BioMEMS and Microfluidics
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Lecture – 32

Hello and welcome back to this lecture 32 on Bio micro electro mechanical systems.

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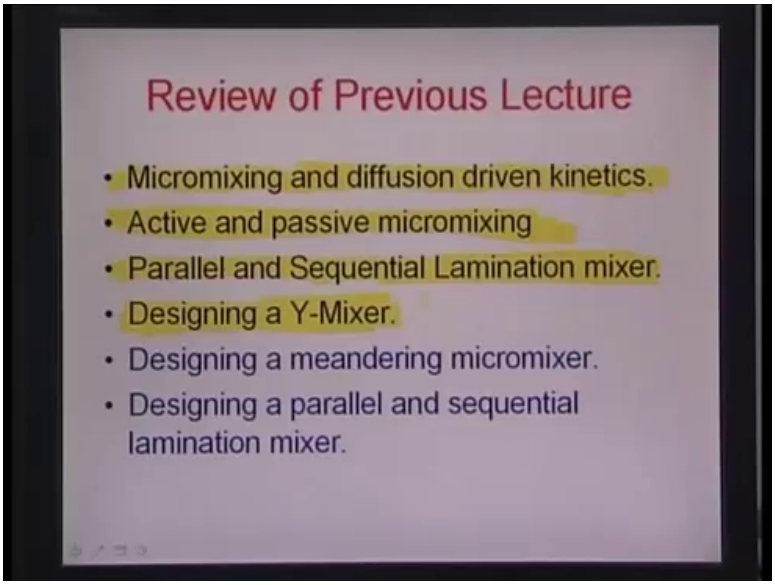

Let us quickly review what have been done last time we talked about the principles of micromixing and the diffusion driven kinetic just like to retreat there in micro scale mixing really is a diffusion will phenomena there is no as such other mass transport except inter molecular diffusion. And, so therefore, diffusion time and residence time and there comparison becomes a very important of criteria for establishing proper mixing.

We talked about active and passive micro mixers active mixers if you may recall are a essentially those mixers, where energy is been supplied externally by a mechanical or non mechanical means and passive mixers are pure mixing by intelligent design, where you can actually split the force apart many times and join them back, so that the form laminar and that way you reduce the inter diffusion length between the different mixing layers.

And, so therefore, the time of diffusion can be reduced in this manner and taken much, much below the residence time. So, that there is mixing till and until the flows inside in the chip and by the time it gets out the totally mixed. So, we talked about parallel and sequential lamination mixers parallel mixers are where will have multiples streams focusing on to a

small cross sectional area. So, that the diffusion length becomes equal to the actual length divided by n, where in is a number of such streams.

And sequential being basically trying to go out of plain and then, back end plain, so that you can physically laminate the flows to gather and therefore, there are there is a reduction in diffusion time by about 4 to the power of n minus 1, where n is the number of stages, where this mixing text place. We also try to this numerical examples design a Y shaped mixer found out, what is the length of the micro channel micro channel for the mixing to be is contentious and proper. We also design the meandering micro mixer and reduced into a small 6 mm by 6 mm by area and try to define number of turns that a channel of finite length would take, if you comes to this particular area.

Then, we also talked about different designs for parallel and sequential lamination mixers based on the diffusion time reduction concept and compared for a single for a certain amount of mixing time ratio both the stages. And we found outs certainly that ion case of sequential lamination mixer lesser number of stages are needed in comparison to there in the case of parallel lamination mixer for proper mixing. So, let us look at today little more of experimental microfluidics.

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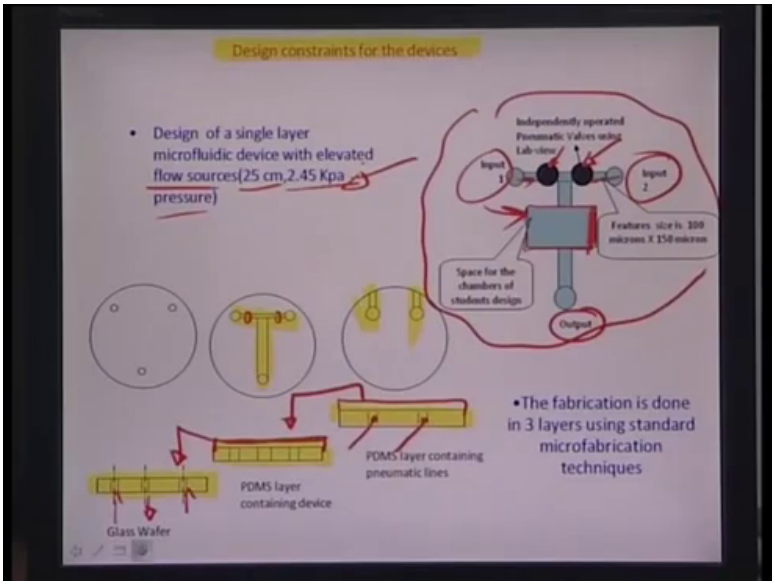

I would like to discuss a small example here, which is actually perform by graduate students and essentially student starting new in this area are kind of left at sounded by the counter intuitive nature of the micro flows. And definitely they are much, much wave we beyond the concepts that you can have from micro scale mixing for micro scale turbulence driven

phenomena. So, here in this design experiment you suppose to design a three layered mixer with the glass layer at the bottom, as you can see here at this glass layer has been drilled with some holes.

So, that you can have this holes for inlets and outlets of the fluid you have another layer at the top of it, which is actually a PDMS layer with t section channel as you can see here in the top view illustrate in the top view and here there is a some short of a continues layer of PDMS of the top of these channels. So, that they are covered they are replicated of the lower surface of the PDMS and this then is bonded to is glass layer.

Then, further you have a another layer where you have this blisters as the third layer and in this particular layer again you have certain thickness of PDMS over the blisters the blisters as can demonstrate at represented here are actually air pockets and this further is bonded back into the top of the first PDMS layer. So, you have a three layered are a stack of three layer devices and here what you do is we use this sport for feeding in and out the fluid flow and essentially you feel these particular ports here to inflate and deflate the air blisters. So, that you can actually compress these channels and both and here as you can here in this particular figure.

So, here as you see there are these two blister walls, which would actually regulate to the flow coming from these two inlets input one and input two the idea is that these two one maybe dye one maybe water and they may be mixing along this output here of the stream are outlet of the stream they will be mixing along this, this particular zone of the stem of a t. And in this particular t again you have an area, which is unknown and the idea was the students in this particular experiment was suppose to design a certain futures and structures and this area, so that they could promote quick and rapid mixing in this particular architecture.

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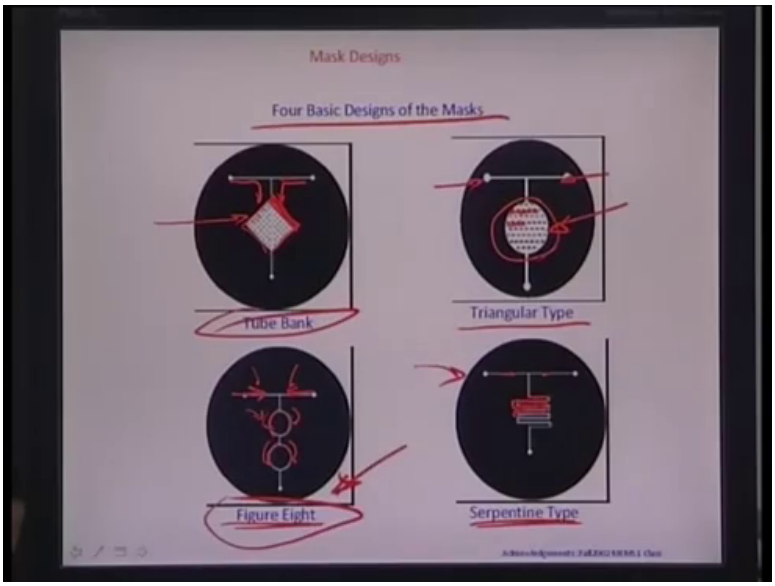

So, several designs of proposed at the first things is by the students are the foremost pronominal designs, which are proposed are tube bank like structures basically there would be small bits in this particular area and this would be corresponding to small pillar is of the PDMS, which get replicated, which gets replicated and top of this. So, this was one illustration, where this central area here is introduced with this kind of feature or structures and the flows go from the arms of the T and mix along this particular area, which is also along the stem of the T.

