Bio-Microeletromechanical Systems

Prof. Shantanu Bhattacharya

Department of Mechanical Engineering

Indian Institute of Technology, Kanpur

Module No. # 01

Lecture No. # 33

Hello and welcome back to this lecture 33 of Bio-Microelectromechanical systems, I would like to briefly review what happened in the last lecture. We talked about micro mixers in detail parallel, sequential lamination mixers as passive mixers or active mixers. There would be either chaos introduced or some kind of piezo vibration, so that there is cavitation or there is some active energy pumping into the system and there is mixing of two or more phases.

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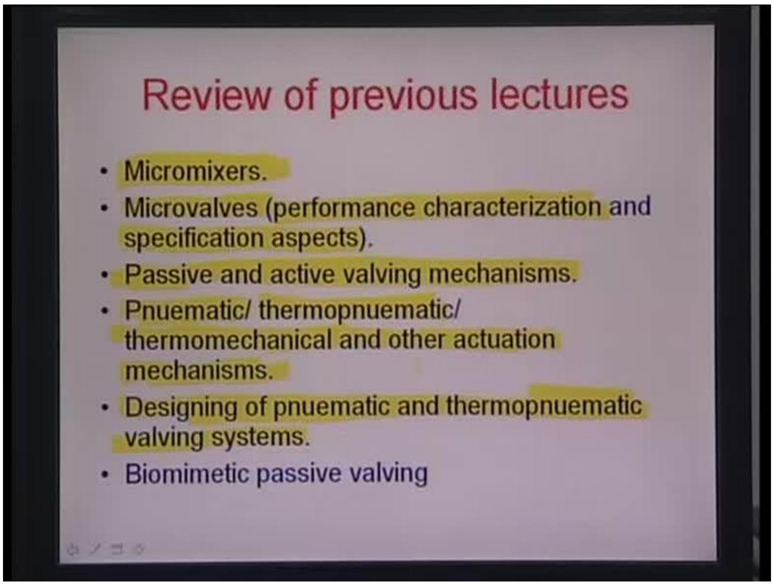

We detailed about microvalves essentially, tried to study some basics about their actuation mechanisms, their performance characterization and also specifications. Some of the aspects like valves capacity, the leakage ratio, the power requirements and the other aspects like material selection biocompatibility etcetera were discussed for designing micro-valves or micro-valving systems. We further categorize valving into passive and active valving mechanisms. We discussed different kind of actuation mechanisms like pneumatic, thermo-pneumatic, thermo-mechanical, electrical, magnetic and some other actuation mechanisms.

We also tried designing some of these pneumatic and thermo pneumatic valving systems and saw that special designs have to be made in a manner which rhymes with the micro-scale and it makes an area ratio between the inlet and the valve seat. So, that the amount of forces that are needed for actuating the valve member is small, because we talking about micro fluidic systems or micro flow systems. The inlet area is typically small which makes automatically the actuation forces very small as we saw in the example, about designing this pneumatic system.

We further can mount a cylinder and use same kind of distributed load by means of hermetically sealing the cylinder and adding temperature, so that the system has PDV work and there applies pressure on the walls and effectively a force because of this heating effect.

We also talked about bio-pneumatic passive valving mechanisms and tried to discuss about what happens to the human body particularly in the vasculature with a pressure gradient and the way that the valves close and open. We talked about hydrogen valves here particularly which are sensitive to PH and it swells and blocks or de-swells and unblocks certain flow and flow rates can be calibrated to the PH values respectively.

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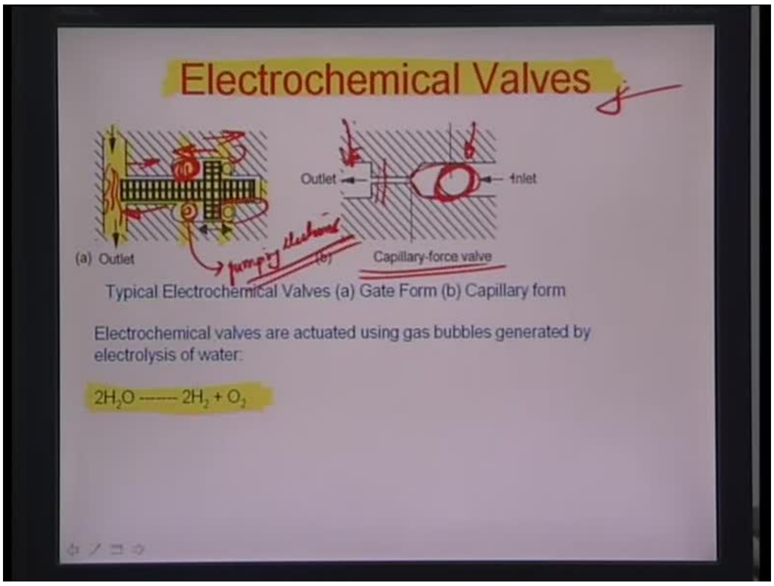

