Microfluidics
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Lecture - 31
Microvalve

Okay. In this lecture we will talk about microvalves. Microvalves are another important component in microfluidic devices, which is used to manipulate flow rate inside microfluidic devices okay. And the microvalves can be categorized as into 2 different types, 1 is the passive microvalves, which is does not require any external energy, typically it will have a spring and when the inlet pressure exceeds a certain value, then the spring will reflect and the flow will come in from an external source into the valve chamber.

And in active valve, there will be an actuator, which will be controlling the force exited on to the valve chamber and accordingly the valve port can open okay.

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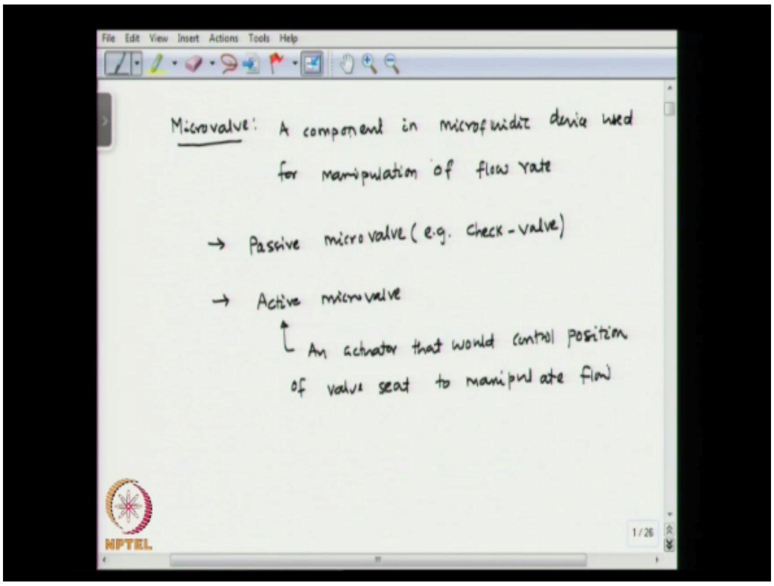

Microvalve is a component in microfluidic device used for manipulation of flow rate okay. So, the microvalves can be categorized into passive microvalve, which does not require any external energy so, one example would be the check wall that we have discussed when we were talking about micropump and the second one is active microvalve okay.

So, in the active microvalve, we would have an actuator, that would control the position of the valve seat to manipulate flow and the flow can be manipulated in 2 ways, one is the analog mode and the second one is the digital mode okay.

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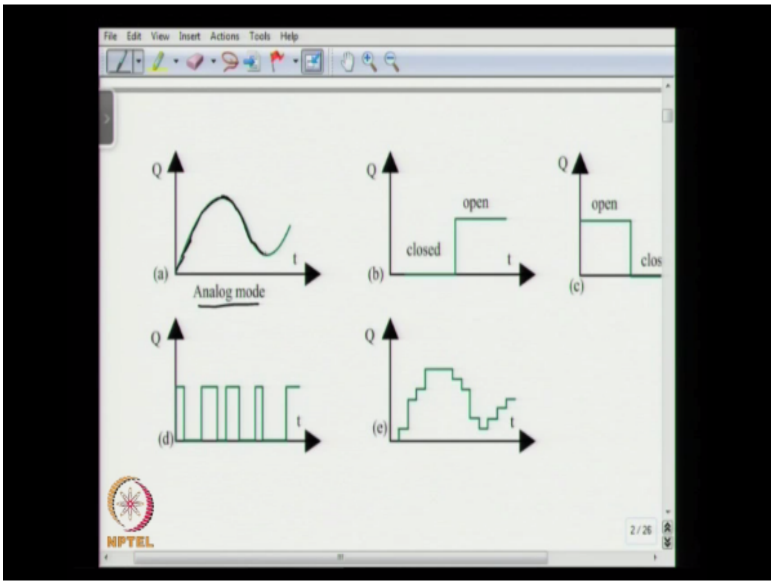

So, in the analog mode, as you can see here, in analog mode, the valve actuator will control the gap between the valve seat and the opening to control the flow rate. So, as the gap varies as the gap increases, the flow rate will increase and as the gap reduces, the flow rate will decrease.

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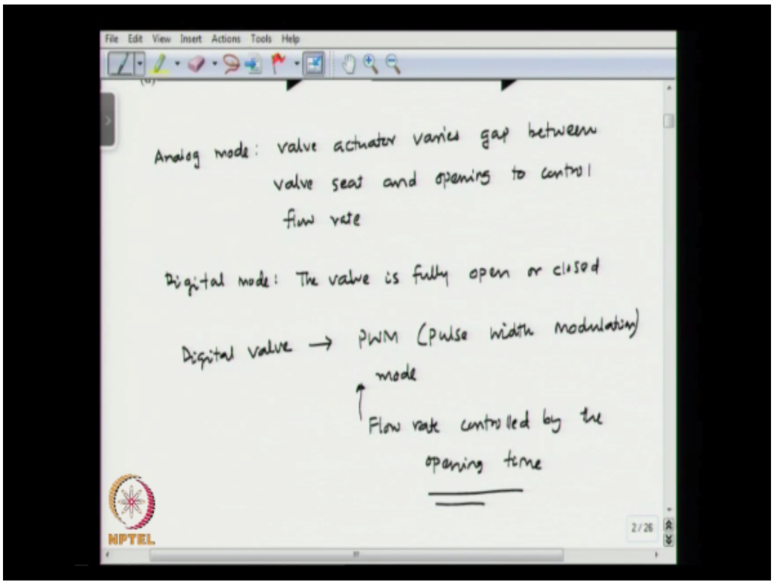

So, in the analog mode, the valve actuator varies gap between the valve seat and the opening to control flow rate okay. And the second one is the digital mode and as you can see here, in the digital mode, the valve is either open or closed as you can see here, this is the closed cycle of the valve and then are some arbitrary time t0 the valve starts to open and so here, initially the valve is open and then are some arbitrary time t0 dash, the valve starts to close okay.

