity increasing, pressure reducing, and vice versa. So, in the volute, velocity is reducing, and pressure is increasing (P increasing). In the volute, as velocity reduces, pressure increases. The impeller gives very high velocity due to centripetal force, which leads to reduced pressure in the impeller eye area. When it's giving high rotation, the pressure in the impeller eye area becomes lower because the fluid particles are trying to move up. So, the suction pipe takes in some fluid, and then that fluid gains energy and moves away. When they move away, the area they vacate is filled with more fluid from the suction pipe, and this process continues continuously.

The shape of the volute allows the channel to widen, creating a wider area. With this wider area, a diffuser action occurs, resulting in pressure development. This pressure forces the liquid out of the pump discharge.

Now, looking at the same picture as before, this one here, you can see the impeller eye, the blades, and the exit angles. There are 1, 2, 3, 4, 5 blades in total, and fluid enters through the impeller eye, then exits in this manner. Now, if you look at the picture I've taken from my student Hamid Siddiqui's thesis, he conducted computational fluid dynamic (CFD) analysis on the same impeller. I want to show how the pressure changes.

This picture shows low pressure in the impeller area, high pressure in the delivery area, and a transition from low to high pressure as fluid moves from the inlet (low pressure) to the volute (high pressure). So, this figure illustrates this phenomenon.

Another colorful figure is available here. This figure shows the impeller and blades, with the white parts representing the blades. The volute is also visible. The white blades rotate at a very high speed, rotating like this.

If you provide opposite rotation, then fluid will not be delivered; instead, it will be drawn in from the opposite direction. In this impeller, the blades are white, as you can see. There are one, two, three, four, five blades. When it rotates, you can observe how the streamlines move. The fluid moves and exits, and velocity reaches zero in this vicinity. Somewhere nearby, the velocity becomes zero, and as it exits, the velocity becomes very high. You get a very high velocity near the exit. Because it continuously adds energy, both pressure and velocity increase. The red color indicates very high velocity, while the blue color represents much lower velocity.

Now, speaking of the shaft, let's start by showing one impeller. This is called a multi-stage centrifugal pump or ESP (Electric Submersible Pump). Actually, an ESP consists of multiple stages, not just one. I've taken six stages of impellers here for the centrifugal pump. This whole impeller can be placed like this. It's quite small, less than a four-inch impeller diameter, and it has a diffuser impeller. It's connected to a metal rod, as you can see. This is a metal rod because the shaft is typically connected to your motor. Normally, the motor is at the bottom, although sometimes it can be at the top. There will be a motor protector, then the pump. When the motor rotates at a very high speed, the pump also rotates.

When the shaft rotates, it's a cylindrical element. What happens if you have a shaft rotating at a very high speed and the impeller initially resists rotation because it's static? When it's static, it's not rotating. You're trying to force the impeller to rotate. The impeller might ask, 'Why should I rotate?' That's when the shaft takes action by having a specific shape so that the impeller cannot resist. Let's say this is the hole in the impeller, and the shaft is passing through it. If the shaft is cylindrical and rotating but the impeller is not, we need to add a keyway. A keyway looks like this, as you can see in this picture. This is the actual impeller that was tested in my laboratory, so I'm showing the actual impeller. You can see the hole in this impeller properly; there is a dent. This dent is long. The impeller has a dent; if I make a shaft, the shaft will also have a dent like this. So, now both the impeller and the shaft have a dent. For example, there is a dent here. Instead of a circular cut, some small portion is removed from the material. Now, put this one in. Both of them have a dent, and in between the dents, you put a pencil or some metallic material. The metallic material will fit like this, okay? This is the keyway. You put this one, and it has a dent in between. You put this small key in. What will happen is that the small key will restrict relative motion, and then they will rotate together. It will be rotating together, and when rotating together, the shaft will transfer torque, so the impeller cannot refuse. The impeller will say, 'Okay, let us rotate together, fine.'

Why don't they use welding or other methods? Sometimes you have to remove your impeller. If it's welded, you have to break things, and threading is also impossible. Actually, threading can be removed, but sometimes you can put a tight fit and hammer it in. There might be a problem. So, they put a keyway and hammer the key and put it if required. You can also remove that key.

Another thing is that they will put some softer material for the key. So, the key will get broken if there is any extra load. The key will make the system safe. The key will provide restriction and move together, so there will be no relative motion between the shaft and the impeller. The first thing is, the second thing is that it will be softer material. So, it will be safe. If there is any extra load, the key will be broken, and the shaft will rotate, but the impeller will not. In that case, the system will be safe. But what will happen if you have a very high load on the impeller, and the impeller is not rotating while the motor is trying to rotate? If the motor is trying to rotate but cannot because of some blockage, something will get broken. The easiest way to solve the problem is to put a softer key. It's like having an electrical fuse at your home. If there is any extra voltage, the fuse will blow, and your system will be safe. So, in that way, the keyway, the key will break, and the system will be safe.