Today, we will be talking a little more on that line about or some other non-conventional valving mechanisms. One of the most popular in the category is also electro chemical valving mechanism. Let us see, what electro chemical valves really are? Essentially, a very simple system of reaction as can be seen here, H 2 O is electrochemically converted into hydrogen and oxygen. Basically, if you look at the overall architecture of this system this is basically the outlet of a micro pipe and this is a gating device here. Essentially, there are 4 electrodes in this region, this region, this region and this region and this electrodes pump in electrons, so that bubbles get formulated (Refer Slide Time: 03:54).

If you really control the differential of size between bubble 1 here and bubble 2 here, you can make this gate mechanism move back and forth. Suppose, this is bigger and smaller the gate will push back vice versa, this is smaller and that is bigger, the gate will push forward. Therefore, the flow path here is kind of blocked because of this mechanism.

However, this an electro chemical valve because hydrogen and oxygen bubbles here are produced just by virtue of pumping electrons. Therefore, the valve is really operated or actuated electrochemically. Similarly, you could have a blocking mechanism wherein, this is the bubble which is generated by an electrode maybe. The bubble is too big and blocks this port after a while and cuts off the flow from the inlet side to the outlet side, so that is again called capillary force valve. There may be a tendency of the bubble to squeeze past and then go the other direction. We ensure a pressure gradient between these two points, so that the valve keeps here and protects the flow going from inlet to the outlet side or stops the flow. So, that is how an electro chemical valve would operate.

What is interesting for me to share here is that if we really look on a comparative basis between - let us say - a thermal setup which would generate the same bubble and the electrical setup which will generate the same bubble. You find that there is a lot of difference in the valving efficiencies and that is exactly why conventional means are not very well suited on the micro-scale. Rather, you prefer doing something which is non-conventional like electro chemistry based or magnetic base or electrical field based, to prevent this extra amount of work which needs to be asserted for translating into the micro-scale. Therefore, we always fetch for rather non-conventional systems for doing actuations in the scale.

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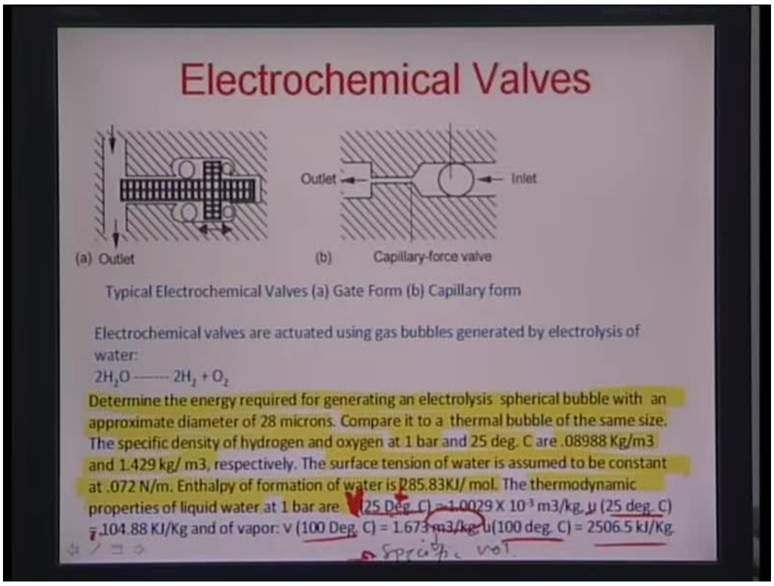

Let us do this example; here we have an electro chemical valve as which is described above is based on the principle of electrolysis of water. Essentially here, we have to determine the energy required for generating an electrolysis spherical bubble with an approximate diameter of 28 microns. We have to compare it to a similar bubble generating thermal mechanism, which is generated by evaporation of water of the same size. Some parameters given are the specific density of hydrogen and oxygen at 1 bar pressure and 25 degree celsius it is 0.08988 kg per meter cube and 1.429 kg per meter cube respectively.