So, in the digital mode, the valve is fully open or fully closed okay. And the valve can also open in the digital valve can also operate in what is called pulse with modulation mode. In which case, the opening time of the valve will control the flow rate okay. So, the digital valve can operate in pulse with modulation mode okay. So, in that case the flow rate controlled by the opening time okay. Now, let us talk about different types of microvalves that exist.

So, these different types of microvalve are categorized based on the actuator, the actuating principle that drives this microvalves okay.

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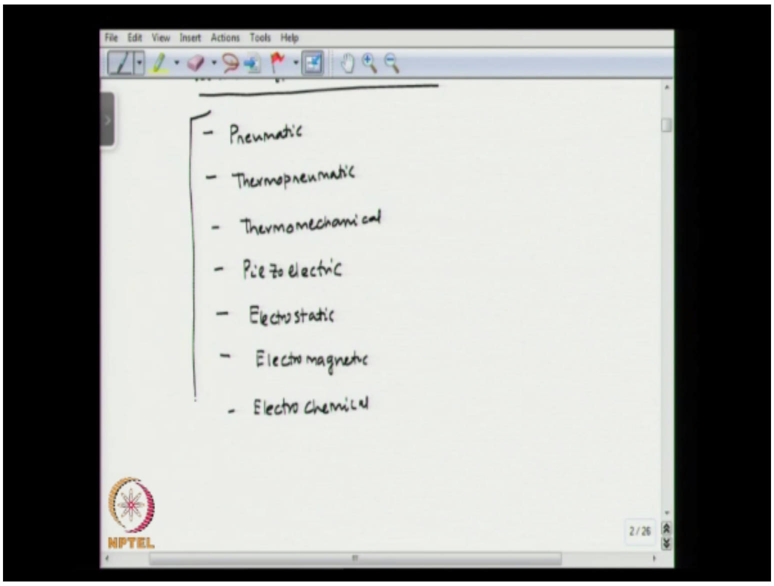

So, let us talk about different types of microvalve okay. So, one is pneumatic, which uses the principle of external pressure, then you have thermopneumatic, which uses external heat to generate pressure inside. Then we have thermo mechanical, which uses external thermal energy to generate mechanical energy, then piezoelectric, then we have electrostatic, then we have electromagnetic and we have electro chemical okay. So, we will be discussing each of these types of microvalves okay.

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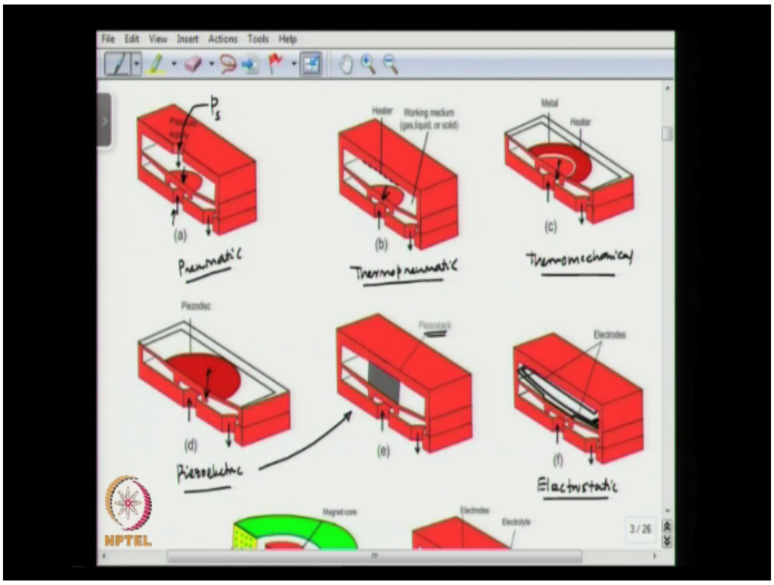

SO, let us first look at the designs of different types of microvalves. So, this is a pneumatic microvalve, so this is the inlet supply connected to the external fluid source okay and this sis the valve actuator okay, this is the disk which is being actuated by external supply. When this line is connected to the external supply and the external pressure, the p supply pressure is > the spring constant + the inlet pressure, then the valve would be in the closed state okay.

And when this external pressure is taken of, the membrane goes back to its original position because of the spring force so the valve is open okay. In similar way here, this is the pneumatic okay and this is thermo pneumatic, here we have an array of heaters and there is the fluid present here inside and when the heat pulse is supplied to the heaters, there is the bubbles are formed and this bubbles expand when they expand, they will actuate this membrane okay.

So, that is how the valve will be controlled. So, this is actually a thermo mechanical valve okay and here, the heater is present on top of the membrane as the thermal energy is supplied, because of the thermal expansion, the valve will be actuated. And this is the piezoelectric actuator okay and here, by applying an external electric field, a strain could be developed in the piezo material, which is used to actuate the valve and this is a piezo disk and here, we are talking about a piezo stalk okay.

Several of these disk placed on top of each other, piezo stalk. And this is electro static so that basically relies on the attraction force between 2 oppositely charges electrodes to fluctuation of the membrane.

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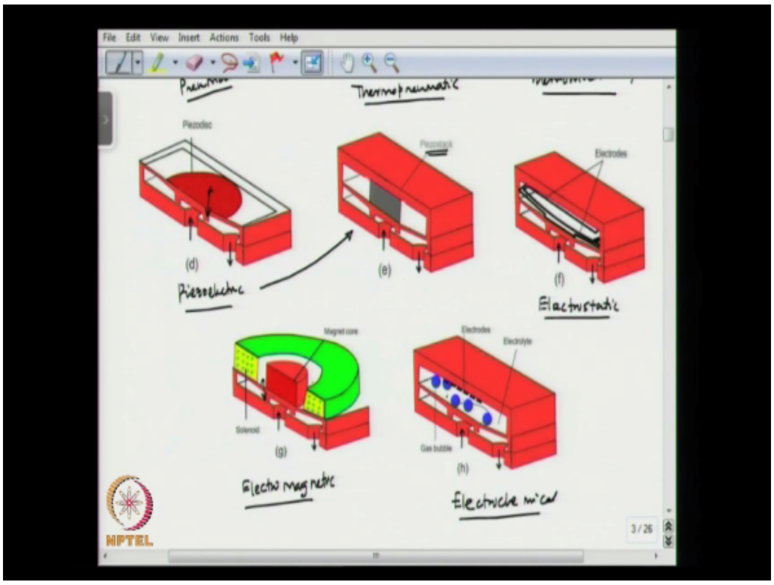

This is electromagnetic okay and this one is the electro chemical. So, in electromagnetic, the magnetic force is actually trying to actuate the membrane and here, in electrochemical, electrolysis of the electrode generates this gas bubbles, which tend to expand and contract when the thermal pulse is taken away. So, that is how the membrane is actuated okay. So, now let us define some parameters that specify different microvalves okay.