Similarly, here if you see in this particular example you have a let say flows coming from both and here and mixing along this circular area, which is essentially made up of small, small triangular species of resist. And if you just do the replication and top of this it becomes triangle pieces of PDMS pillars on the top surface of the reservoir, which is shown here in this particular example. The third design was a figure eight type of a system, where there would be repeated amount of mixing and split ups of the flow see you have flow one and two coming from both this direction and they would makes and they would split up again and then, again makes so on and so forth.

So, this is the figure eight kind of design and then in the fourth design the students plan the meandering shaped micro mixer, where they would have all this fluid go length wise side by side with the certain inter facial area along a bigger track, which is define by this meandering channel between the small region on the stream of the T. So, all this four designs are investigated for mixing if I flows die was used from one it was gravity fed the idea was, which was given in the constraint that you should have the flow sources elevated to about 25

centimeters, which means there are pressure of equal to 2.45 kilo pascals is to be generated.

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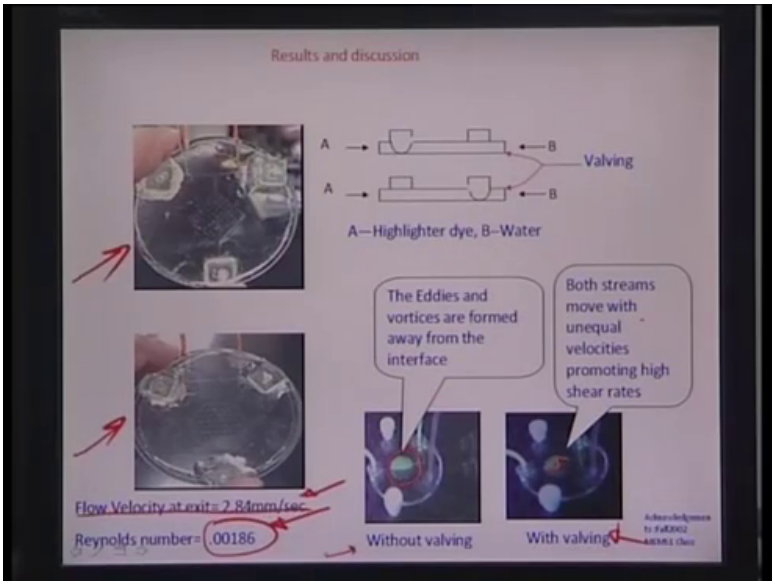

After flowing of this kind of pressure driven flow through this micro channels a following results came and they were really, really counted yet duo to. So, when you actually use these a structures whether it is a tube bank kind of structure of the triangular type you have really as you see here the florescence die and the water flowing parallel, what is interesting to observe here that was although there are lot of this small, small PDMS pillars around, which the fluid should routed and should create local vertices or eddies they are too small to cause any mass transport particularly across the interfacial layer.

So, even though there exist somebody some vertices away from the interface they are not significant to contribute any kind of mass transport across the two layers. And therefore, until and unless you really start operating the blusters and block one flow at a time and try to move this cross section as you have seen here in this case and the flow line with the die as been pinch and, so the flow of the die as reduced to one side. And similarly, with other inverse effect is done with the water line pinch the die would try to go.

So, it switched passed the interface switch is passed in a very serpentine like manner as you actually try to open and close the die on the water one at a time a through this automated blister side. And that does result in some amount of mixing although not very appropriate. So, the take on message here for the experiment was and even though you have structures and futures, which would cos the it is to develop there would be two for away from the interface are they own be much significant effect of this eddies and vertices away from the interface to

cross the mass transport between the two streams.

So, couple of things here to be mention one is the flow velocity at the exist as a about 2.84 millimeters per second that is how it was define and corresponding to that the Reynolds number was really, really low about 0.00186. So, this is without valving and this is with valving.

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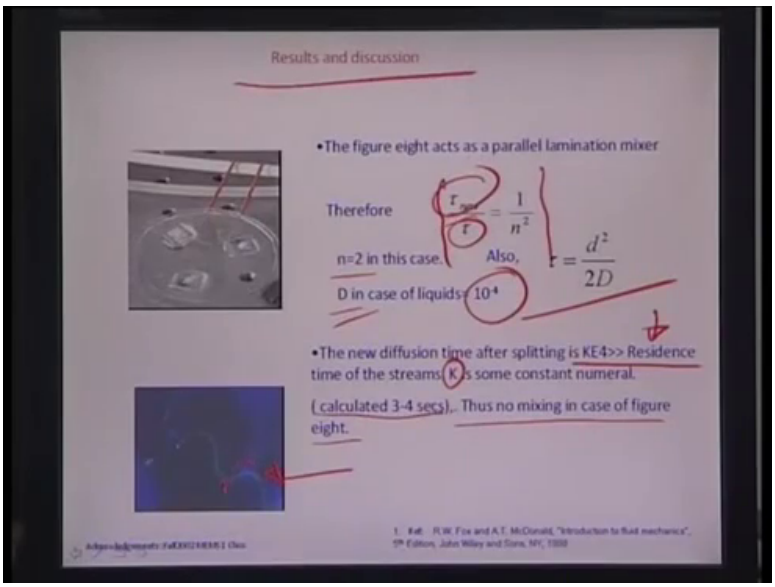

$$\frac{\tau_{new}}{\tau} = \frac{1}{n^2}$$

$$\tau = \frac{d^2}{2D}$$

The other two design also very evaluated the figure it type design basically would be something like a parallel lamination mixer and as we all know for in the case of parallel lamination mixer the time mu be actually the 1 by n square times of whole time. And in two in this case and be essentially in this case about 10 to the power of minus 4 being a fluid. So, if you see here this kind of illustrates how these fluorescent dies would behave with water you can see there is some portion of the die a stream of dies, which actually go is in here in the second illustration.

And similarly, I we find that there is a component water which goes in this certain illustration here. The new diffusion time of after splitting is about some numerical constant k times about 10 to the power of 4 seconds and this particular case it is much, much greater than the residence time of the two streams k has been calculated to be about 3 to 4 seconds in our

particular case.

So, there is no mixing no, but there is in the lamination of at which is created and there is some streams dyes in which goes into the dye particular in the second junction, which is pretty much, what we expect case of a parallel lamination mixer.

