Microfluidics
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Lecture – 27
Microfabrication Techniques (Continued...)

Okay, so let us look at micro pumps; micro pumps are important component in microfluidic systems that are used to transport fluid in microfluidic devices in a controlled manner, okay. So, micro pumps can be divided mainly into 2 categories; one is mechanical pumps, where mechanical energy is added to the boundaries of a micro pump to generate increase the pressure of the fluid inside, so thus that transport the fluid inside the chamber gets transported, okay.

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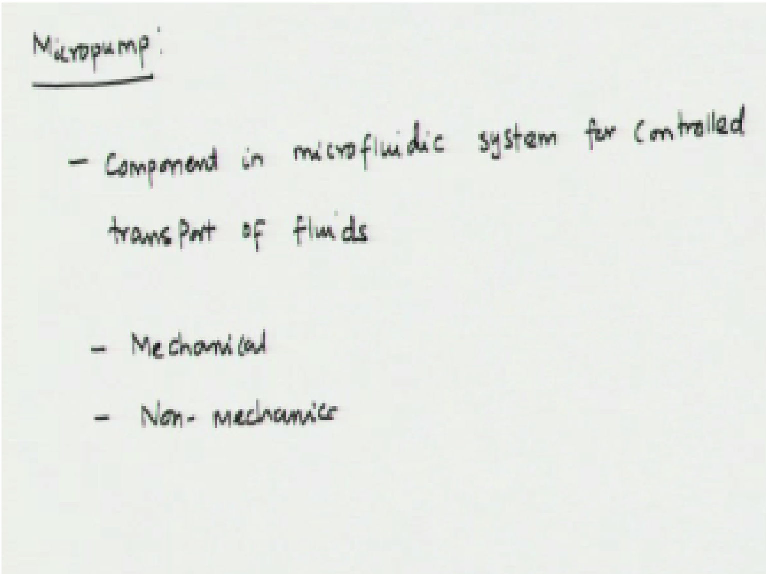

The second type in non-mechanical; non-mechanical energy like electrical energy or magnetic energy is added to a; you know the fluidic; fluid present inside a micro pump and in doing so, the momentum of the fluid increases and also the increase in the momentum results in increase in pressure, so that is how the fluid get transported inside microfluidic channel, okay. So, we look at micropump, okay.

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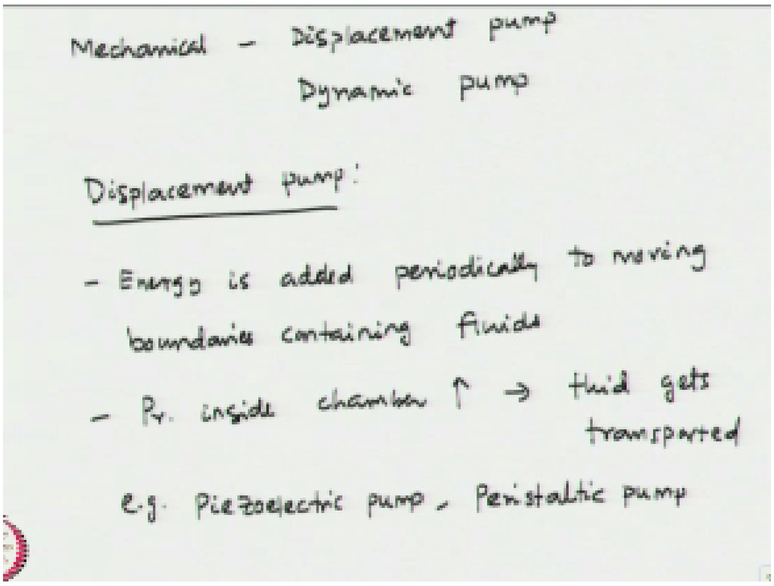

So, micropump are a component in microfluidic system for control transport of fluids, so micropump can be categorized into mechanical micropump and non-mechanical, okay and the mechanical micropump can be the; mechanical micropump can be categorized into displacement pump and dynamic pump, okay. Now, let us first talk about displacement pump, so in displacement pump the energy is added periodically to moving boundaries containing fluids okay.

So, in displacement type of mechanical pumps, the energy is added continuously to the boundary containing fluids and as the energy is added, the pressure of the fluid present inside the boundary increases, so that is how the liquid gets transported to another location. One example of a displacement type pump would be piezoelectric driven valve less micropump okay. So, when energy added the pressure inside the chamber increases, so the fluid gets transported.

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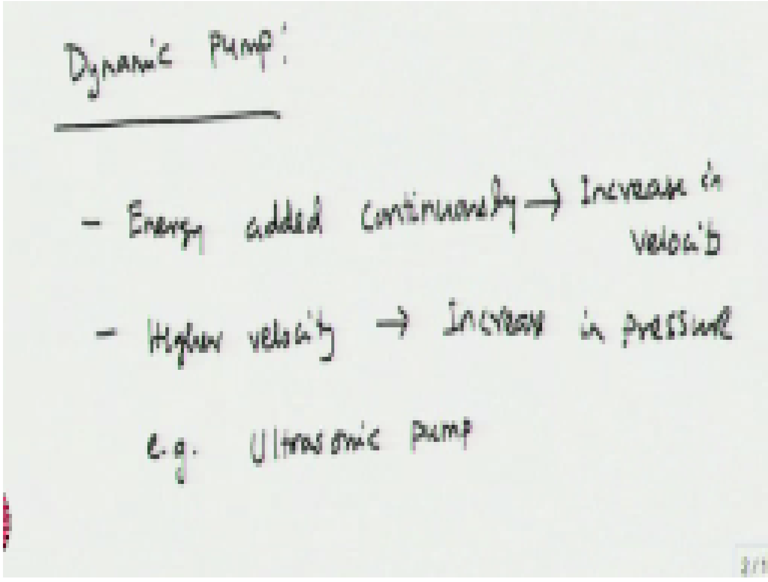

And some of the examples of displacement pumps are piezoelectric pump and we have peristaltic pump okay. Now, in case of dynamic pumps; in dynamic pumps, the energy is added continuously, in displacement pump the energy is added periodically. In dynamic pump, the energy is added continuously thus increasing the pressure inside the chamber, okay, so energy is already continuously to increase the velocity of the fluid present inside the chamber.

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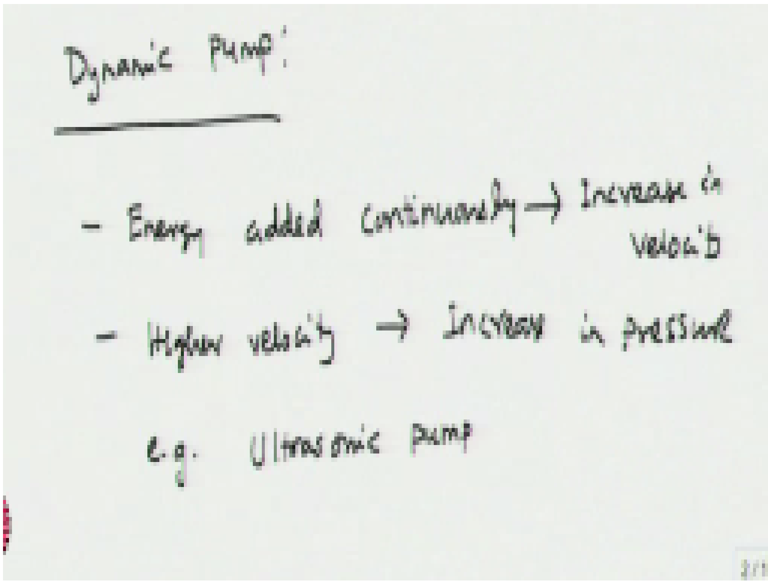

And as the velocity increases, the pressure also increases okay, so in dynamic pumps, energy added continuously and so that continuous addition of energy gives rise to increase in velocity okay, so and this higher velocity leads to increase in pressure okay and one example of dynamic pump is the ultrasonic pump okay.