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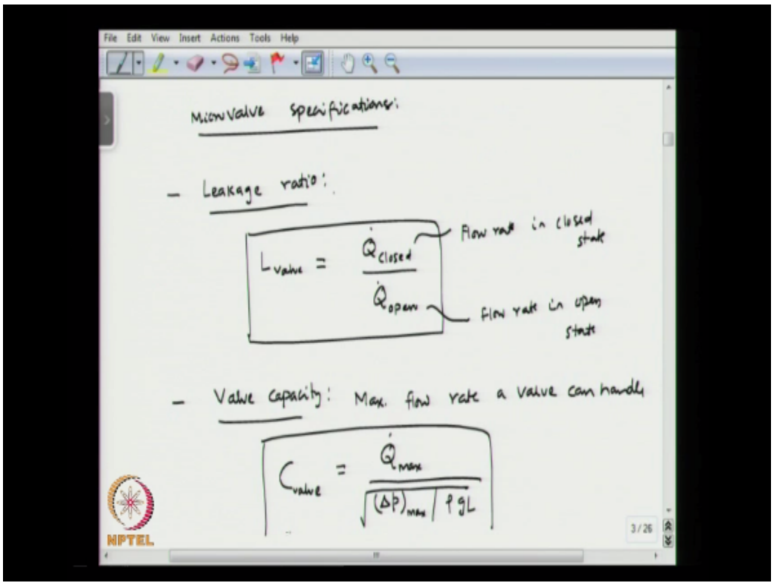

So, let us look at the microvalve specifications. So, the first thing is the leakage ratio. So, leakage ratio is the flow rate through the valve in a closed state to that in the open state okay. So, the leakage ratio, which is specified as L valve is defined as the flow rate through the valve in the closed state divided by the flow rate in the open state okay. And if there is no leakage in the closed state, the leakage ratio is going to be 0 okay. So, this is the flow rate in closed state and this is flow rate in open state okay.

The second parameter that we are defining is the valve capacity. Valve capacity has the maximum flow rate that the valve can handle okay. So, this is the maximum flow rate valve can handle so, we specified by C valve, which is given as Q max, which is the maximum flow rate divided by delta P max divided by rho gL square root of that okay. So, that is how we specify the valve capacity.

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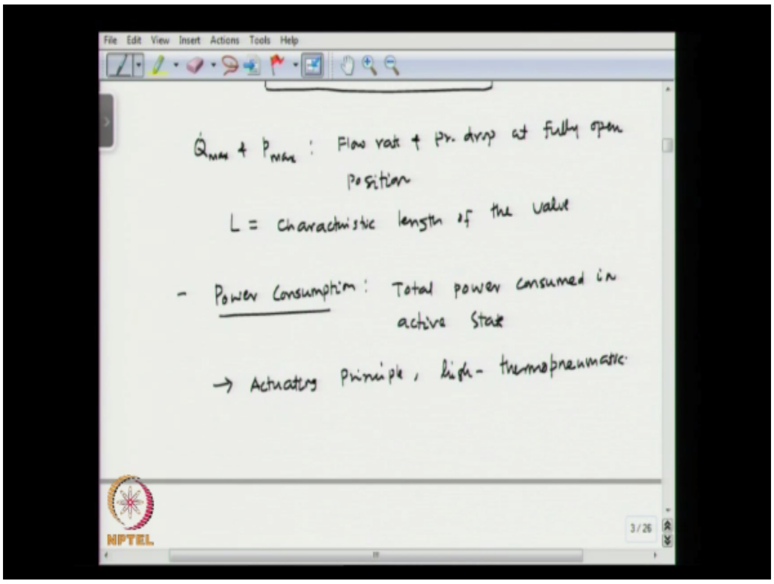

Now, here Q max and P max are flow rate + drop at fully open position and L is the characteristic length of the valve okay. The third parameter that we specify is the power consumption. So, it is the total power the valve will consume in active state and so, this will be the total power consumed in active state and the power would depend on the actuating principle and this is going to be high for thermo pneumatic okay.

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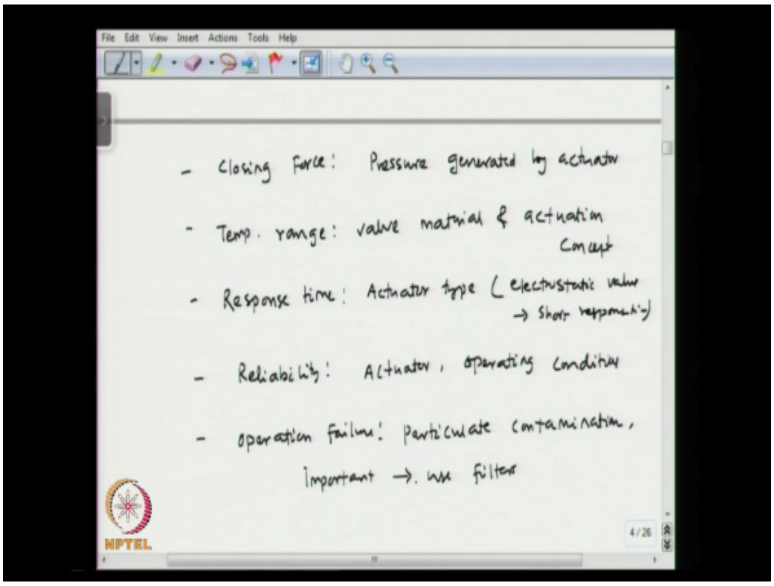

The next parameter that we specify is the closing force. So, closing force would depend on the pressure generated by the actuator and the next one is the temperature range, which would depend on the valve material and the actuation concept. Then the response time, how quickly the valve is going to respond, that would depend on the actuator type and electrostatic valves have got very less response time okay. So, electrostatic valve short response time okay.