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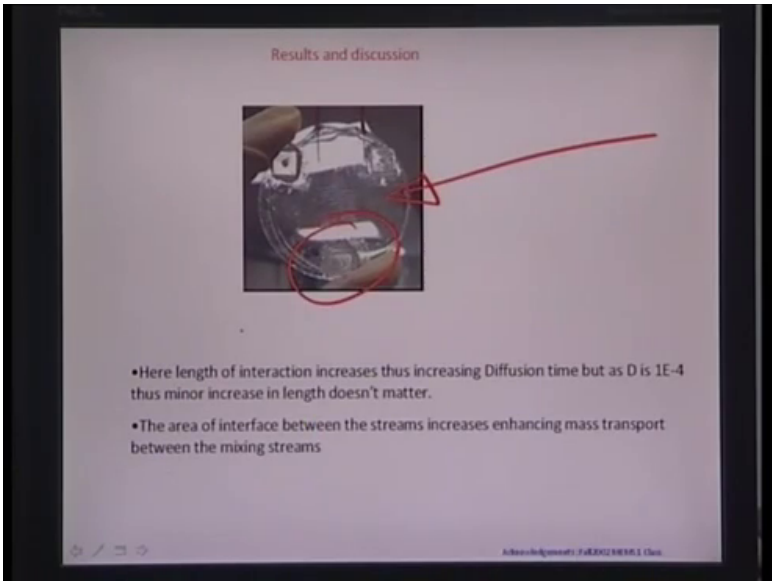

The only design, which worked in our case in this particular experiment was a serpentine design you can see this design here although I do not have in the mixing illustrations import this particular slide. But, then what effectively we observe here is that they would be an interaction between the green die and water if you pass it through a serpentine length one of the reasons that is source, because we thing that the interface area, which is also proportional to the mass transport of the constant flux of diffusion.

Being more in this case, because of more length of the second would promote a mass transport rapidly between the two flowing streams. And this rapidity of mass transport continues for a long a time, because of the meandering shape and the long length of the chance you are actually trying to reside the flows for a long time. So, that this overall inter facial area gets significant higher and we did see some mixing at this end here in this particular kind of illustration are design.

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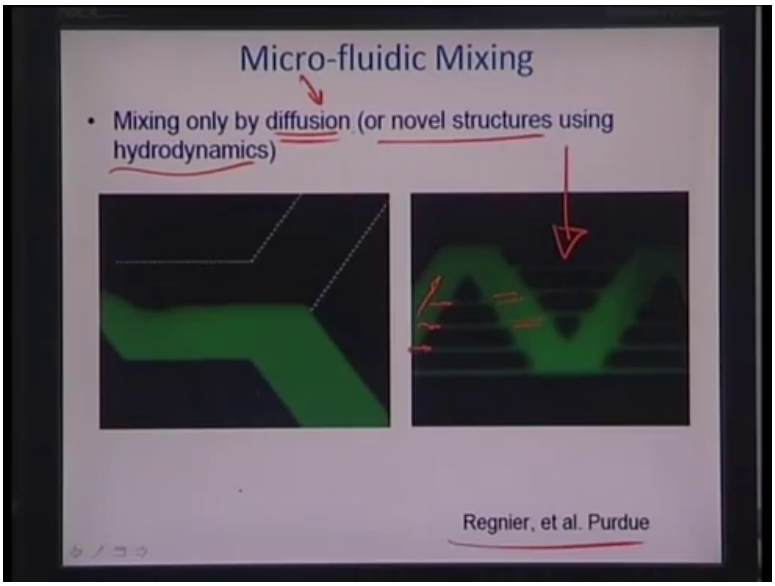

So, some other examples this has been cool from this paper Regnier, et al. Purdue who talks about how you can actually introduced novel structures in order to promote mixing, where as you can see there is a small amount of fluid being taken away from this flow path and being put into the next zone here as laminar are bans. And as you see go along this is really very rapid form of micro mixing that can happen. So, although all this structure novel structures using this different concept of hydro dynamics the mixing principal is really, really all the diffusion.

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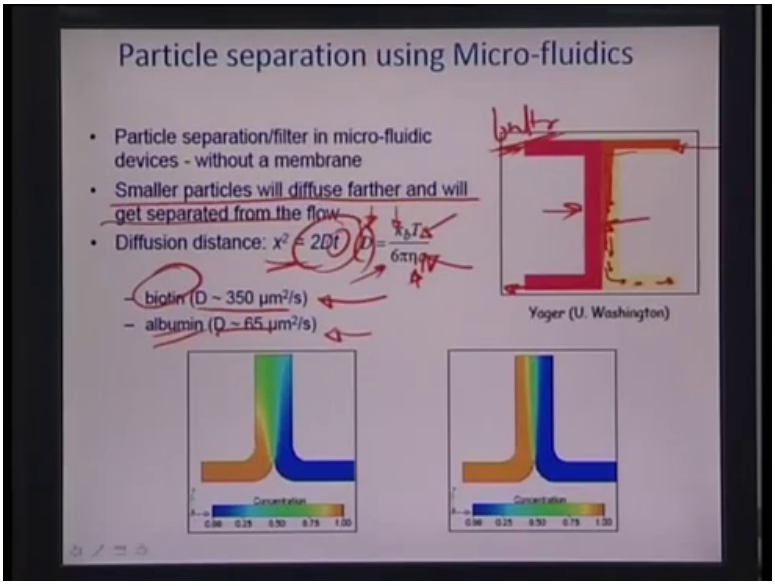

$$x^2 = 2Dt$$

$$D=\frac{k_b T}{6\pi\eta}$$

This is a another example by Yager, which talks about the separation are particles separation just by using microfluidics set up without any filtration mechanism here are without membrane. So, here the concept is very, very simple as you know the diffusion length x square at the molecule would travels is also proportional to the diffusion time and the concert of proportional to d, d is the diffusion constant.

So, if you really calculated the value of d it depends on several factors like the size of the molecule the viscosity at a medium and this k_bT is basically Boltzmann constant into temperature T of a particular medium. And, so if suppose diffusion constant is given in this manner and you have a diffusion constant higher in case of one species and lower in case of the other species, then by virtual of quality here the distances is that may have to move would be much higher in the same kind of time.

And, so therefore, the velocity of a heavier molecule the one with diffusion coefficient more velocity of the molecule with the higher diffusion coefficient is definitely more. Also interesting is the fact that lighter the molecule is are lesser the size of the molecule more would be the diffusion coefficient. So, biotin in this case is much, much smaller in comparison to albumin, which both of them a proteins essentially.

And, so because of it is smaller size the diffusion constant in case of biotin is about 350 micro meter square per second in comparison to albumin, which is 65 micrometer square per second it was one fifth. So, size of effectively is also about 5 times in case of albumin. So, smaller molecules diffuse faster that is very natural tendency and this effect can be in principal use for separation how.

Let say you have two fluids this is the buffer solution, which you are running through this particular channel and there is also some kind of you know a mixed this solution, which you are running here essentially from this end. And the idea is that as the flow goes past this the is the phase separation, because the idea is that the heaver molecule will not be that mobile in comparison to lighter molecule. The lighter molecule here as we assume would diffused towards this end actually and flow in this direction.

And, so assuming that to happen the once which are left behind in this yellow region as you can see are the heaver molecule. So, the heaver molecules typically go out with the lighter molecule can be separated and can be extracted as carried by a transport and by this buffer of

this particular length. So, therefore, smaller particles diffusing further will kind of gets separated from the stream by virtual of higher diffusion constant are higher velocity in comparison to the smaller size particle. So, you can use this mechanism really for particle separation.