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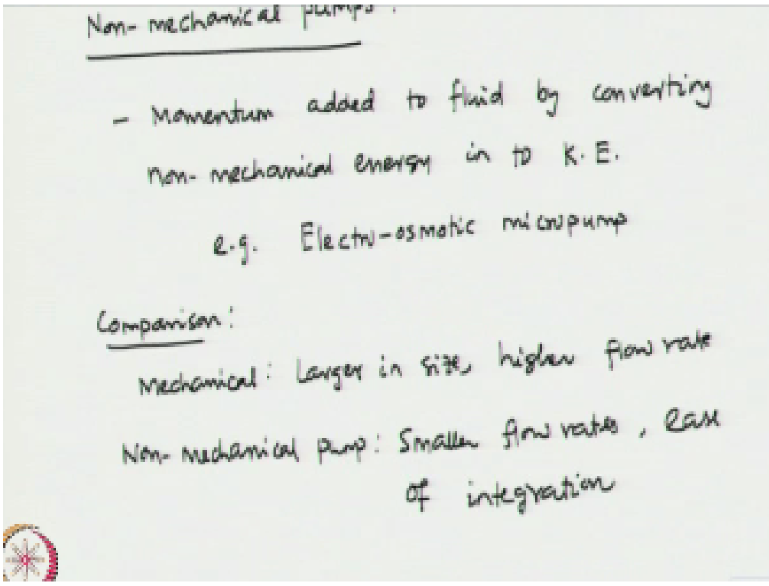

Next move on to non-mechanical pumps okay, so in non-mechanical pumps, the energy; non-mechanical energy in the form of electric field or magnetic field is added on to the fluid present inside a chamber and due to addition of the momentum, the fluid velocity would increase and the pressure of the fluid will increase okay. So, momentum added to fluid by converting non-mechanical energy such as electrical or magnetic energy into kinetic energy.

And the example could be electro osmotic micropump, okay now if we compare the non-mechanical type pumps with mechanical type pumps; mechanical type pumps normally offer higher flow rates but they are relatively larger in size okay and non-mechanical pumps are offering relatively smaller flow rate but they are smaller and easily integrated with the microfluidic systems.

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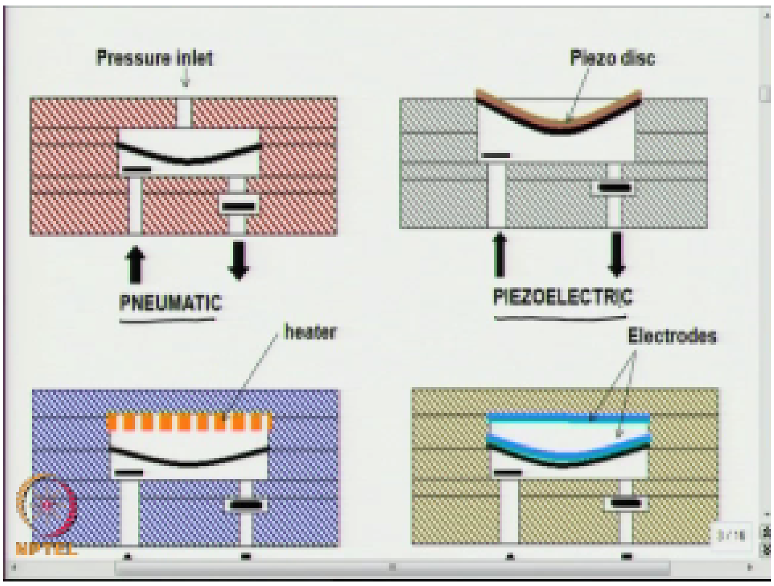

So, if you do a comparison, then the mechanical pump are larger in size and offer higher flow rate, whereas the non-mechanical pumps would offers smaller flow rates and the provide ease of integration, okay. Now, let us look at what are the mechanical pumps and what are the non-mechanical pumps. So, here you see a pneumatic micropump okay, so pneumatic micropump is the displacement type, a mechanical micropump okay.

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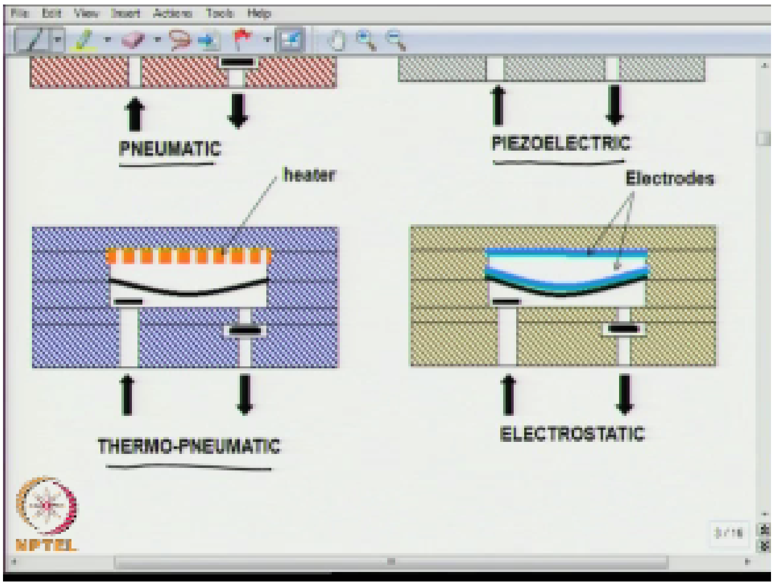

And another displacement type mechanical micropump is piezoelectric micropump okay. So, here you have the thermo pneumatic micropump, which is non-mechanical type because the energy source is come from the thermal energy okay and here in electrostatic micropump, which is a non-mechanical micropump okay. So, if you do a categorization, we do first mechanical micropump okay.

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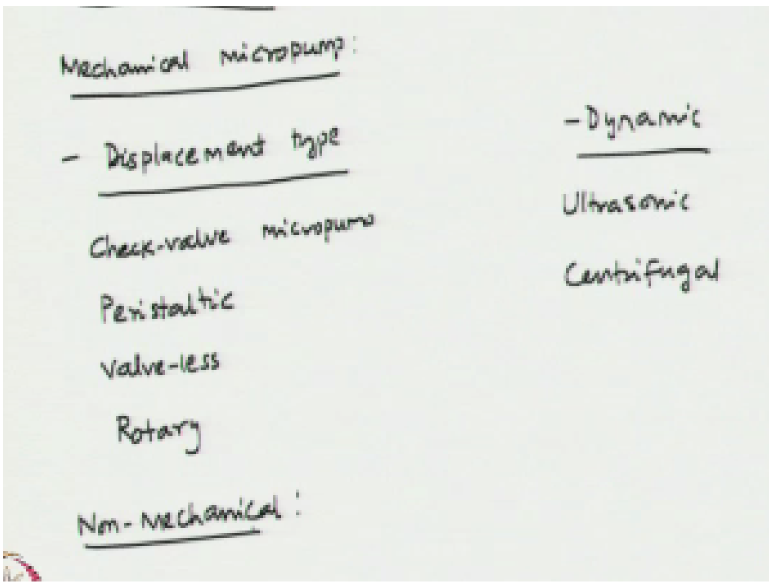

So, the mechanical micro pump would have the displacement type and dynamic, so on the displacement, we have check valve micro pump, then we have peristaltic micro pump, then you have valve less micro pump and we have rotary micro pumps and in dynamic, we have ultrasonic and centrifugal.