The surface tension of water is assumed to be constant and that is taken as 0.072 Nano meters. The enthalpy of formation of water is about 285.83 kilo joule per mole. Some other thermodynamic properties of the liquid, like water at 1 bar pressure, for example, u or the internal energy at 25 celsius there at 100 degrees celsius, sorry, this is very specific volume at 25 degree celsius, internal energy at 25 degree celsius. Similarly, this specific volume at 100 degree celsius and internal energy at 100 degree celsius are given.

Basically, specific volume - let me reiterate as the units here - indicate is volume per unit mass. You have say 1 kg of mass of both hydrogen and oxygen or other gases, you really find out how this 1 kg would be able to occupy in terms of volumes. So, that is why make a common base or a common denominator and see a volume comparison based on that. So, that is called specific volume it is different than the normal volume, it is per unit mass or per unit weight.

Let us see, what the differences in terms of energy requirements and whether they are any different or if it is thermal as opposed to electrochemical. Let us first do the thermal the electrochemical part.

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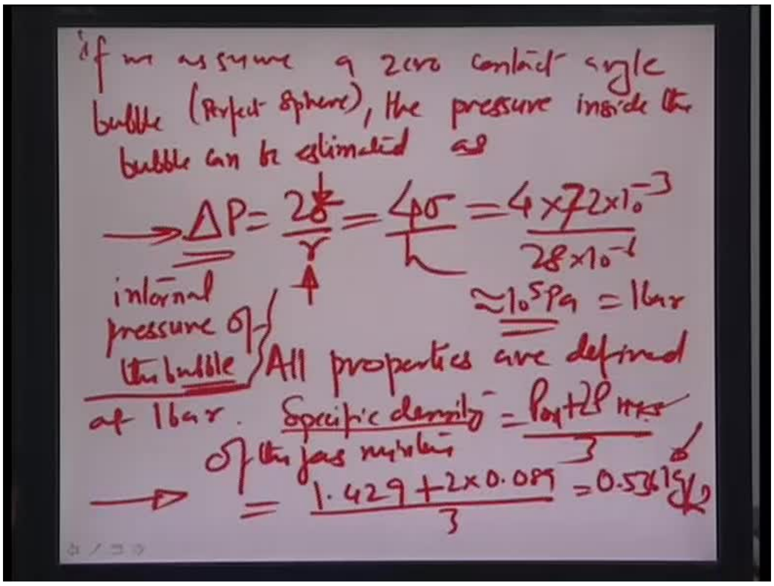

If we assume a 0 contact angle bubble or a perfect sphere, there is no contact angle whatsoever. The pressure inside the bubble can be estimated as delta P equal to twice sigma by r; sigma is the surface tension of the bubble and r is the radius of curvature of the particular bubble. In this case, it is sphere so it is essentially the diameter by 2, so it is 4 sigma by h. As we know from the example here, the diameter of the bubble is approximately 28 microns which makes the radius about 14 microns.

Here, the surface tension force as we know is about close to 0.072 Newton per meter for water molecules. The radius of the bubble is about 28 microns which makes the pressure gradient, so this is essentially the internal pressure of the bubble. So, 4 times of 72 into 10 to the power minus 3 by 28 into 10 to the power minus 6, this comes out to be about 10 to the power 5 Pascal’s or 1 bar pressure. All the properties are really defined at 1 bar therefore, we can find out the specific density of the electrolysis gas mixture of hydrogen and oxygen at 1 bar pressure. So, let us go ahead and do that.

All properties are defined at 1 bar, so the specific density of the mixture of gases can be obtained as specific density of oxygen at 1 bar pressure and 25 degree celsius times of specific density into 2 of hydrogen divided by 3. This comes out to be equal to 1.429 kg per meter cube plus 2 times 0.089 kg per meter cube by 3, it is further about 0.536 kg per meter cube. So, that is what specific density of the gases mixture is in this particular case.