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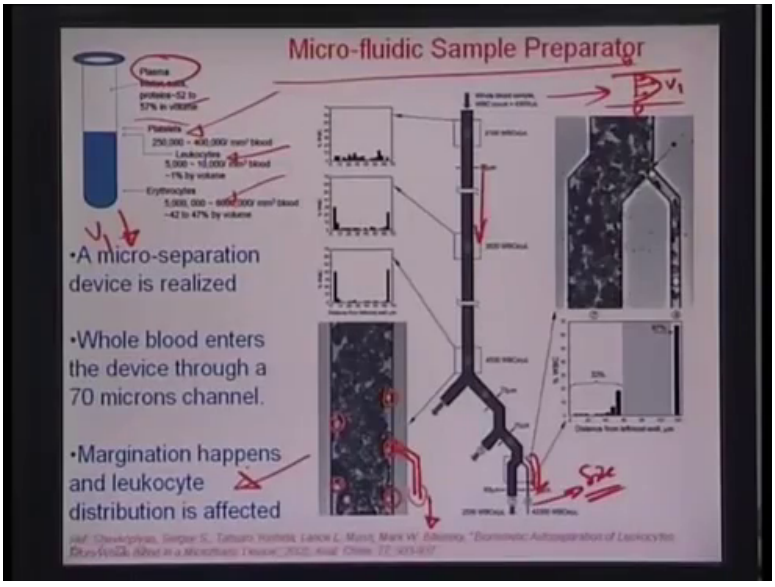

Another interesting example of where what microfluidics can do comes from this paper by XX et al., where the talk about a biometric auto separation, leukocyte leukocyte size are if you compare the size is are pretty much you know higher in size of diameter, then the most abundant species inside the human blood that is a red blood cells. If you look at really human blood contains a plasma, plasma is again bunch of ions present in solution this the liquid plasma.

So, you have difference solid and water above proteins 50 to 57 percent by volume, which is in most are inmost species this plasma are platelets, which about 25000, to 4,00,000 per mm^3 of the blood, leukocyte which are about 5000 to 10000 per mm^3 of blood and this above one percent by volume again and all through sides red blood cell which are about 5000 to 6000 per mm^3 of a blood and about for 42 to 47 percent volume.

So, what you have seen here is the blood is really very diverse component with the lot of different sizes of the cells with its red blood cells are leukocytes which are flowing around and, so therefore, can be reviews microfluidic principles for separating the blood flow. So, as you know as we have been talking about before that that is a parabolic flow profile which the develops in channels, which have fixed or static both sides and the flow them is given by a

the cost impact area let suppose you have a parabolic profile.

So, you have a channel here you have a parabolic profile like this so; obviously, it means that more towards the center the velocity more and there would be assume zero velocity and 0 slip and both. And, so therefore, com side to center the v should actually continues the reduce and suppose you have a case we are following through this end through a pressure flow a bunch of different cells we must in a solution one, which is bigger another, which is smaller what you think will happen the bigger cells would try to move towards the edges by the principle of conservation of momentum because of velocity that they will encounter by doing.

So, the edges are much smaller nature in comparison the velocities are center. So, automatically by the principle of conservation momentum there would be a tendency of this bigger cells to kind of margin towards the sides smaller to come towards a center this actually a principle, which happens inside the human body. Also particularly for leukocytes this principle is known as leukocytes margination, because of smallest smaller sizes of the capillary and the flow of different constant using a pressure giving for the pressure is created by the heart at the by within the human vascular system.

And, because it is a special given flow there is tendency to marinate by virtual sizes and go more towards the edges of the and in comparison to the red blood cells, which kind of accumulated more towards the center. So, if I can actually biometrically represent the symptoms of a micro channel, let say like this and then, we pull out different branches of this micro channels let say this is a branch, which you are pooling out here and this particular end.

So, you have to ensure though that this has the size base selection and on the selects the size of the leukocytes. So, the size of distance that the leukocytes, so what would happen is that this leukocytes which have already margin at conceive by this white cells here and there are more a abandon towards the side then in somewhere in the center and of course, the red lecture more abandon to was the center.

So, you can actually pool this out by designing a channel which you have the same size as this leukocyte is and, so you make leukocyte it samples by this kind of a this kind of a separator then lot of uses for this technology normal leukocytes are separated from the whom blood by a process called a process. But, we use a density gradient cos in agent like we call plat two kind of make a density of different size is of the size with in a solution this is a say, which can actually replicate that the buff coat process, which is two intensive both in terms of lab our as well as in terms of as well as contamination form.

So, here with the small say you could have a rapid throughput you can get really a leukocyte with sample towards the end lecture here in this particular case the smaller channel you could investigate that for further purposes.

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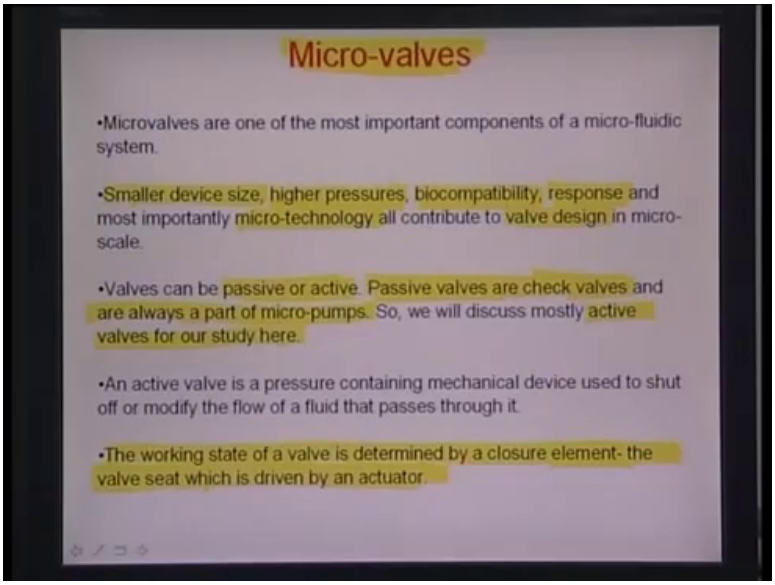

So, these are some of the wonders microfluidics can do two different systems and processes. So, I would like to now actually go into ah little different domain of micro valves. we talking about microfluidics very important mechanism that we must cert*a*in is a control of fluidic flow and for doing that we need to design different valving systems which can actually stop or block or gate in the flows running process this small channels or capillaries. And also able to meter or control the flows in the forage that we deserve desire inside in sections of particular micro channel micro valves are definitely used for those purposes we have the most important components of a microfluidic system.

So, what are is important for valve designing you have to consider the size of the device is means devices are very, very small you have to consider pressures, which are very, very high that is why most of the pressure sources sometimes of chip the mechanism of try and involves energy source is represent is source is chip not on the same chip. We should be a wear of bio compatibility choose if you are designing valve material a choose valve materials a valve should have a proper response to the flow process.

And most importantly micro technology should be use for fabricating such micro valves a particularly for using or getting the flows in micro scale valves can again we depending on the mechanism of their closing are working and that can classified into passive and active

micro valves. So, passive valves can be like check valves where by virtual of change in property material maybe it well some block the valves and blocks are alternately by motion of fluid.

Let say you have a one directional from one side to pressure generated from one side to valve closes one side automatically and open this reverse is back to other side. So, they are passive valves where there is no mechanical energy any other form of energy which are use for operating is like check valves passive valves are normally part of micro pumps you study this pimp topic and more detail. So, active value are essentially those which are the some kind of energy put to the valves system.

So, an active the valve is a pressure containing mechanical device normally use to modify the flow or stop the flow or siege the flow although it can mechanical as well as non mechanical there maybe instants is, where you can use electronically to close particular channel or electrochemically close a get a particular channel actually consider some of this illustration on designs later on well design this different valving techniques.

So, the working state of a valving really as you can see here is determined by a closure element the valve seat, which is much in typically send are the valve into beyond this is taken by a actuator that is how we driving process can be done in case of micro valves.