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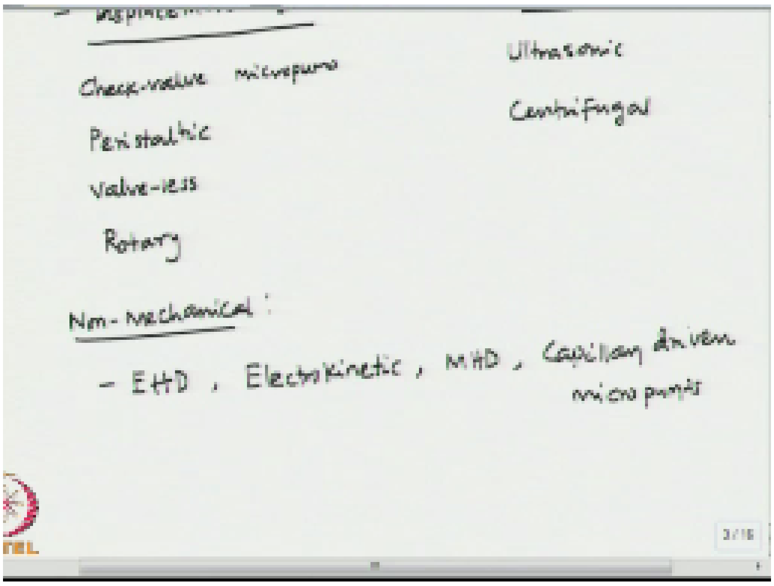

Similarly, in non-mechanical; non-mechanical micropump, we have electro hydrodynamic micropump, EHD micro pumps, then we have electrokinetic micropump, which we have already discussed, which works on the principle of electro osmosis and we have magnetohydrodynamic micro pump and we have capillary driven micropump. So, look at each of these micro pumps in detail.

Now, here if you look at the pneumatic micropump, the way it is; it works is the; so this is the chamber and one side of the chamber is open to a pressure source okay and the other side we have the fluidic inlet and fluidic outlet through walls. Now, when the pressure here is less than the inlet pressure okay, so the pressure here is in less than the inlet pressure, the fluid will come out into the chamber okay, through this valve.

So, the valve will open simultaneously and the fluid will come inside the chamber and when the pressure will increase than the outlet pressure and simultaneously this outlet valve will be opening and the inlet valve will be getting close, the fluid will go to the outlet, so that is the principle based on which pneumatic micro pumps work. Similarly, piezoelectric pumps will work in a similar manner.

But here the actuation principle is based on piezoelectric mechanism okay rather than pressure driven membrane actuation okay and similarly, in the non-mechanical in thermo pneumatic, we would have heaters and there will be a fluid present here and when you supply a; you know thermal pulse, then the fluid will evaporate and there will be nucleation and bubble growth, so that would actuate.

So, depending on the heat pulse onto the heater that will actuate the membrane. Similarly, in the electrostatic micro pumps would exploit the electrostatic force between 2 parallel plates, so here is one parallel plate, the second one is on the membrane to actuate the movement of this membrane with respect to the top parallel plane, okay. So, let us look at what are the ranges of the flow rates that the different micro pumps can offer, okay.

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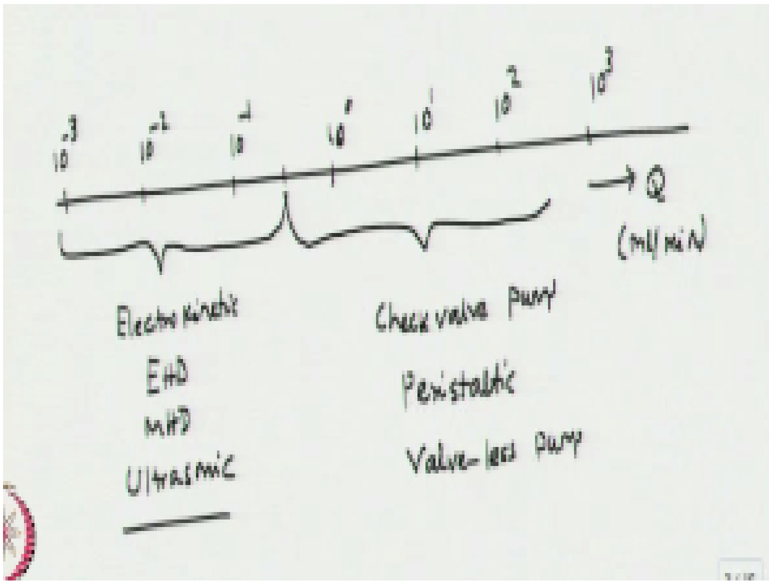

So, if you draw a scale here and let us say this is 10 to the power -3 and this is 10 to the power -2, 10 to the power -1, 10 to the power 0, then 10 to the power 1, 10 to the power 1, 10 to the power 3, okay. Let us say this axis is the flow rate, which is in millilitre per minute. Now, the pumps that can deliver 0.5 millilitre per minute and the ones that can deliver higher than 0.5 millilitre per minute are categorized separately.

So, these are going to be mostly non-mechanical pumps, so you have electrokinetic pump, electro hydrodynamic pump, magneto hydrodynamic pump and also you have this ultrasonic, which is a dynamic mechanical pump. So, these pumps can offer flow rates < 0.5 millilitre per minute and on the higher side, we would have check valve pump, would have peristaltic pump and we will have valve less pump, okay.

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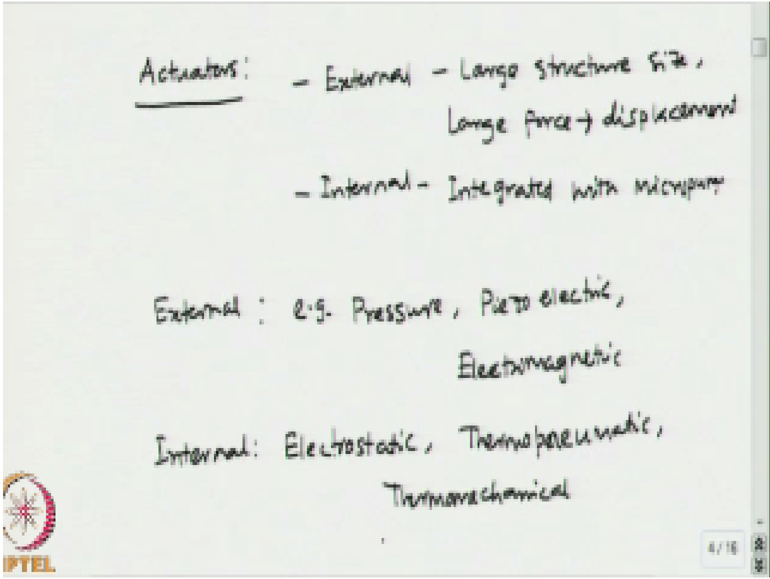

So, these are the different flow capacity of different micro pumps. Now, let us look at the actuation principle of this micro pump, okay. So, the actuators can be divided into 2 categories; external actuators, internal actuators. The external actuator based micro pumps are relatively larger in size because the actuation principle is outside the micro pump, whereas the internal actuator based micro pumps, the actuation principle; the mechanism is actually integrated with the micro pump, okay.