Then reliability, so reliability will depend on the actuator and the operating conditions and operation failure. So, one major reason why valves would fail is when there is a practical inclusion in the flow okay. So, when the particles will be included in the flow, what happens is these particles will tend to stick between the valves seat and the valve structure. That is how the leakage of the valves will fail okay. So, one way to handle that is to use filter okay.

So, operation failure 1 major reason is because of particulate contamination and so it is important to use filters okay. Now, let us look at few parameters that we would be using to design micro pulse. One important parameter is the energy that is supplied by the actuator okay. How we can calculate the different energies for different types of microvalves okay.

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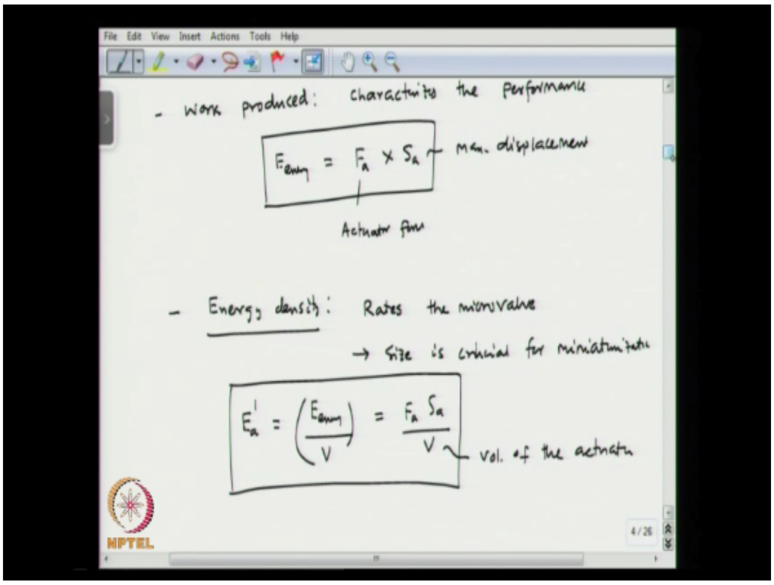

So, let us look at the design considerations. So, first important consideration is the work produced, which basically characterizes the performance. So, the work produced could be the actuator force into the maximum displacement okay. This is the actuator force; this is the maximum displacement okay. Now, we define energy density. So, in micro scale in addition to talking about how much work is produced, the actual physical size of the device is also important.

So, it is the energy density, which will rate a particular microvalve okay. So, this rates a microvalve and this is because the size is crucial for miniaturization. So, we can define energy density dash as the work produced per unit volume okay. So, that is a Fa*Sa divided/V. so, V is the volume of the actuator okay.

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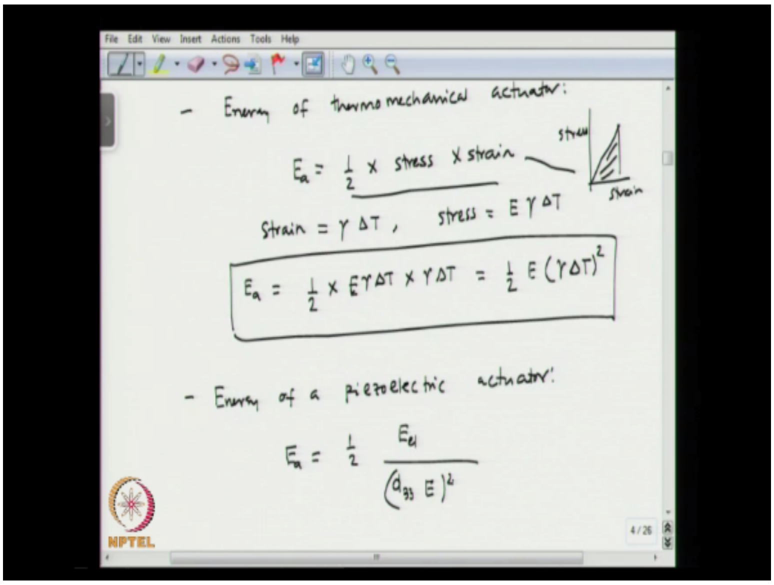

So, now let us find the energy of thermo mechanical actuators. The energy is given by the expression half*stress*strain okay. So, the strain in case of thermo mechanical is going to be the thermal expansion coefficient*temperature difference. Similarly, the stress is going to be Young's modulus times the strain so, gamma*delta T. so, you can find out the energy which is going to be half*E gamma delta T*gamma delta T and which is going to be half E gamma delta T square okay.

And this is because the stress is proportional to strain and the energy is area under the stress incurred okay. So, let us say this is stress and this is strain, then we would have the energy within the area okay. Next, we can find the energy of a piezo actuator. So, the energy of a piezo actuator is half*the electric field divided by the piezo electric coefficient*young's modulus square okay. So, this is the electric field, this is Young's modulus and this is the piezo electric coefficient okay.

Similarly, you can find the energy for an electrostatic actuator. You can find energy for an electro static actuator.