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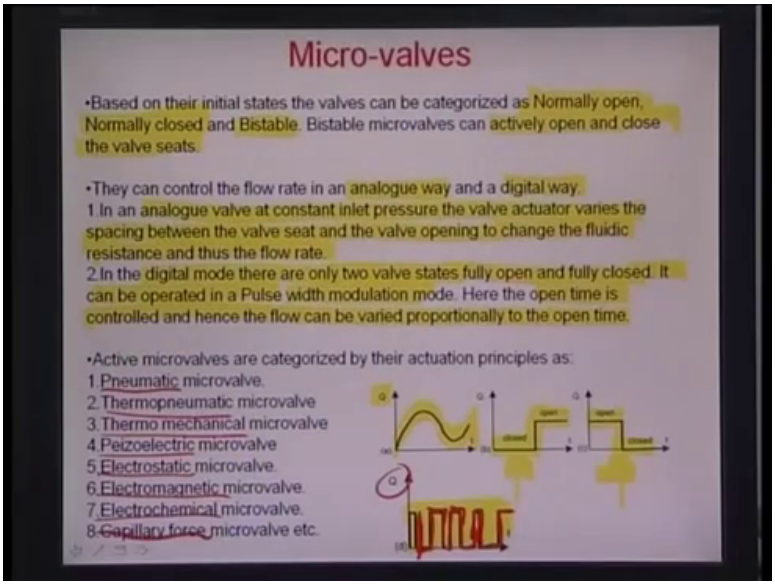

So, some of these micro valves again can base on not their initial states are whether they are normally open valves and normally close valves can be classified in use to subtypes or a bi stable valves which can close and open actively they are vales seats. So, you have three

categories here normally closed where valve normally after actual opens are normally open, where the valve actually is normally working closes an actuation and bitable, which can also which, can actually close and open both on some active energy being system the valve seats.

So, valves come further control flows either in analog manner or a digital manner which means digital as just an often on kind of mechanism have the fluid flowing at one instant and not flowing another instants, where is in analog mechanism it is a actually a slow closer of the valve and slow decrease in the flow rate across the valve and vice versa. So, you can categorize them into an analogue way and the digital way.

So, as I illustrated that in analogue valve at constant inlet pressure the valve actuator varies the spacing between the valve seat and the valve opening and this changes the fluidic resistance and thus the flow rates. So, it is a analogue control on the rates and the digital mode how ever there are only two valve states fully open and fully through closed it can be operated in a pulse actually pulse width modulation technology and here the open time is a controlled and flow can be varied proportionally to the open time.

So, essentially if you look at some of these output responses this is again what an analogue valve would typically look like this is the discharge rate and versus time plot of that show the time as you see as the valve is fully open the flow rate is maximum it, now closes in the flow rate maximum goes down slowly, but then there is a analog response. So, there is a slow convergent of the flow rate into maximum and the slow convergent is the flow rate again to minimum it is not rapid one short close and open phenomena this is the digital micro value.

Again, where you have only two stage the close and the open and then the interconnection between this is really very, very small n times. So, you do not need much opening time or closing time it automatically either opens or closes. So, here this is a normally open system this is normally close system this is normally close is normally open system and by modulation what you mean is you can actually use this technology to vary the flow according to you are interest have more open time here as you are seeing this small loops like this formulating the open time.

So, this is the small open time this is this is slightly larger open time this is slightly this is the largest open time similarly this is the closer times the time of which the value are close you consider all different times closes. So, pulse wood model basically would mean that if you have the pulse rate to be more in case in this particular case you have the flow going on for longer amount of time.

So, pulse wood modulation effectively therefore, means that if you increasing open time the flow rate would be more reduce the open time of flow rate would be less and that way you can have a differential flow rate q with respect to t. So, active micro valves again and characterize on the basis of their actuation principles the actuation can be are actuation actually means the way that you are delivering.

The energy you can actuate a microwave you can do that thermo pneumatically thermo mechanically. We can also use a piezoelectric crystal to actuate a micro valve it could use electro static method for micro electromagnetic electro chemical capillary force surface tension all different kind of forms can be used for actually closing and opening a valve system.

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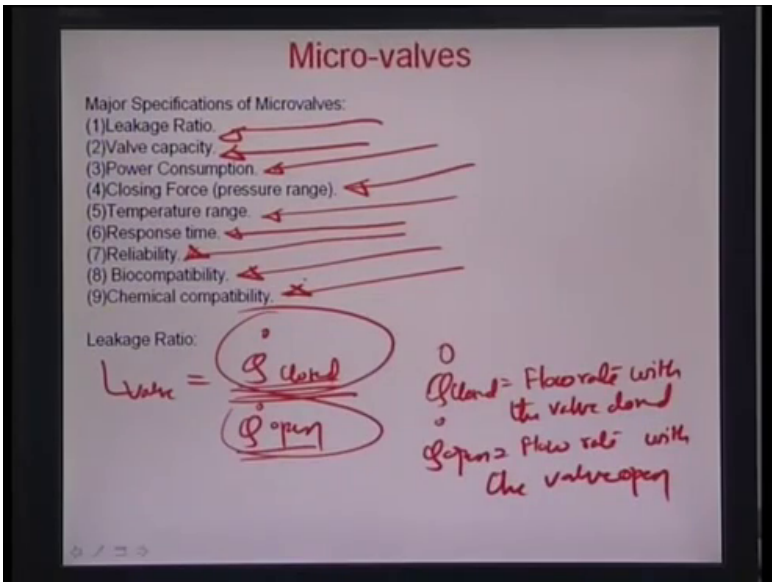

$$L_{valve} = \frac{\dot{Q}_{closed}}{\dot{Q}_{open}}$$

So, if you look at some aspects of micro valves and the way that you have specified characterize the systems you have different parameters, which you use for finding out the performance criteria of such valves one is leakage ratio. So, leakage ratio essentially can be represented as the flow rate of the close system divided by the flow rate of the open system. So, this is the fully open mode what is the flow rate and this is fully close what is the flow rate.

So, this is the ratio between what is the flow rate and the closed mode in respect to what is the flow rate of the open mode. So, basically this kind of represents the how what kind of

leakages valve would have this ratios more than zero that means definitely in the ah the close mode the valve is leaky there is some flow which can be a fraction of the fully open flow and the fraction effectively cannot we done a and the valve would still be in it is fullest operating and most stringiest operating condition would be able to let this flow past it or through it.

So, that is would be leakage ratio would mean Q dot closed is flow rate with the valve closed and Q dot open is the flow rate with the valve the pressure head that is actually driving the flow through this valve of the of the square root of the pressure driving through this particular valve, let us illustrate this little properly. So, therefore, valve capacities C let say of the valve is defined as Q star maximum is maximum flow rate and divided by root of delta P maximum, which is the pressured reference across.

The valve divided by row g row is the density g is the access the gravity is therefore, this really is a indication of what is the pressure how it what is the height available you know causing the pressure gradient what is the height of pressure that is available across both ends of the valve.