So, actuators are external actuators and internal actuators and these are; you know, they have large structure size and they require large force for actuation and offer large displacement okay whereas, internal actuators are easily integrated okay, so integrated with micro pump. Now, the examples of external actuators are what we have seen earlier is the pressure; pressure based actuation or we have the piezoelectric or electromagnetic.

So, these are outside the micro pump okay, internal actuators are electrostatic, so these are actually inside the micro pump itself electrostatic, then we have thermal pneumatic, where we have; we can integrate hitters inside the pump chamber; thermo pneumatic and we would have thermo mechanical, so it should work on the principle of the difference in the thermal expansion coefficient; thermo mechanical micropump okay.

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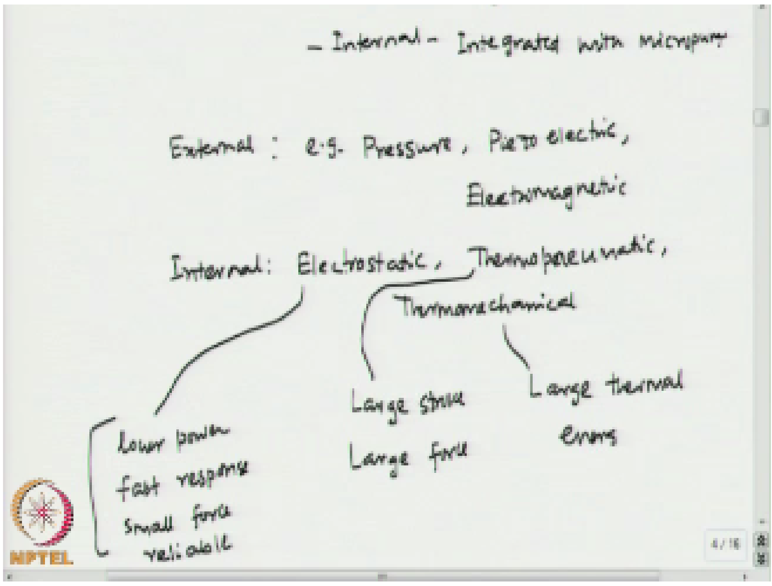

And these have distinctive advantages; electrostatic for example, will have; will require lower power for operation okay and they have very good response, they have first response and however, the small; the force that they exert are relatively small and they are also reliable. So, these are the characteristic of electrostatic based actuation. Similarly, thermo pneumatic have large stroke okay, so the displacement volume is large.

And the force that they can exert is also large and thermo mechanical will use large thermal energy because we are talking about the expansion of the pump; part of the pump material, so it will use large thermal energy okay. Now, let us look at the mechanics of the pump membrane; pump membrane is an important part of you know; mechanical micro pumps, so let us look at the pump membrane mechanics.

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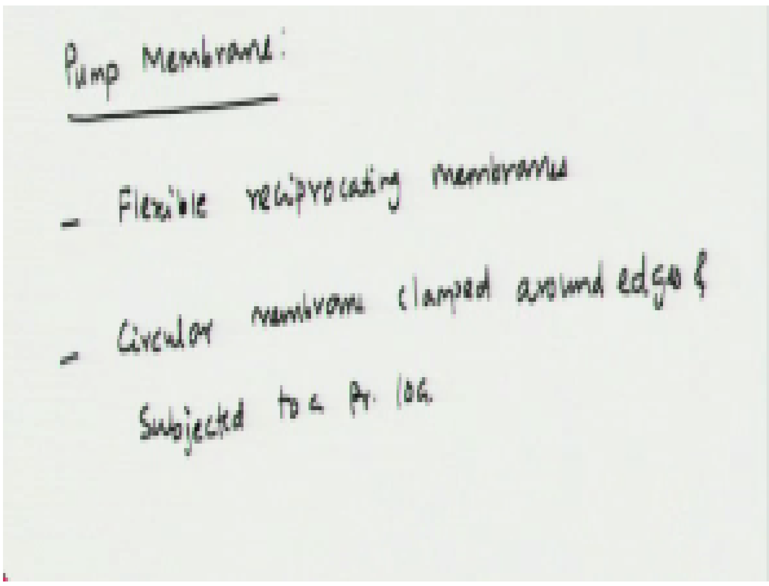

So, the pump membranes are normally; you know are flexible and reciprocating nature; is a flexible reciprocating membranes and here if you consider a circular membrane clamped around its edges and it is subjected to a pressure load okay so, this is the situation we would have, okay.

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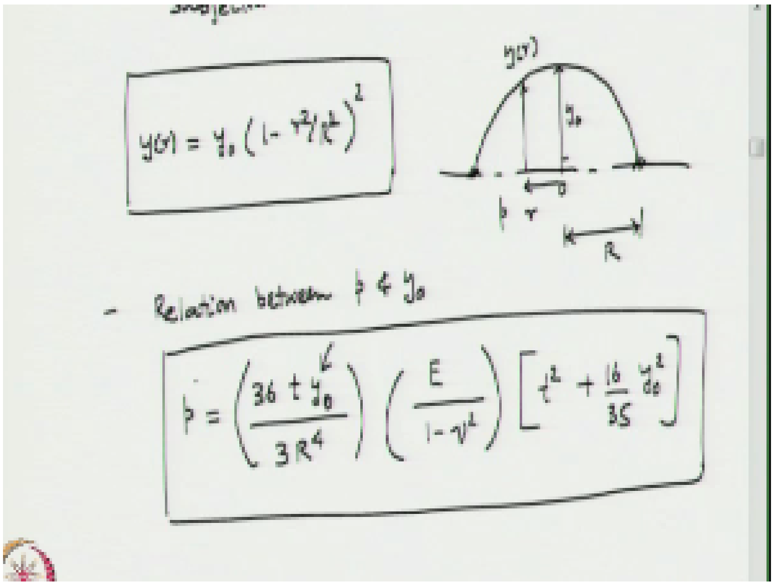

So, we would have the pump membrane, which is clamped around the perimeter and this would be maximum deflection y0 and at any r is called this is the deflection at yr, where this is going to be the r and the capital R is going to be the radius of the membrane, okay; r, right. So, in that case, we can write the deflection at r as the maximum deflection * 1 - r square/ r square whole square okay.

So, that is how the deflection of the membrane will vary along the radial direction, okay where y0 is the maximum deflection, r is the membrane radius okay. We can also establish the relation between the pressure, so that this is the pressure that is acting on the membrane for the deflection. So, you can you know establish the relation between the pressure and the maximum deflection, so relation between pressure and y0 has been estimated as P.

So, this has been also analytically derived, so this is going to be 36t; t is the membrane thickness * central deflection y0 / 3R to the power 4, okay * E is the Young's modulus of the membrane material – 1 - Nu square; Nu is the Poisson's ratio and * t square + 16/35 * y0 square, so this is how we can relate the pressure that is acting inside the membrane to the maximum thickness of the membrane, okay.