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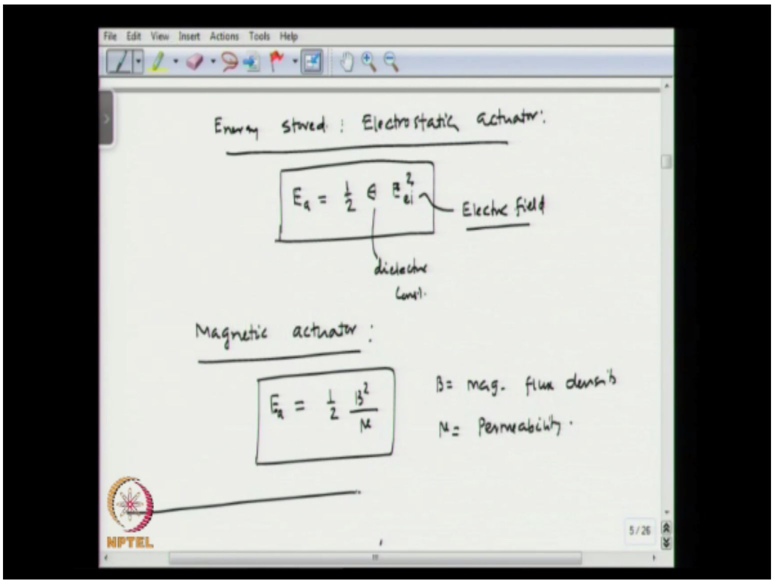

So, for the electro static actuator, the energy is given by half*epsilon*the square of the electric field okay. So, this is the dielectric constant, this is the electric field. So, when you are talking about electrostatic actuator, we are talking about the energy stored between the 2 parallel plates of the electro static actuators and here in this case, so the expression is given by half*epsilon*electric field square. So, epsilon is the dielectric constant of the medium between the 2 parallel plates and this is the electric field okay.

Next, we talk about for a magnetic actuator, for a magnetic actuator, energy will be given by half into B square over mu, where B would be the magnetic flux density and mu would be the permeability of the medium okay. So, with that design conditions, let us look at the response time and the pressure characteristics of different types of microvalves.

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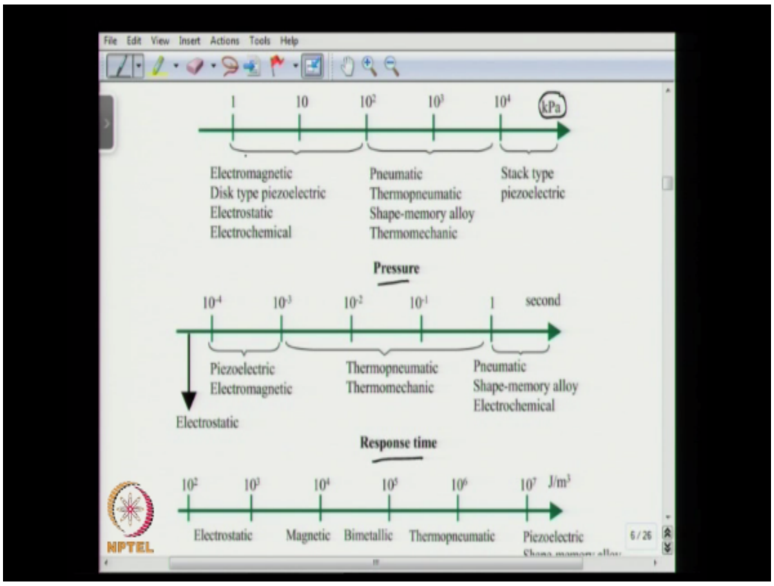

So, here we see the pressure, the response time and the energy density of different types of microvalves. You can see the pressure is given in kilopascal and you can see for low pressure range, somewhere between 1 to 100 kilopascal we would have electromagnetic, piezoelectric, electro static and the electro chemical. In the medium range, between 10 to the power 2, 100 to till their 4 kilopascal, we would have pneumatic, thermo pneumatic, shape memory alloy and thermo mechanical.

Piezoelectric type microvalves can offer the highest pressure okay. So, anything higher than 10 to the power 4 kilopascal can be obtained using piezo electric type micro pump, especially stack type piezoelectric, where we have multiple disk mounted on top of each other okay. If you look at the response time, as you discussed before, electro static microvalves have got very low response time and the piezoelectric and electromagnetic microvalves have response time between 10 to the power -4 to 10 to the power -3.

And then the response time of thermo pneumatic and thermo mechanical is between 10 to the power -3 to 1 second okay. And the microvalves like pneumatic, shape memory alloy and electro chemical, their response time is very poor okay. So, they have response time higher than 1 second. So, you can see that there is a tradeoff between the pressure and the response time. And if you look at energy density, the electro static microvalves have very low energy density.

So, they have energy density between 10 power 2 to 10 power 3 followed by a magnetic, which is less than bimetallic and the thermo pneumatic microvalves have energy density of the order of 10 to the power 6 joule per meter cube and the piezoelectric and shape memory alloy have got very high energy density of the order of 10 to the power 7 joule per meter cube okay. Now, with that let us look at the pneumatic micro pump, so we look at what pneumatic microvalve is. So with that let us look at pneumatic microvalve.

So, we will first look at, so we will try to understand what a pneumatic microvalve is, understand the operational principle and take on a design problem okay.

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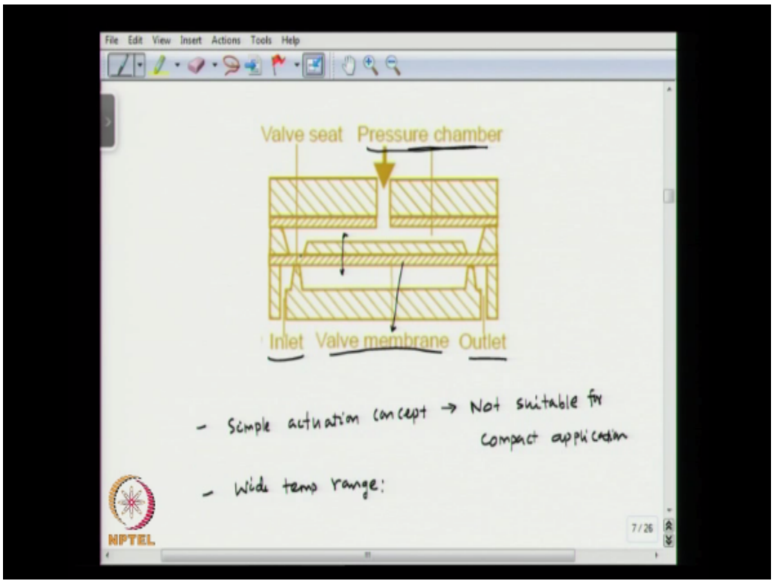

So, let us talk about pneumatic microvalve. As you can see here, this is the valve membrane okay. So, this is the valve membrane as you can see here, this is the inlet to the fluidic source and this si the outlet and this one is the valve seat okay. So, this is the topside of the membrane is connected to a pressure chamber okay. Now, when this pressure is more than a critical value, then the membrane will deform and the valve will be closed okay.