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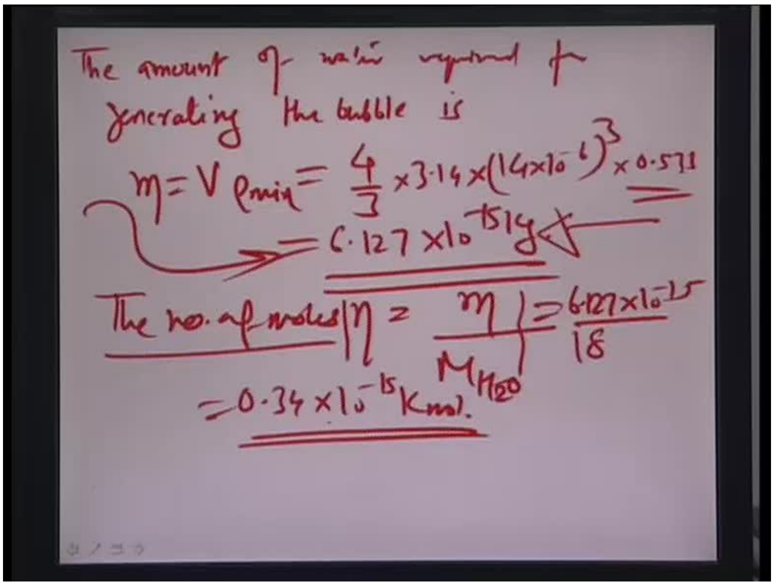

The amount of water required for generating the bubble would be actually equal to this particular specific density times of the volume of the bubble which is needed. This much amount of water if you assume continuity between the 2 phases would have to be essentially decomposed in order to create an equal volume of the gas mixture H 2 and O 2 which would formulate bubble.

Let us just write this presumption again here, so the amount of water required for generating the bubble is m equal to V times of rho mix which is 4 by 3 pi times of r cube times of 0.536, which is the density at this particular pressure and temperature. So, this comes out to be equal to about 6.127 into 10 to the power of minus 15 kgs. Effectively, you are electrochemically converting about 6.127 femtograms of mass in order to get a bubble which would have pressure differential of about close to 1 bar and at that particular gas mixture density at 1 bar pressure and about room temperature about 25 degree celsius or so.

With this, it is convenient to assume in terms of number of moles, how many moles of water would be needed so many kgs of water that has been generated here, to be electrolyzed for creating the bubble. The number of moles this case n will be equal to mass by mass of H 2 O, which is 6.127 into 10 to the power minus 15 by 18 or about 0.34 into 10 to the power minus 15 kilo moles. That is how number of moles of H 2 molecules would be need to make a volume which would support a pressure differential of about 1 bar.

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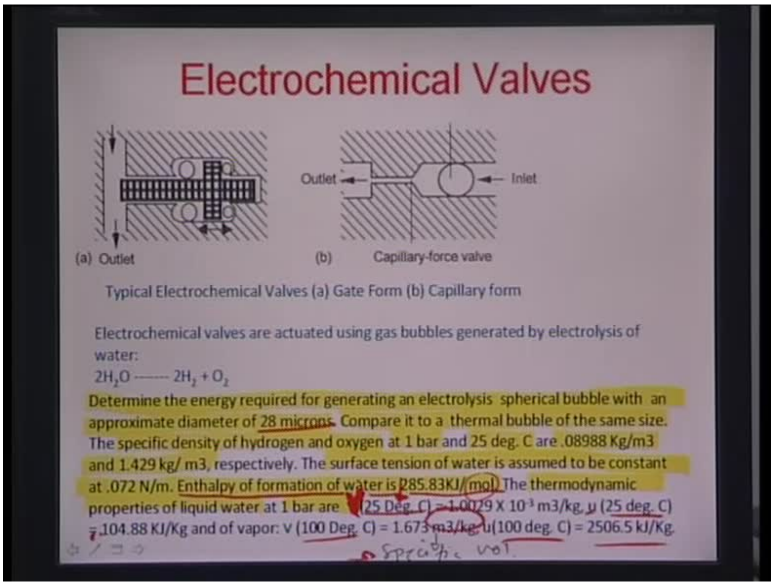