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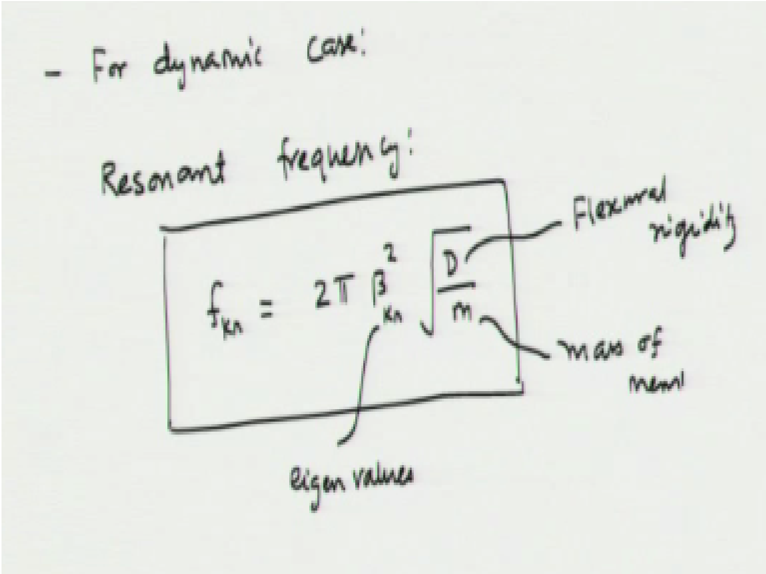

So, all these parameters are known, which use for a membrane. Now, for dynamic case, the dynamic case, we can determine the resonant frequency, so the resonant frequency can be expressed as so, fkn is going to be 2pi beta kn square * D over m, so fkn is the resonant frequency, beta kn is the eigenvalues, so these are the eigenvalues and D is the flexural rigidity okay and m is the mass of the membrane.

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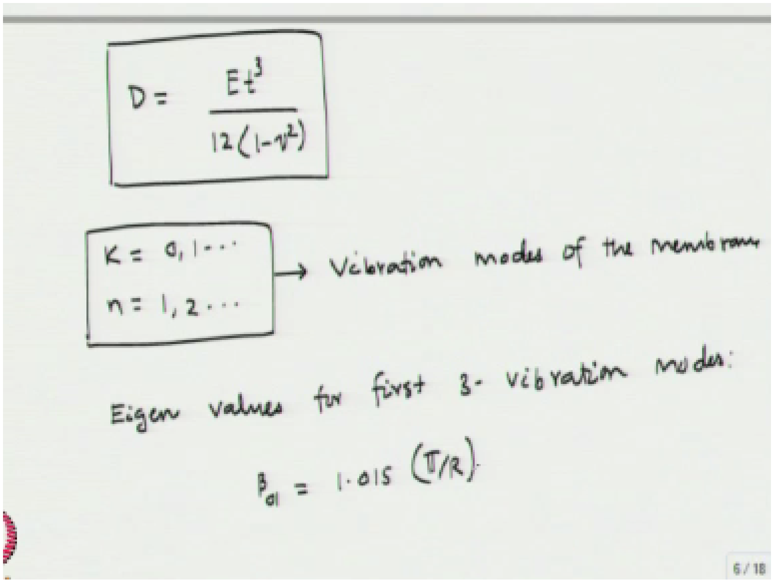

So, m is the mass of the membrane, so the flexural rigidity D can be written as Young's modulus * thickness to the power 3, 12 * 1 – Poisson’s distribution square, so this is the expression for the flexural rigidity and k, the subscript that we are talking about; k will vary as 0, 1 and n will vary as 1, 2 okay. So, these are the vibration modes; these are the vibration modes for the membrane, okay.

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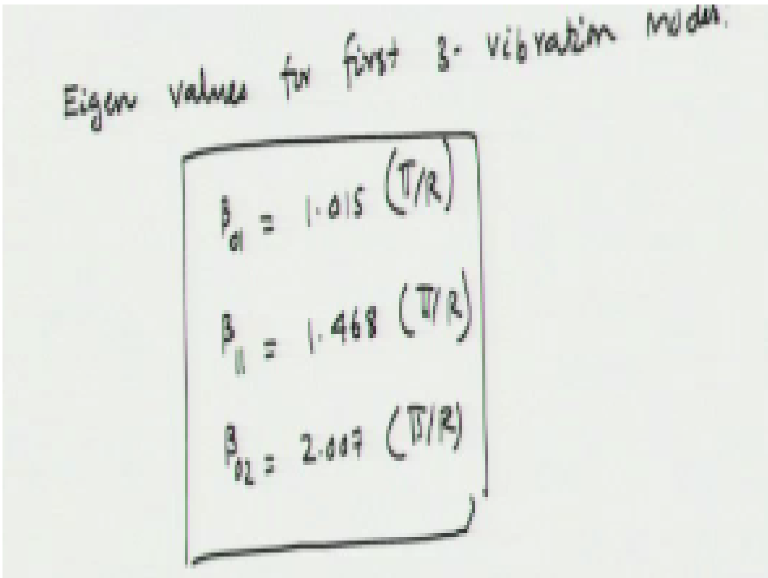

And so, considering the first 3 vibration modes, we can write the value for the Eigen value; value of the Eigen value. So, the Eigen values for first 3 vibration modes can be written as; so beta 0, 1 would be 1,015 pi over r, okay and beta 1, 1 would be 1.468 * pi over r and beta 0, 2 would be 2.007 * pi over r, so these are the first 3 Eigen values for the first 3 vibration modes okay.

So, using these values for a particular configuration of a; you know membrane, we can calculate what is going to be its resonant frequency, which is an important design parameter okay. So, now let us look at what are the pump parameters, so the important parameters for the pump will be the pressure rate, the flow rate and the power consumed by the pump and also we are looking at the efficiency; the energy efficiency of the pump.

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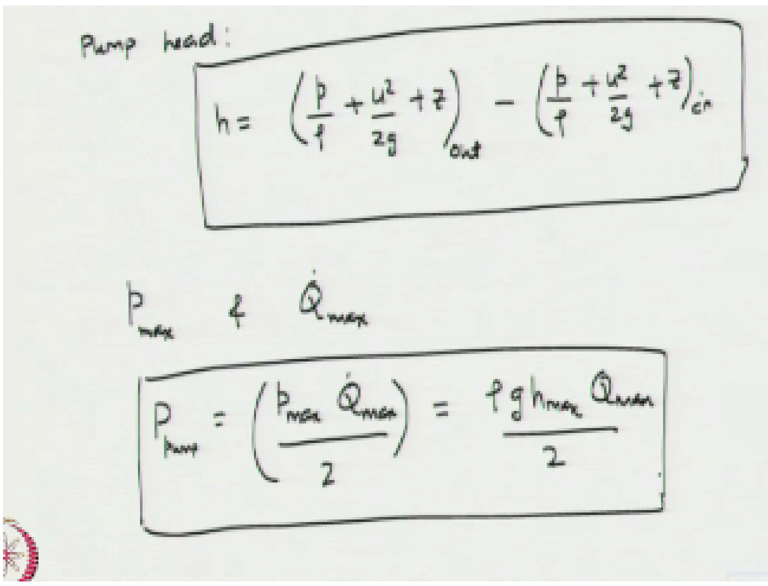

So, let us look at the pump parameters; the important parameters here are the pump head, so the pump head will be the total head at the outlet - the total head at the inlet, okay. So, H the total pump head will be P over rho + u square by 2g + Z that is at the outlet of a pump - p over rho + u square by 2g + Z at the inlet of the pump. Now, if you say that the maximum pressure is P max and the maximum flow is Q max.