And when the supply pressure is taken off, then because of the spring constant of the valve membrane, the valve is going to open up okay. So, the actuation of the valve is going to take place by controlling the pressure inside the chamber and which can happen by controlling the external pressure okay. So, what are the characteristic of pneumatic microvalve? The pneumatic microvalve have simple actuation concept okay.

So, the actuation concept is very simple but since we are talking about connecting with external pressure source and these external pressure source are larger in size and you would require interconnection mechanism to connect fluidic supply with the microvalve. The size of the microvalve is a concern okay. So, because of that these microvalves are not suitable for miniaturization okay or they are not suitable for compact application and they have widest temperature range okay.

This is because when we apply a pressure irrespective of the temperature, the membrane is going to deform okay. So, this pneumatic microvalves will have wide temperature range okay. So, this is because the membrane deflection occurs irrespective of temperature okay. And the pneumatic microvalve should be optimized.

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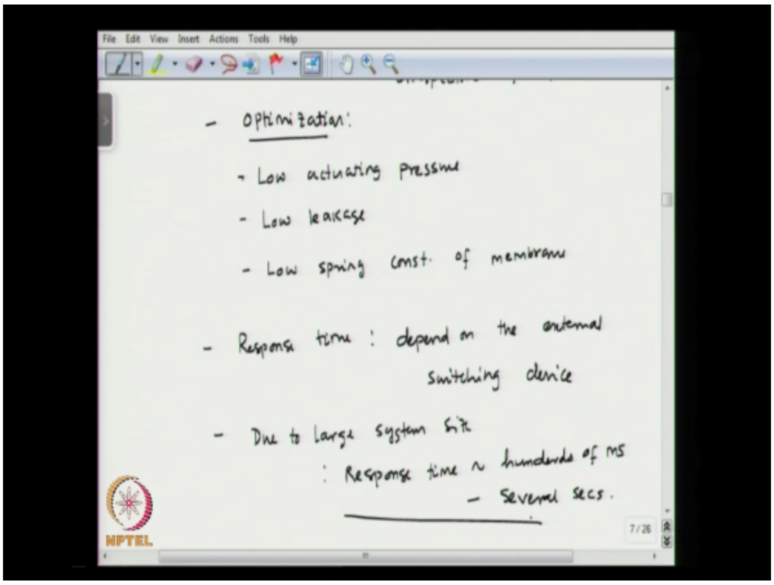

So, the optimization criteria we should try for low actuating pressure. There should be 1 design goal and we should try for low leakage and we should also try for low spring constant of the membrane okay. Now, since we are controlling the microvalve or the membrane actuation using an external supply, the response time of the microvalve would depend on how the control is happening for the external supply okay.

So, the response time would depend on the external switching device okay. And due to large system size, the response time is typically large okay. The response time is of the order of

100's of milliseconds to several seconds okay. So, the response time of pneumatic micro valve is poor. So, with that let us look at a design problem.

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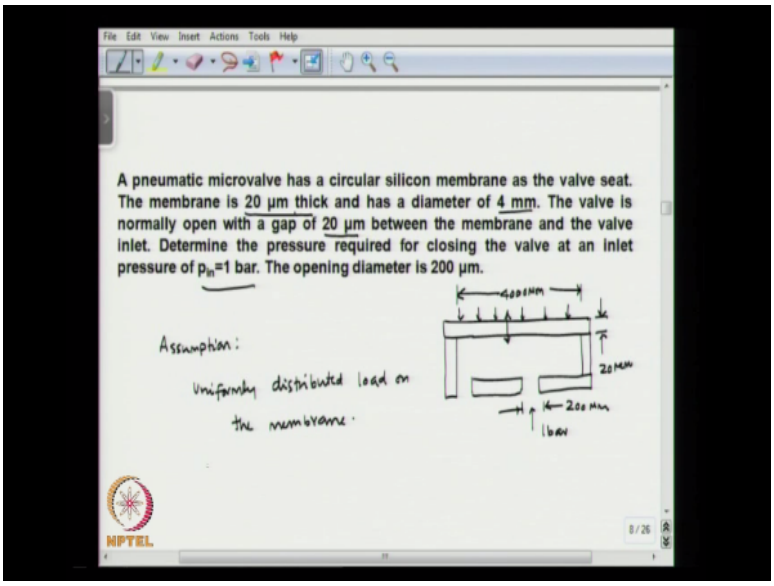

So, this is the problem we have, we have a pneumatic microvalve that has circular silicon membrane as the valve seat. The membrane is 20 micron thick and as a diameter of 4 millimeter okay, that is 20 micron thick and it has dia of 4 millimeter. The valve is normally open with a gap of 20 micron between the membrane and the valve inlet and we want to determine the pressure that is required for closing the valve at an inlet pressure of 1 bar okay. And the opening diameter is given which is 200 micron okay.

So, typically we have a configuration something like this. So, we have one inlet okay. So, this is the inlet and this membrane is going to deform to actuate the valve okay. And this is abouT20 micron and this is 4000 micron diameter okay. And we have the supply pressure is 1 bar and this gap is 200 micron okay. So, now if we assume a distributed load on the membrane, so let us say the external pressure applies in uniformly distributed load on the membrane.

So, we make an assumption which is uniformly distributed load on the membrane and we say that the Poisson's ratio nu is .25 and Young's modulus is 170 giga pascals that is per silicon okay. These are for silicon.