Now, as for housing, if you have a surface pump, then you will require one housing. But if you have a semi-submersible pump, in that case, you have to hold this outer casing properly inside the tubing. Then you have to rotate your shaft; it will be delivering fluid to the top. Okay, we have already seen the suction pipe, keyway, housing, delivery, and suction pipe, alright?

So, the impeller will have this wider area, and this area will be narrower. Right, so we will have the impeller rotation direction like this, yeah? Okay, rotation direction, this one, and this will be connected to your water sump or water tank. If it is a surface pump, it will look like this. If it is not a surface pump or a submersible or electric submersible pump used for wellbore, then the system will not look like this. But to understand the basic fundamentals, we draw the simplest diagram like this, okay?

So, the simplest means, to make life simpler, take water. Okay, no combustible fluid, not petrol or diesel, take water. Then water will be passing through one net, one valve will be there, a one-way valve and a strainer. Okay, this is the suction pipe and your water level. You have atmospheric pressure. If you switch on the pump, ideally, it should start sucking and delivering. But if the pump is placed at a very high level, then it will not be able to suck, okay? And if you have a gas field instead of liquid, and your pump is filled with air, what will happen? You are giving a very high rotation. You are rotating at a very high speed. This metal is very heavy, so I am doing like this so that it should not fall on my computer. But this is not metal; it's non-metal made actually for a laboratory experiment for our laboratory, okay?

So, the simpler it will be rotating, and if liquid is there, liquid will be having higher density. Water has a density of 1000 kg per cubic meter, which means 1 gram per cubic centimeter or 1 gram per second. So, 1000 kg per cubic meter. So, water will have a very high centrifugal force because of density. But if you have air, air is very light in density. So, very light density means when air is moving up, it will not create so much vacuum or so much low pressure that water particles can be sucked. So, if it is filled with air, air will not be able to suck water because it is getting very low pressure, actually, because water particles are moving. But that moving zone away will be a very low-energy system. Okay, so this will not suck your liquid.

Then what you have to do? You have to fill the system with water; that is called priming. So, priming means fill the pump with liquid before starting. Okay, before starting, you have to fill the pump with liquid, so no air must be there. So, what you do normally, there will be one hole here. So, from this hole, you put water, pour water, water, water, water, so it will be starting to fill. But this one-way valve, I have shown here. If I don't have a one-way valve, what will happen? You put water from the top, but what will it do? It will go down to your reservoir. So, what are you actually pumping? That impeller you will not get filled.

So, you have to get a one-way valve. So, whenever the pump delivers water, it will stay there, filling this whole suction pipe and impeller. And from that entry hole, if you see, no more water is going; that means the pump is filled. You close that valve. Okay, so that one-way valve is called a foot valve. Okay, this is called a foot valve. Now, when using a foot valve, there will also be a strainer. Okay, why will a strainer be there? So that no debris should enter your suction pipe. It is going to the debris, and the debris will be going to your impeller section. So, that blocks your flow channels because channels are very narrow channels. So, if any big particle or debris or something goes in, it will block the system. And when it gets blocked, there will be a problem. Okay, that's why there will be some strainer, and the foot valve is one-way valve.

When you switch on the impeller or pump, it will be sucking through the suction pipe, so the valve will be opening, giving a flow path. Again, you switch off; the valve will be closing. The whole fluid will not go to your tank. Okay, and the delivery of a suction pump can only suck a limited amount of head. Okay, suction head should be limited because this depends on your net positive suction head criteria. And whatever fluid you are pumping, what is the temperature, what is the piping, and inlet conditions—all those factors will be there. Based on that, you have to decide what your inlet pipe length should be or where your inlet water level should be. If it is submerged in liquid, still you have to check whether the fluid is getting sucked. And if there's a huge pressure drop in the suction side, then the pump can cavitate. When it is cavitating, the pump can fail because of vibration, noise, erosion, wear and tear, and so many things can happen, and the system can fail. But the delivery pipe, delivery, is dependent on the head developed by the pump, and it is already limited; we have seen from your HQ curve. Okay, so if you want to deliver, let's say, a very high head, then in that case, you create multiple stages. If one stage gives a 5-meter head, let's say, this is a 5-meter head, this will be 10-meter, 20-meter, 25, 30, 35, okay? So, one, so in that way, you increase. You want to get 100 meters, and it is giving 5 meters. So, 5, 5, 5, 5, 5. You add all the head. Okay, 100 meters means 100 divided by 5 equals 20. So, 20 stages will be required.