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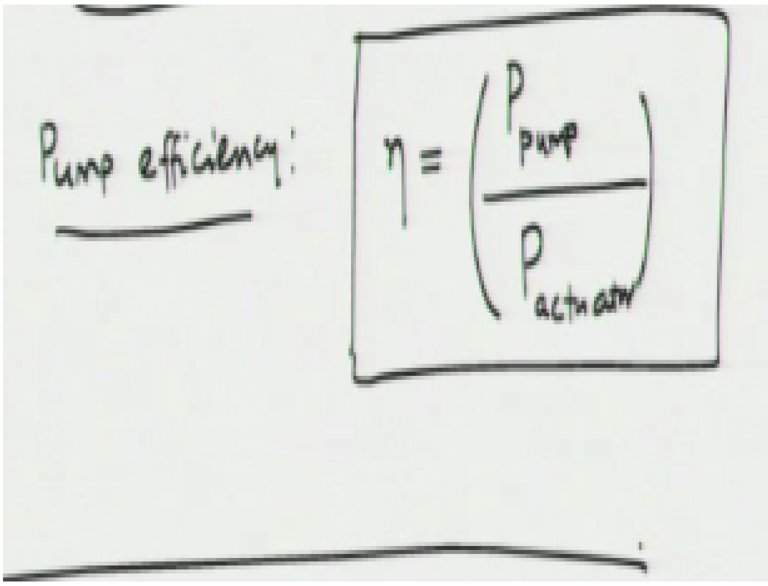

You can write down the expression for the power consumed, so get this; power for the pump is P max * Q max, so this is flow rate, so there is a dot there Q max/ 2, okay and if you know the maximum head instead of pressure, then you can write rho g h max * Q max / 2, okay. The other parameter that is important for the pump is the pump efficiency. So, the pump efficiency can be defined as; so, ETA the pump efficiency is the power delivered by the pump okay, which is P max Q max over 2/ the power, the energy; rate of energy supply to the actuator.

So, in case of; for example, a thermal pneumatic based micropump, the actuation comes from the thermal pneumatic mechanism, so based on the heater power that is consumed by the pump and if you know the power delivered by the pump, you can find what is going to be the efficiency of the micro pump. So, now let us look at the simplest possible micropump, which is the check valve micropump.

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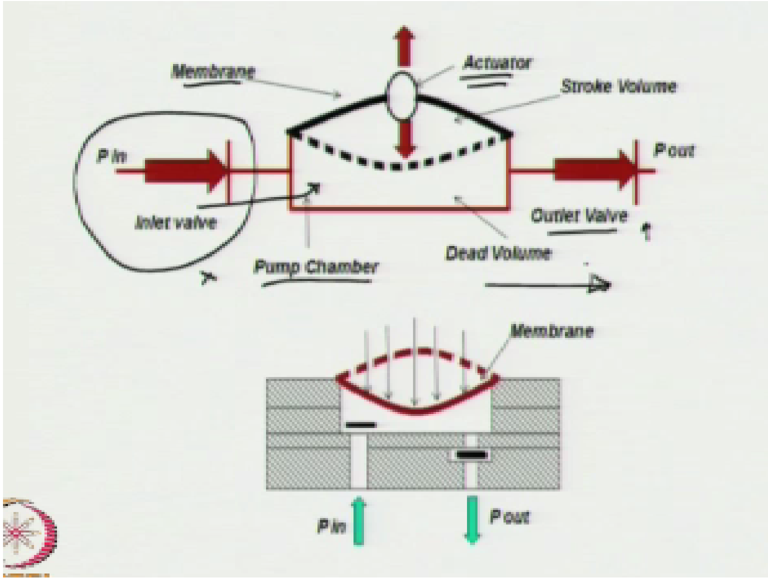

So, typically you will have a chamber with an actuator on top and on either side, we would have 2 valves; one to control the incoming fluid and the other one to control the outgoing fluid okay. So, the first pump that we look at the check micropump. So, here you see an image of the check valve micropump, so this is the pump chamber okay and on top of the chamber, you have an actuator, so this could be any actuator.

It could be piezoelectric, it could be thermo pneumatic and that actuator is going to actuate the membrane okay, which is the boundary of the pump chamber and on the inlet side, you have an inlet valve and on the outlet side, you have the outlet valve, okay. So, when the membrane expands the liquid comes into the chamber through the inlet valve, so the inlet valve opens and the liquid comes to the chamber.

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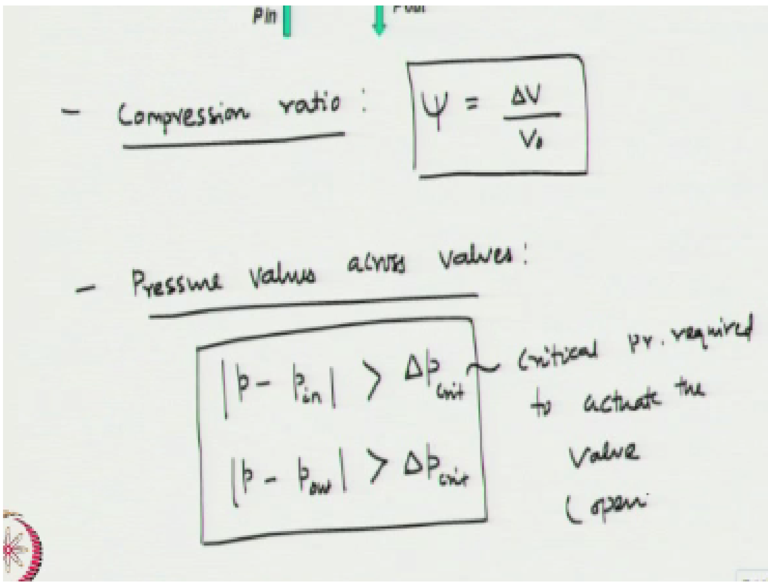

And in the forward stroke, when the membrane comes down, this valve is opening and this valve gates closed okay. So, we have a fluid gets transported from inlet to outlet okay, so let us look at the important parameters to define this; the check valve micropump and one such parameter is the compression ratio and compression ratio is defined as the stroke volume/ the dead volume okay.

So, compression ratio is defined as; so compression ratio is defined by psi, which is the stroke volume/ the dead volume V0, okay. Now, the second important criteria is the pressure that is required to actuate this micro valves, okay. So, for the inlet valve, the pressure difference between the incoming supply and the pressure inside the chamber has to be greater than the critical value of the critical pressure that is required to open the inlet valve okay.

So, the other important parameter is the pressure values across the valves and here we should have p - pin should be the mod of that should be > delta p critical. Similarly, we need to have p – p out has to > the delta p critical. So, the delta p critical is the critical pressure that is required to actuate the valve to open or close the valve. This is the critical pressure required to actuate the valve mainly opening okay.

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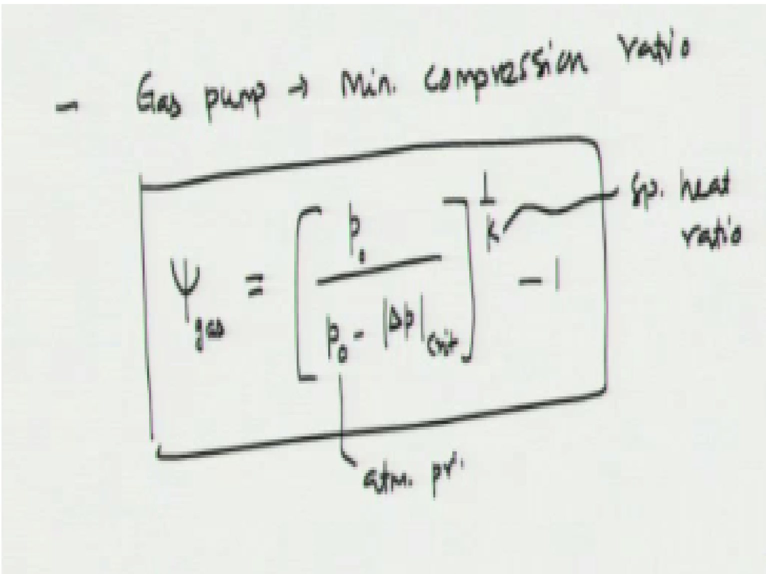

Now, for a gas pump, we have an expression for the minimum compression ratio. For a gas pump, the minimum compression ratio has been estimated as minimum compression ratio for a gas pump is given by; so, delta V to dead volume will be p0/p0 - delta p critical to the power 1 over k; k is the specific heat ratio – 1. So, this is the specific heat ratio and p0 is the ambient pressure; atmospheric pressure.