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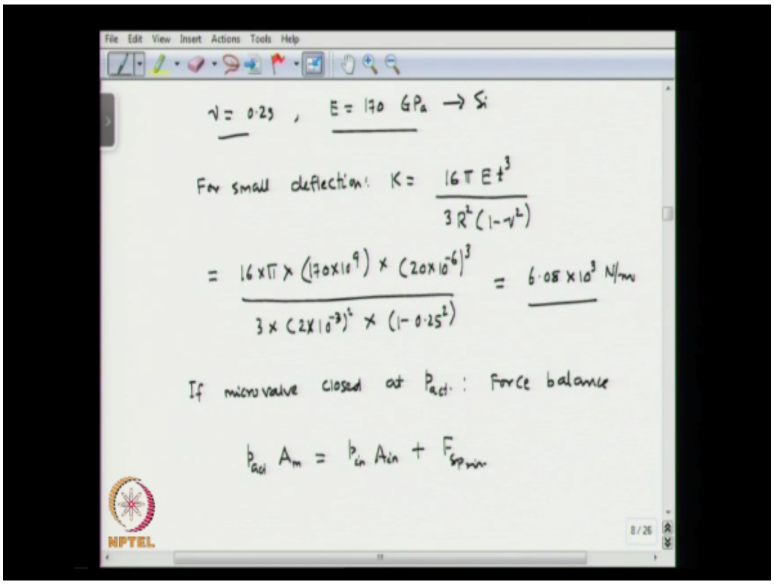

Now, if you assume that the deflection is small, we have an expression for the spring constant of the membrane okay. So, for small deflection, the spring constant can be written as 16 pi E t cube over 3 R square*1-q nu square okay. So, we can plug in the values 16*pi is 170*10 to the power 9 and thickness is 20 micron. So, divided by 3*2 *, sorry this is R square, the radius is 4 millimeter so the diameter is 4 millimeter so the radius is 2 millimeter*1-.25 square.

So, we will get the spring constant as 6.08*10 to the power 3 newton per meter okay. Now, if the valve is closed then the total pressure that is exited on the membrane because of the external pressure will be = the pressure that is at which the fluid is trying to come in + the spring force exited by the membrane okay. So, if microvalve is closed at the actuation pressure, then we can write down the force balance.

Switch will be the actuation pressure * the area of the membrane is going to be P in*A in + spring force okay. So, the pressure inlet is here so, the force it will try to exert will be on this area. So, that is A in and area of the membrane is the entire area top area here okay.

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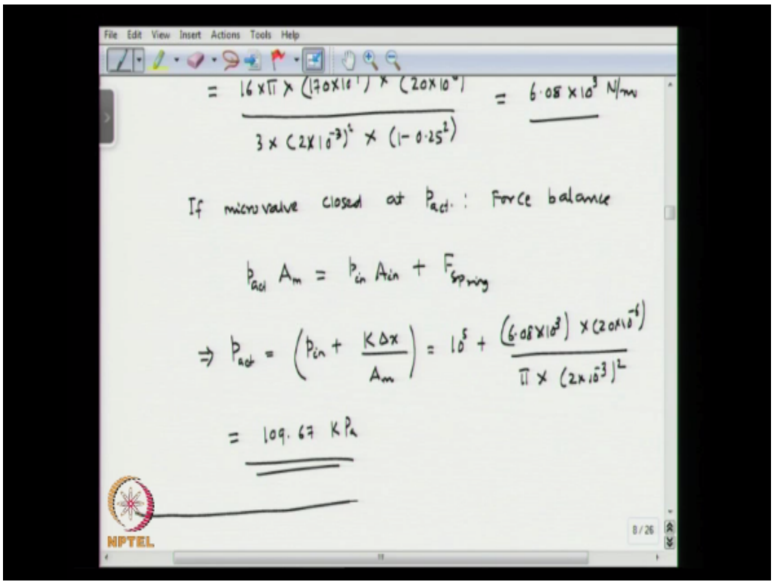

So, you can write the P actuation would be P in + K*delta x over area of the membrane which is given by 10 to the power 5 + 6.08*10 to the power 3*20*10 to the power -6 divided by pi into 2*10 to the power -3 square okay. So, that would be abouT109.67 kilo pascal okay. So, we need this amount of pressure to close the microvalve okay. So, with that let us move on and talk about thermo pneumatic microvalve.

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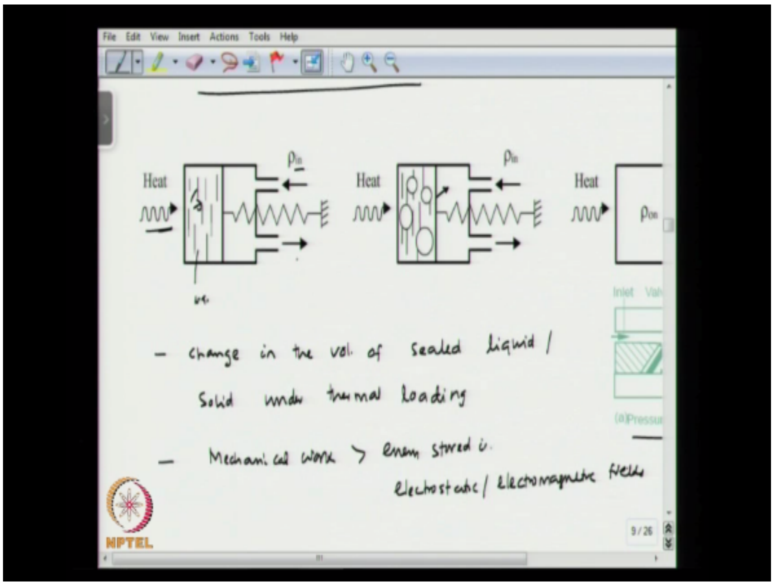

So, let us talk about thermo pneumatic microvalve. So, the thermo pneumatic microvalve basically rely on the change in the volume that happens inside a chamber because of some kind of a change okay. So, it cud be because of hitting the fluid that the liquid will convert into gas. Or a solid will convert into liquid that the volume of the chamber would increase. So, that would actuate the membrane for actuating the valve.