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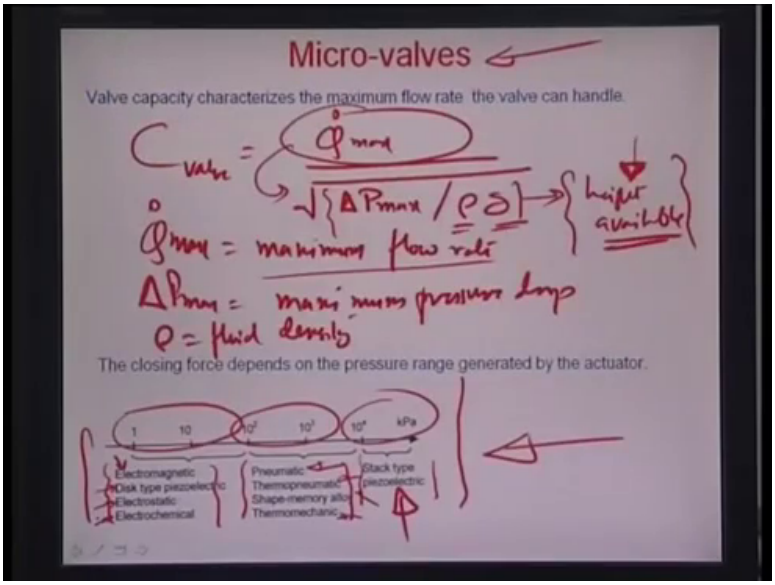

$$C_{valve} = \frac{\dot{Q}_{max}}{\sqrt{\frac{\Delta P_{max}}{\rho g}}}$$

So, the ratio between the maximum flow rate times and the root of this particular available height is what makes these the capacity of what defines the capacity of the valves. So,

therefore, if the if the pressure head that can be withstand which stood by the system is more the valve capacities lower vice versa the pressure rate that can be stand by this system is higher the valve capacity is higher.

So, the closing force depends on the pressure generated pressure range in which generated by the particular equation here in this particular illustrations we can see some of the different actual mechanisms and the way that pressure can be the pressure change can be generated by different actuate mechanisms. So, here for example, so let me just write these things down Q dot max is maximum flow rate delta P max and maximum pressure drop row is a fluid density g of courses you know is the acceleration due to gravity.

So, for electromagnetic disk type piezoelectric electro static and electro chemical actuation the pressure ranges that can be generated by this actuated roughly about one to ten kilo Pascal's. So, go a little bit higher to pneumatic thermo pneumatic shape memory alloy based thermo mechanical actuators the pressure range is would be in the range of about hundred to thousand kilo Pascal's and the highest pressure range that can be actuated is given by this stack type piezoelectric crystal there are multiple piezoelectric, which are stacked one on another.

On other hand the effective pressure that is felt the result of pressure that is felt result of series and this different piece of crystals taken together and here the action pressure can be as high as about ten thousand kilo Pascal's. So, that is what essentially the valve capacity would characterize. So, therefore, what it mean is that the maximum flow rate which it can ha hold per unit pressure head available is what the capacity is that.

So, therefore, it suppose the pressure head is let say fixed and you have valve we can hold let say one centimeter cube per minute other which can hold ten times this value centimeter cube per minute flow rate. So, for a similar kind of pressure head on both ends you know C valve the valve capacity would be much more and case are ten centimeter cube per minute flow closing valve in comparison to the one centimeter cube per minute flow closing valve.

So, that is what valve capacity is characterize as there are some other performance factors which include what kind of power is consumed by the system what are the closing forces in terms of pressure ranges, which you need for the valve to fully close what kind of temperature ranges you can use the valve and these are some other specifications. If you design such valves what is the response time it is a big criteria how valve can open and close particular flow.

Is there in reliability issue or the valve operation is effectively we not come every time all operation is perfectly we need come not every time repetitive or not every time is what is very important design paradigm. Biocompatibility aspect itself the material is very major concept, which is important for designing of selection of material which would make this micro valves and then finally, chemical compatibility again is a highly important parameter for designing specifications of this micro valves.

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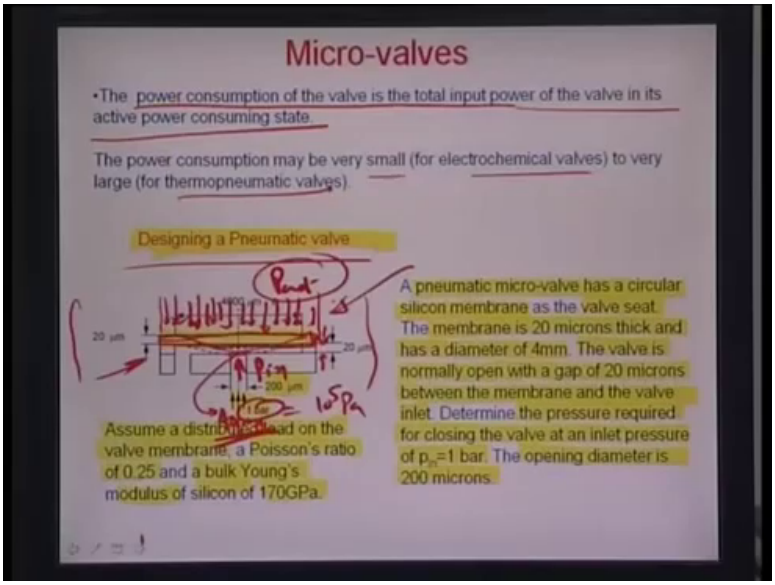

Let us do some, now some real example is a valve designing to see a little more of how this can really be designed for flow systems. So, the power consumption of the valve really is the total input power of the valve it is active power consume state and it may be small for electro chemical valves and very large for thermo pneumatic valve depending on what is the actuation mechanism and how in the things can be actuated from this particular example here you want to design and pneumatic micro valves system let suppose.

So, by let us now solve this example of designing only and designing a pneumatic valve system. So, we have a pneumatic micro valve here which has a circular silicon membrane. So, this right here as membrane circular as seen in the top view and the side view and the cross sectional side view actually. So, silicon membrane essentially is valve seat in the particular valve, which means the silicon membrane kind of bends and deforms like this it kind of blocks the particular valve the valve seat is actually just below this membrane.

So, primarily it is it bends and blocks the entry of the here flow into the system. So, the membrane is about 20 microns it has a diameter about 4 mm i.e. 4000 microns and the valve

is normally open with a gap there is a no pressure over this particular region here and it is as if the valve is open at the very outside and the gap in the particular case is about other twenty microns looking the membrane and the valve inlet.

So, you have to determine the pressure required for closing the valve at inlet pressure about of 1 bar as you can see here opening diameter is 200 microns which is here. So, we had assume that the load is distributed on the valve membrane and there is a Poisson's ratio about 0.25 and there is a bulk young's modulus of silicon, which is about 170 giga Pascal's. So, we have to design the system, so let us actually look at how we will design this.

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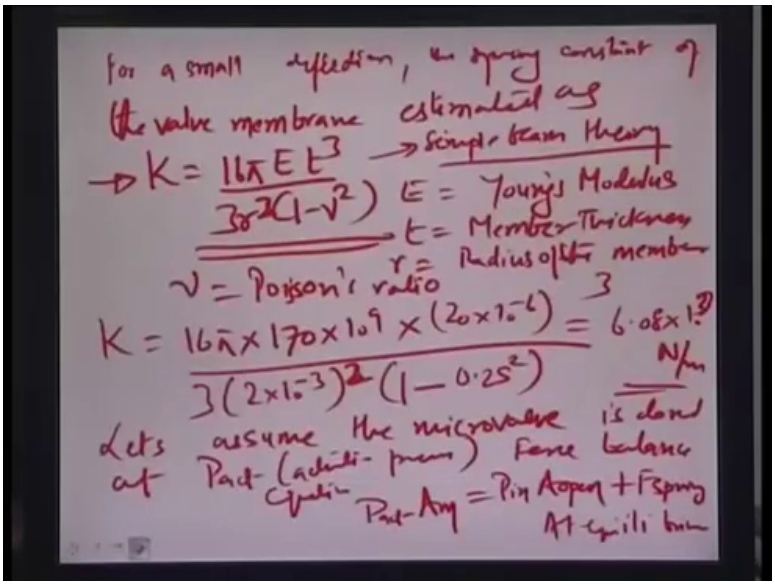

$$K = \frac{16\pi E t^3}{3r^2\left(1-\nu^2\right)}$$

$$K = \frac{16\pi \times 170 \times 10^9 \times \left(20\times 10^{-6}\right)^3}{3\left(2\times 10^{-3}\right)^2\left(1-0.25^2\right)}$$

So, for a small deflection and this spring constant of the valves membranes can be estimated as k equal to 16 pi E t cube by 3 r cube times of 1 minus *u* square of this comes from a simple beam theory and any standard mechanics of solids textbooks would be able to demonstrate how this spring constant in case of thin beams can be reported with the various parameters are E is young's modulus t is the membrane thickness and membrane which is deforming and is be the valve r is the radius of the membrane , mu is the Poisson's ratio.