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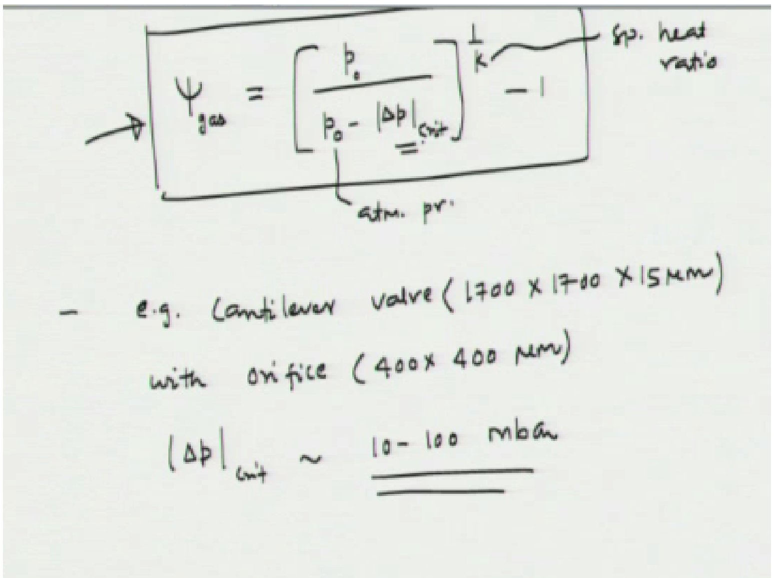

Just to give you an example, if you have a cantilever valve, so just as an example, we have a cantilever valve that has dimension 1700 * 1700 * 1500 micron thickness okay. So, it is basically a cantilever plate that is getting actuated because of the inlet pressure okay, so normally the valve will be; the cantilever will close the valve port and when the pressure exceeds, then the valve port will be opening because of the deflection of the cantilever.

So, if you have a cantilever which has 1700, 1700 * 1500 micron dimension and with the orifice, where the fluid tries to get in is; 400 * 400 micron, then typically the pressure; the delta p critical will be of the order of 10 to 100 milli bar, so that is the kind of pressure; actuation pressure we are talking about, when we are talking about micro pumps, okay. Now, if you look at this equation, if you assume that we are talking about low pump frequency and the small critical pressure, then you can simplify the expression okay.

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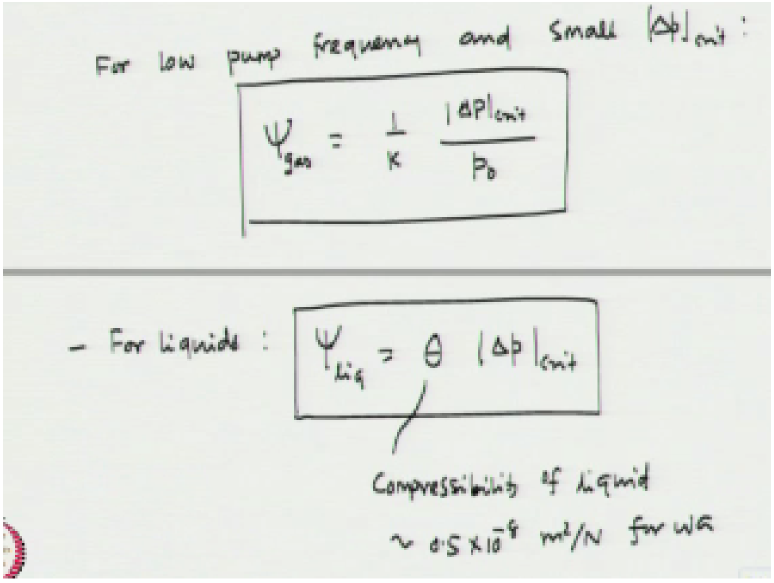

So, for low pump frequency and small critical pressure, you can simplify the compression ratio of gas as 1 over k * delta p critical/ p0, okay. Now for liquid, we also have an expression for the compression ratio or liquids; the compression ratio is theta * delta p critical, where theta is the compressibility of liquid, so this is the compressibility of the liquid and which is typically 0.5 * 10 to the power - 8-meter square per Newton for water.

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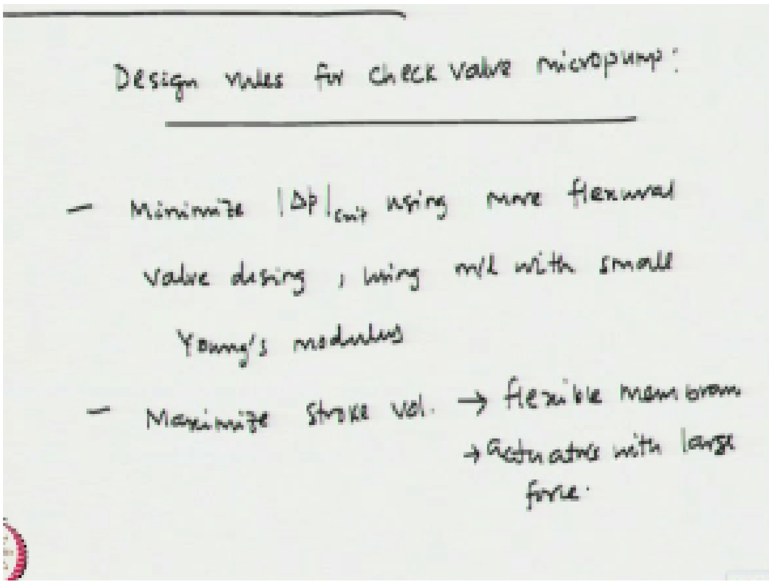

Now, let us look at the design rules to make to design a check valve micro pump, so the design rules for check valve micro pump, so one important design rule would be the critical pressure that is required to open the valve has to be minimum and that can be achieved by using a more flexural valve or you know materials having small Young's modulus okay. So, one important thing will be to minimize the critical pressure using more flexural valve design or using material with small Young's modulus.

The second design objective has to be to increase the stroke volume and to increase the stroke volume; the requirements should be the membrane has to be of low stiffness okay, it should be more flexible, okay. So, the second objective would be to maximize stroke volume, so that is possible by flexible membrane, it is also possible by using you know large; the actuators with large force; actuators with large force, okay.

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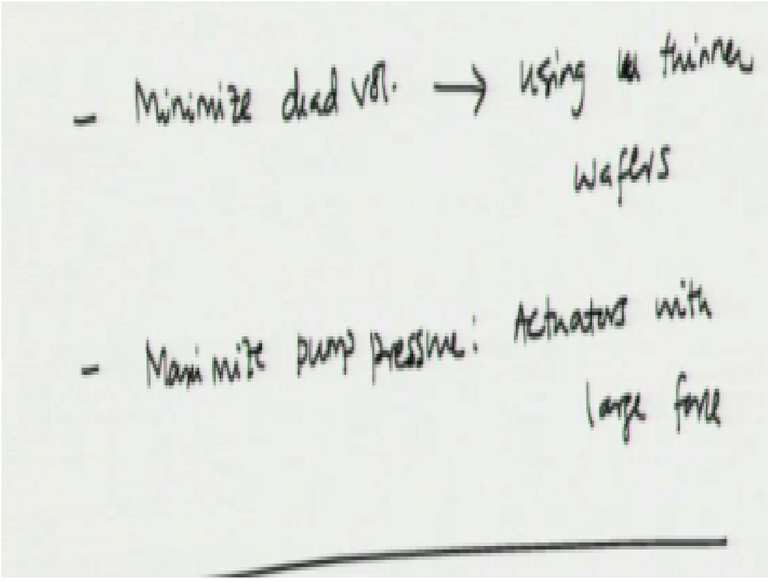

So, the actuators of the large force, the dead volume can be; the stroke volume can be increased and the third objective has to be to minimize the dead volume okay, so that we get the dead volume of more liquid do not stay idle inside the chamber okay. So, we to minimize dead volume and this can be done using thinner wafers; using thinner wafers. So, the chamber depth has to be minimum, okay.