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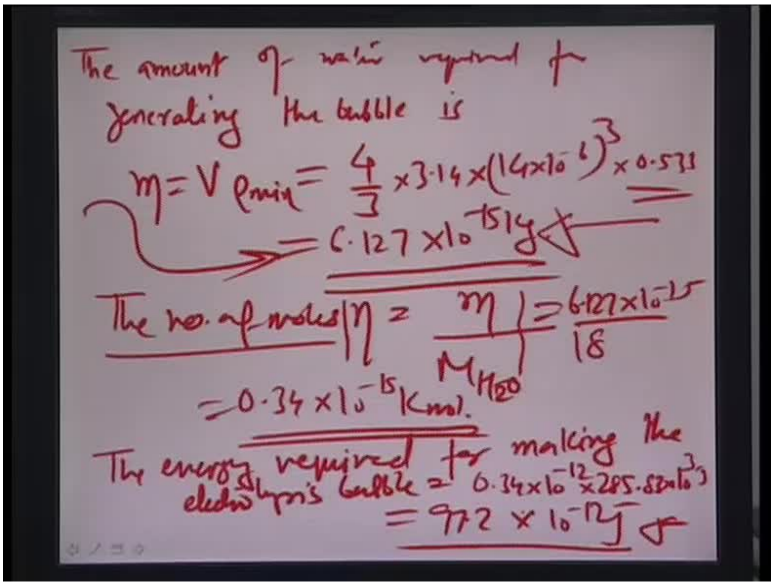

As we also know from the question here, the enthalpy of formation of water - if you see in this region and this is actually the electro chemical enthalpy of formation - is actually 285.83 kilo joule per mole of material. We already know how many moles have to be made, so the total amount of energy which would be needed for making the electrolysis bubble essentially is nothing but this enthalpy of formation times of the number of moles.

Therefore, if we write that down, have the energy required for making the electrolyze bubble is essentially equal to 0.34 into 10 to the power of minus 12 moles times of 285.83 into 10 to the power of 3 joules which is also 97.2 times 10 to the power of minus 12 joules. Effectively, this much of amount of energy is needed to realize the total volume of the gas mixture in form of an electro chemical bubble.

This of course the electrical energy, this much energy has to be given externally through the electrodes through the water for it to be electrolyzed and creating this gas mixture. Let us also compare what would happen, if instead of electro chemical means, you have thermal mechanism to formulate the bubble, you have a change of phase essentially and that creates the bubble. So, let us compare what is the energy difference in both the cases.

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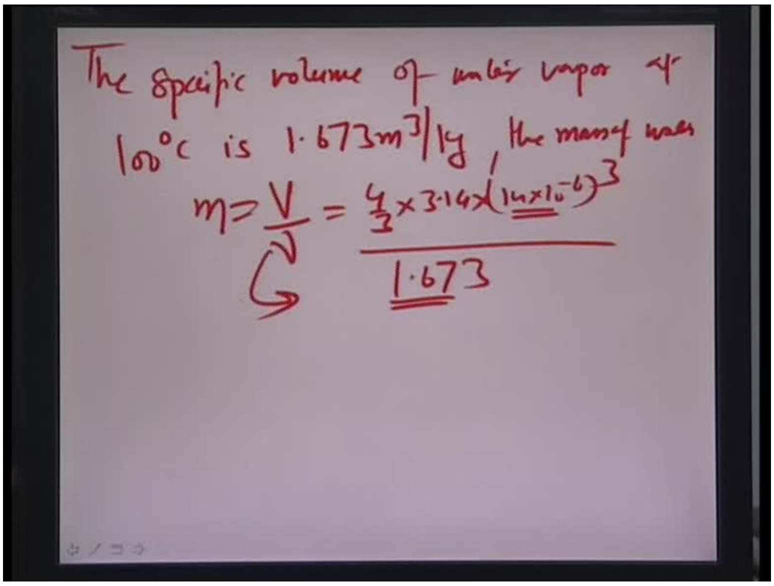

Therefore, if we compare the specific volume of water vapor at 100 degrees celsius and compare that with the mass in order to find out how much amount of thermal energy would be needed to convert that mass to make a thermal bubble. We should be able to have a comparative between the total energies in both cases. Let us say that the specific volume of water vapor at 100 degrees celsius is about 1.673 meter cube per kg, the mass of water therefore, m is as also given by V by nu the specific volume essentially, 4 by 3 3.14 into 10 to the power minus 6 by 3 this is essentially the volume of the sphere of radius14 microns diameter 28 microns which is the size of the bubble divided by the new value which is 1.673, this is essentially the specific volume of water vapor which is actually given in the numerical example at the very beginning.