So, we have pretty much everything on this. So, let us calculate what the k value would be equal to sixteen pi times of e each is 170,10 to the power of 9 and then, modulus silicon is

170 giga Pascal's times of thickness cube. So, it is 20, 10 to the power minus six microns is the thickness of the particular member in question. So, k of thickness divided by three q r, r is basically 4000 microns 2000 microns.

So, it is about two 10 to the power of minus 3 meters cube of this times of 1 minus square of this times of 1 minus mu square mu is 0.25 Poisson's ratio. So, this comes out to be effectively equal to 6.08 and 10 to the power of three Newton per meter that is what the K value is. So, let us assume that the micro value closed at the actuation pressure at the P act. So, let us assume of the micro valves is dozed at P act actuation pressure.

So, the force balance equation for this valve because it is a distributed load basically the actuation pressure which is actually from this psi as you see here this is the P actuation and this is the p inlet. So, you are left with P actuation times area of membrane times of P inlet times area of the open system. So, essentially in this case the open system is nothing, but the area of the membrane itself again. So, P acts P input times of a open plus the spring force mind you the pressure rear is actually being resisted by this down wards spring like moment of this valve.

So, whatever force this P inlet would have a membrane plus the force spring essentially equals to the actuation pressure times area of the particular membrane. So, this is essentially at equilibrium this is at equilibrium this surface is an equilibrium. So, this right here again is the open the area of cross section which is open. So, equilibrium means that the membrane is fully heated over the inlet whole thus valve in the flow and a open is the area of the inlet whole P input is the inlet pressure and that plus the spring force essentially equal to the force the actuation pressure on the other side membrane just about when the actuation begins this equation slightly modifies.

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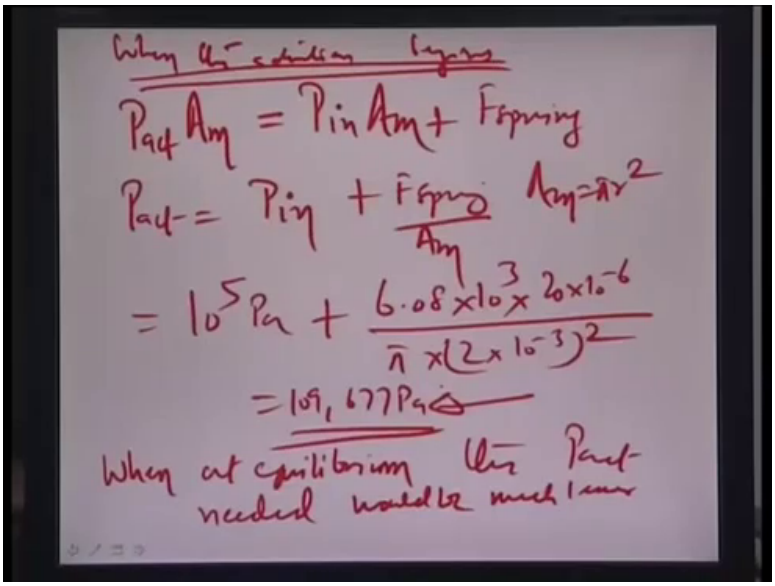

$$P_{act} A_m = P_{in} A_m + F_{spring}$$

$$P_{act} = P_{in} + \frac{F_{spring}}{A_m}$$

$$A_m = \pi r^2$$

$$P_{act} = 10^5 + \frac{6.08 \times 10^3 \times 20 \times 10^{-6}}{\pi \left(2 \times 10^{-3}\right)^2}$$

So, you have now P act times of m on one side which is also equal to P times of Am same membrane n it was in the open position plus thus spring force is still there when actuation just about begins already written this thing the top when the actuation just about begin you can see here. So, let us actually calculate some of these values let see what happens in the actuation begins. So, have P actuation, actuation pressure needed is P inlet plus s spring times one by Am is essentially pi r square r is about 2000 micro meters.

So therefore, the actuation pressure would be 10 to the power of 5 Pascal's the pressure in the inlet side is about close to one bar which is nothing but, 10 to the power 5 Pascal's as a you know plus the force spring, which is 6.08 into 10 to the power 3 times of the deflection, which is again about 20, 10to the power of minus 6 that is essentially the 20 micron displacement that would happens here as you see. Let us assume that port has not yet blocked and the pressure is at released on to the entire lower surface of the seat membrane and this

divided by Am which is pi r square r is two 10 to the power of minus 3 square.

So, this values comes out to be about 109,677 and Pascal's and now on equilibrium go this entirely this paradigm changes. So, an equilibrium the P actuation needed would be much, much lesser more. So, because now the active area over which this one bar pressure is available only this little area here that is the P the area of the opening.

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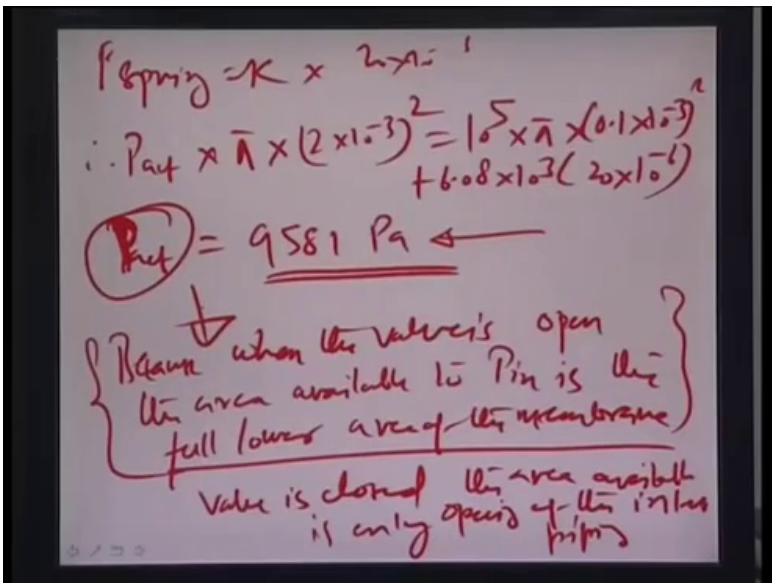

So, let see what that would be force spring and this particular case is again k times of 20, 10 to the power minus 6 and P actuation times of pi times of 2 into 10 to the power minus 3 square would effectively equal to 10 to the power 5 times of pi times of 0.1, 10 to the power of minus 3 square plus 6.08, 10 to the power 3 and 20 times of 10 to the power of minus 6 and P actuation here would come out to be effectively equal to 3.1. So, let me just write down the final value here.