So, as you can see here, here we have a pressure chamber okay and so there is a liquid present inside and we have an array of heater that you can see here. So, when heat energy is added to the fluid, the heat is enough then the liquid is starts to get into the gas phase okay. So, there will be nucleation and expansion of the bubble and because of the expansion, this membrane here is going to be actuated and as the volume inside will grow the membrane will get in touch with the valve seat okay.

So, that is how the valve is going to be closed okay. And when the heat pulse is taken away, again the valve can open. So, that is how the valve is going to be actuated. So, the principle is shown here. Let us say this is the inlet and this is the outlet. So, typically we have a liquid present inside the chamber here and as heat is supplied, initially let us say, there is no fetch ins okay. So, this material is still in the liquid phase.

Now, here the volume expansion would be because of the heating okay. Because of the thermal expansion coefficient of the liquid okay. Now, if the temperature is enough, then the liquid the liquid the nucleation of the bubble will start to occur and as the heat is continuously supplied, this bubbles will grow. So, this membrane is trying to expand okay and at some point, the gas will be completely filled inside the chamber and the membrane will seal the inlet as well as the outlet.

So, that is when the valve is completely closed okay. So, what are the characteristics we are basically relying on change in the volume of a sealed liquid or solid on the thermal loading okay. And in this case, the mechanical work is > the energy stored in electro static or electromagnetic field okay.

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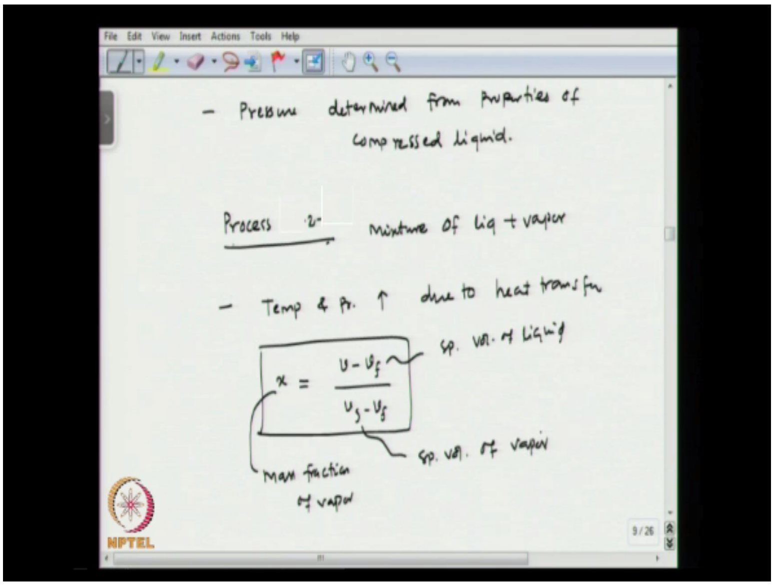

Now, let us say the volume is V and mass is m, then the specific volume v can be written as V over m, which is 1 over rho okay. And as you can see, as the chamber is sealed, the mass is not going to change. So, the specific volume is going to be directly proportional to the volume of the chamber okay. So, chamber is sealed, m is constant. So, the specific volume is going to be proportional to the chamber volume okay.

So, now let us look at 3 different processors that we see here. So, let us say the process here, there is no refer page. So, it is still liquid and there is a change in the temperature. So, in that case, the thermal expansion coefficient will come into play. So, in this case, the change in the volume delta V is going to be V0, which is the initial volume * the gamma f, which is the thermal expansion coefficient*T2 - T1 okay. If in this case, the valve is going to be closed, the specific volume is going to be constant okay.

And the pressure will be determined from the properties of the compressed liquid okay. So, pressure is determined from properties of compressed liquid okay. And let us say the next process, the process 2, let us say so, it is a mixture of liquid + vapor. So, there is a fate change okay. And as there is a fate change, the temperature as well as the pressure both increase due to the transfer okay. And so in that case, we can define something called a mass fraction of the vapor, which will be = V-Vf over Vz - Vf okay.

So, this is the mass fraction of vapor and this is specific volume of liquid and this is specific volume of vapor okay. Now, let us look at the third case. So, here we have the complete vapor and it could be super heated okay.

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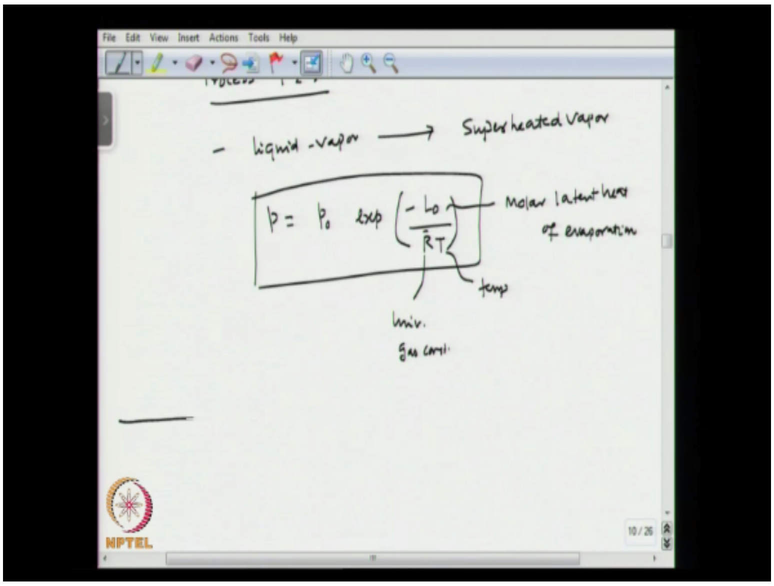

So, in the third case, let us say we call it process 3. So, in this case the liquid vapor mixture is converted to super heated vapor okay. So, there the pressure could be determined. So, P0*exponential - L0 over RT okay. And where this is the universal gas constant and this is temperature and L0 is the molar latent heat of evaporation of the liquid okay. So, let us stop here and we will continue our discussion with microvalve.