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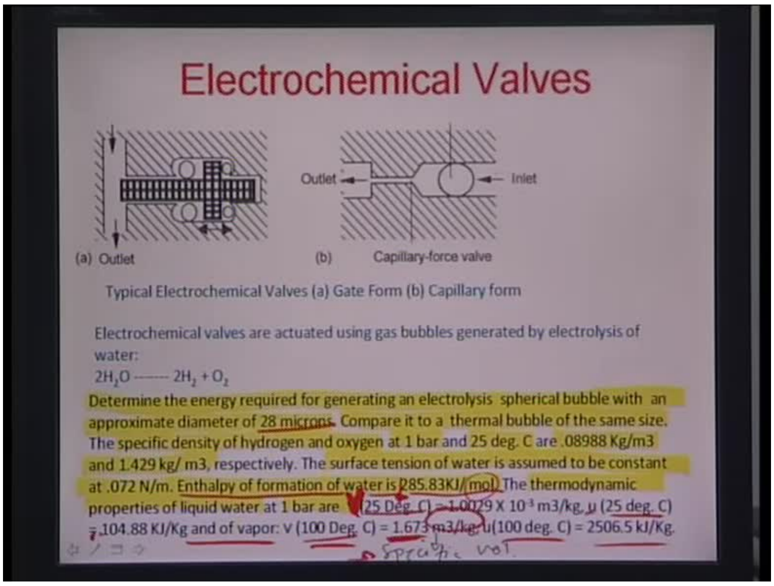

As you see here, specific volume of the water vapor at 100 degrees celsius is given to be 1.673 cube per kg mind you, the thermodynamic state that we have to consider for the bubble to be shaped up is that the water vapor essentially is that 100 degree celsius which is also the boiling point of water. We need to formulate the vapor in order to realize the bubble. Therefore, all specific volumes etcetera which are considered at 100 degrees Celsius.

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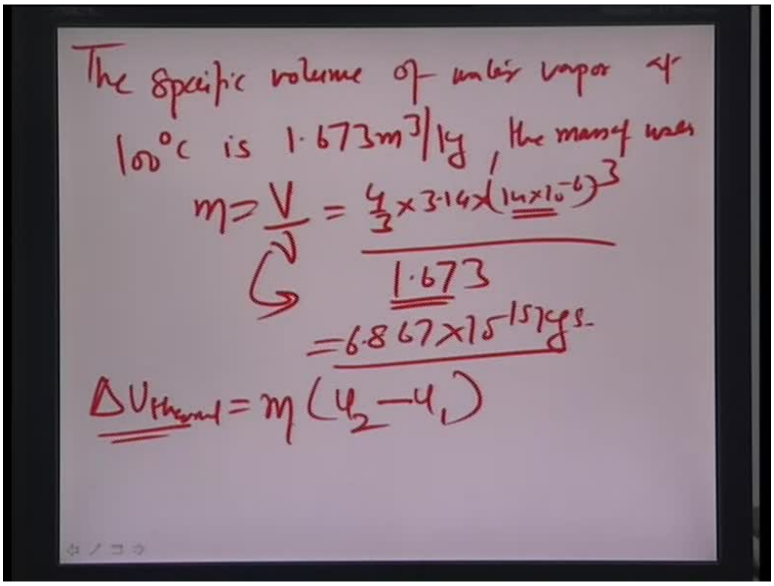

Let us try to look at that figure here and see what the mass would effectively be. In this case the mass comes to be about 6.867 into 10 to the power minus 15 kgs. Essentially, if you ignore the heat losses from the system, we assume that the system is hermitically sealed again. We can find out the thermal energy equivalent required for formulating this amount of water vapor mass 6.867 into 10 to the power minus 15 kgs of water vapor mass.

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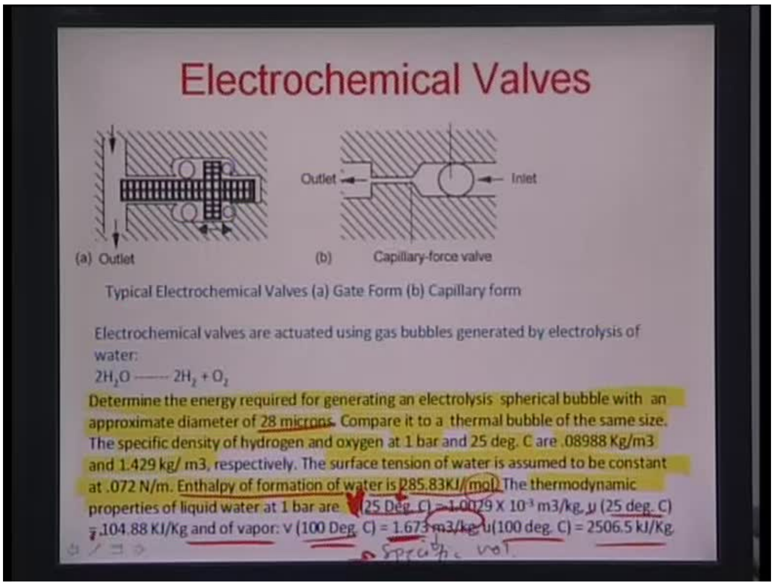