So, it comes out to be about 9581 Pascal's. So, in comparison to the earlier value here which was about close to 109,677 Pascal's. This has reduced to almost to two order of magnitude come 9581 Pascal's. So, why that is shown again because when valve's open the area of membrane of the area of inlet pressure area available to the inlet pressure is the full lower area of the membrane and on the valve is closed on the area available is a only in the inlet or the or the opening of the typing inlet typing.

So, there is primarily the reason why the actuation pressure in the second case where the valve is closed much, much lower in comparison to the actuation pressure in the upper case this is a though an advantage because being at the micro scale the area of cross section of

such valves is very, very small and. So, effectively there amount of force that is generated by the inlet side by design which is also pressure into area the virtue of the area become very small or remains the small and it necessitates lower amount of actuation.

Therefore, in case of negative valves in this kind of configuration it always desire to make the inlet side of opening as small as possible with convey with the micro systems and that can help us have a lower amount of actuation pressure to control valve action we design the same valve the thermo pneumatic perspective; that means, whatever this load distributed load here was obtained on this particular membrane is done through heating some kind of a gas entrapped over the membrane. So, that is called thermo pneumatic system.

So, therefore, fix volume if you actually keep on adding electrical work or energy there is expansion of the gas which would cause a pressure to develop and the pressure would be good enough for the membrane to bent and valve the inflow of the air. And, so those systems are known as typically thermo pneumatic systems. So, for a similar kind of arrangement let us see what would be the amount of temperature there is needed to be reached for sufficient amount of actuation force to be pressure to be generated. So, that the closing action of the valve takes place.

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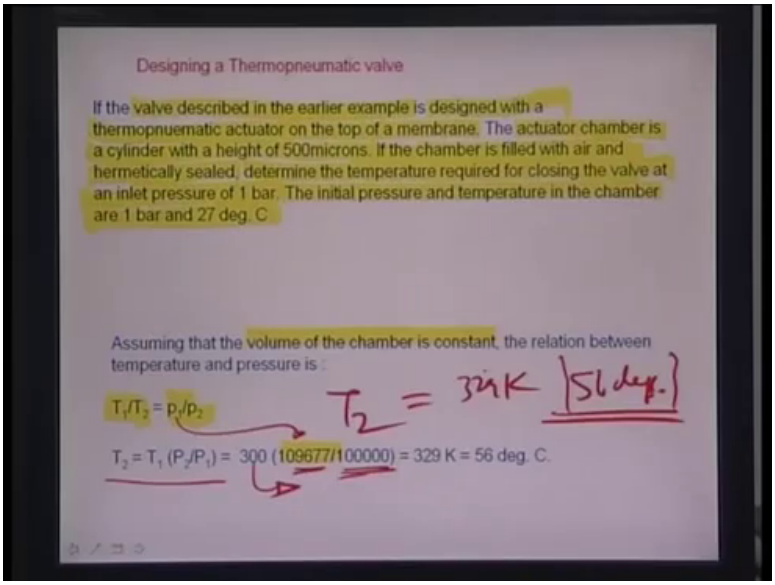

$$\frac{T1}{T2}=\frac{P1}{P2}$$

So, let us suppose you have the valve described in the earlier example and this is designed with thermo pneumatic actuator on the top of the membrane and given that the actuate

chamber is cylinder of height with about 500 microns and this is sitting on a diameter about 400 microns which is also the outside diameter of the valve silicon membrane valves which is in consideration right now.

So, with the chamber is filled with air and pneumatically shield we have to determined the temperature required for closing the valve at inlet pressure about one bar and the initial pressure and temperatures the camper 1 bar at 27 degree Celsius. So, again we use the Charles law on the fix volume and you have pressure kind of proportional to the temperature. So, therefore, T1 by T2 this temperature in the beginning by temperature after the expansion is taken places pressure 1 by pressure 2, so assuming that the volume of the chamber is constant.

So, here of course, the pressure inlet pressure is about one bar and we found out that the amount of pressure that is needed from actuation pressure that is needed from the opening to the closing position or opening position is about 109677 Pascal's. So, this is the p1 which is needed and the inlet pressure p2 is about one bar which is about 100000. And also therefore, if inlet pressure one bar is at 27 degree Celsius temperature, which is about corresponding to about 300 Kelvin.

We find out from this relationship that T2 the temperature required for the pressure you have a 109677 Pascal's is about 329 Kelvin which is close to 50 to 60 Celsius. Therefore, you have to really heat and the constant volume and the cylinder with the height of 500 microns by to almost about 56 degrees for the valve to self close using thermo pneumatic means. So, that is how you design thermo pneumatic valuing system.

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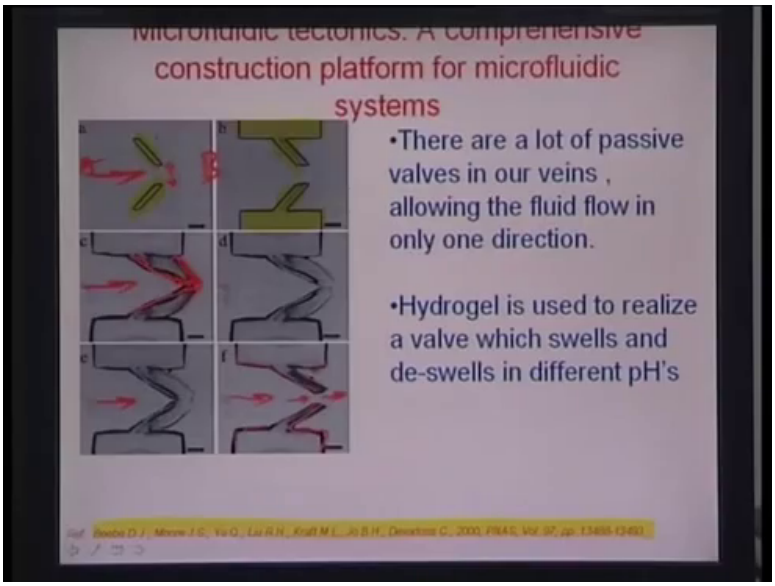

So, can be also passive valves as I recorded last in my last lecture and this passive valves essentially means either the expansion of a structure blocking of flow because this expansion is. So, these valves are beautifully illustrated by in this particular paper coded in as for use hydro gels and essentially as you see here this hydro gels are fixed to certain fixed members in a flow channel, so direction of flow being from direction a to direction b through this channel.

So, typically these are an expanded and you have a gap in between here from where the flow can go from *a* side to *b* side. But, hydro gels are essentially things which expand of swells and different ph's particularly form the pH more like acidic the valves would swell in volume, so it would be expand. So, if you have this valves expanding in volume they become this b and by virtue of their size they can block the flow.

So, other flow is blocked because this hydro gel kind of swelled and the blocking the flow direction in this particular channel as a result of which these valves can be very good pH senses. So, small change in pH can resultant swelling and flows top edge of the particular valve and calibrate the change of pH to the to the volume of swelling the could difference that would the valve would make by swelling and therefore, the volume of flow past the valve can be calibrated to the corresponding pH.

So, here of course, as you or seeing can reversibly change the orientation in the flowing back basic ph that the valve kind of swelling and gives way of opens the flow and these where being made up of hydrogen and soft materials they can be bio metrically pattern they are

based on some of the flow valves that are the hot probably posses where expansion and contraction keeps on either confining the on to the chamber of the hard are releasing the at a certain pressure.

So, this kind of brings us to an end of this particular lecture and next lecture we are going to talk about some other valuing mechanisms particularly non conventional mechanism like electro chemical or surface driven valuing are flow closing mechanisms. So, this I would like to close this lecture.

Thank you.