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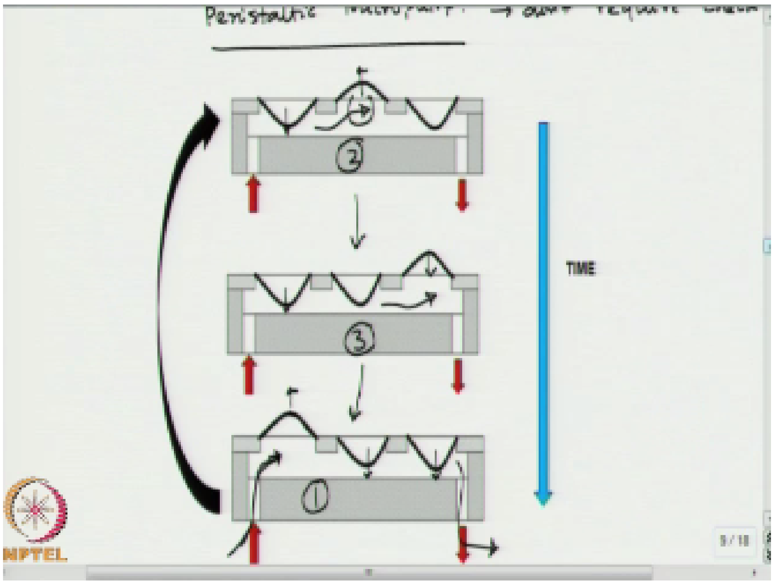

And the final objective has to be to maximize the pump pressure; maximize pump pressure which can be achieved using actuators with large force okay. So, let us continue our discussion with peristaltic micropump. So, let us continue our discussion with very static micropump, so these peristaltic micropumps, they do not require any check valves, they do not require check valves.

Normally, they do not require check valves and you know their motion is based on the peristalsis motion that we use; you know how the food goes from our mouth to our stomach, so based on peristalsis motion okay. So, if you look at the mechanism here, what happens is so, here in this particular case, we have 3 different chambers with 3 different membranes actuated sequentially.

So, this is the first step, what happens is this membrane is going up, okay, so that it creates a negative pressure so the liquid from the inlet comes inside okay and so in that stroke, these 2 membranes; these are all controlled using a control system, the actuation of the membrane are automated. So, when this expands, these 2 membranes are going down, okay. In the next stroke, so the liquid has already come in here, in the next stroke this membrane will go down.

So, the second membrane will go off, so the liquid that has come in from the inlet will pass on to the second chamber okay and at the same time, the third membrane is going down. So, the liquid cannot escape okay, in the third cycle; so this is the second cycle. In the third cycle, the first membrane will go down and the second membrane; so the fluid is now present here. Now, second membrane will go down and the first membrane is going down anyway, so the fluid has only option to go to the third membrane.

So, it will go into the third chamber and you know again, it will go back to the first cycle and so when it goes back to the first cycle, the liquid present here; if that membrane will go down in the third cycle, so the liquid is going to exit okay and at the same time, the liquid comes out here through the inlet because this chamber is moving up. So, this motion of the different membranes is occurring sequentially in a controlled manner to drive the fluid from the inlet to outlet using peristaltic motion, okay.

One issue with the peristaltic micropump is that when the micro pump is operational, it is fine the liquid will go from the inlet to the outlet however, in situations where the micro pump is idle and you have already pumped some fluid from inlet to outlet to a high pressure source. If the micro pump is not operational, there is a possibility of backflow okay. Now, to win that we would need, one check valve upstream; one directional check valve up stream, okay.

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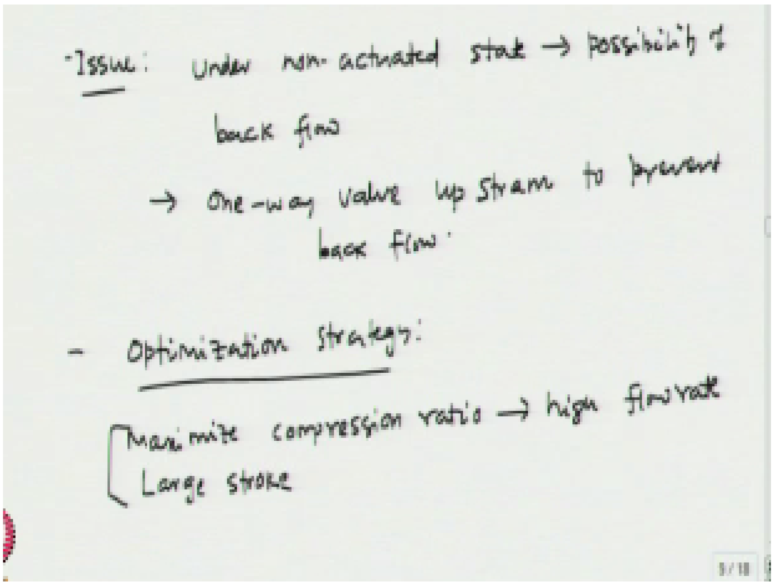

So, one issue with check valve micropump is that under non actuated state, so there is a possibility of backflow; there is a possibility of backflow, so we need you know; one-way valve upstream to prevent backflow and some of the optimization strategy for the peristaltic micropump; optimization strategy, we want to maximize the compression ratio; maximize the compression ratio, so that gives us high flow rate.

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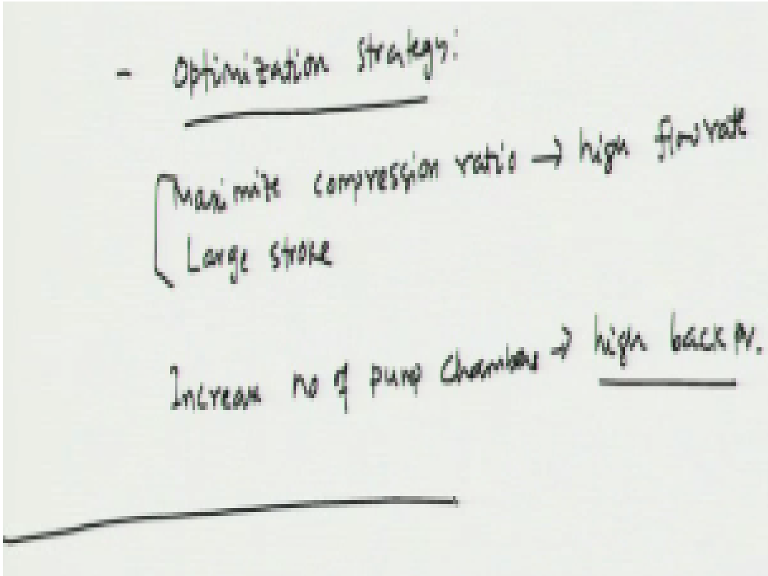

So, this together with the large stroke would give us the high flow rate and we also need to increase the number of pump chambers, so that would give you a high back pressure okay. So, with that let us stop here.