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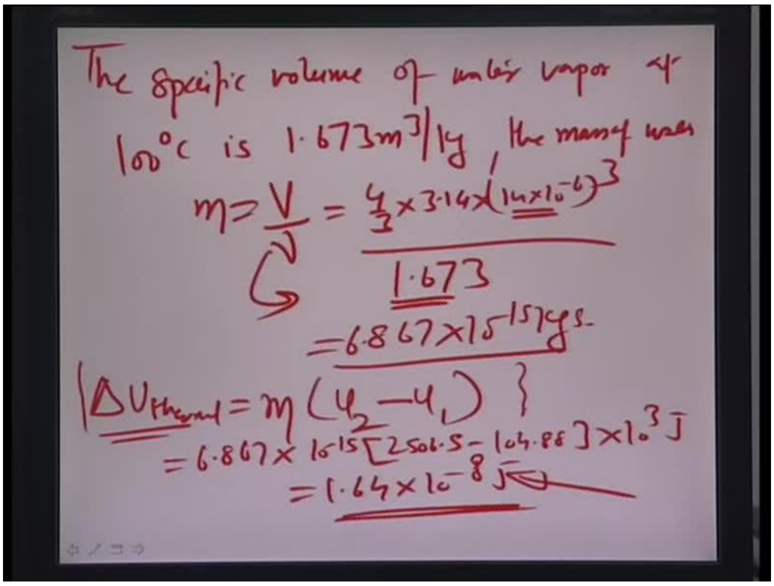

How do we do that? We know that the delta u thermal the amount of internal energy that needs to be supplied for converting a water sample from 25 degree celsius all the way to about 100 degree celsius is also given as the mass that is needed to be converted in kgs divided by the internal energy at 100 degrees minus internal energy at 25 degree celsius. If you look back in the example of both these values are given here as internal energy at 100 degrees is about 2506.05 joules and that at 25 degree is about 104.88 kilo joules per g.

We are multiplying the mass and kg's, so we are left with this equation which is in kilo joules of energy. We reduce this to 6.867 into 10 to the power minus 15 times of 2506.5 minus 104.88 times 10 to the power of 3 joules, so it comes to be 1.64 into 10 to the power of 8 joules. Essentially, that is the amount of thermal work that is needed to be done for creating this particular bubble in this example.

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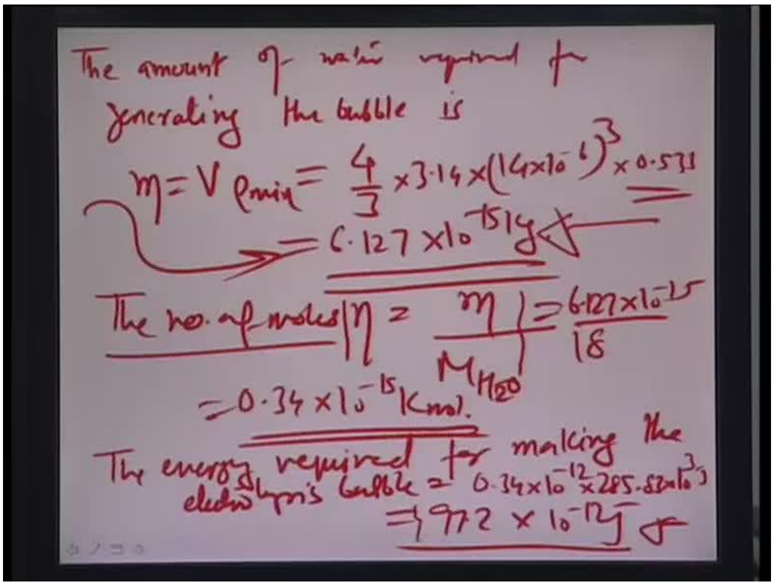

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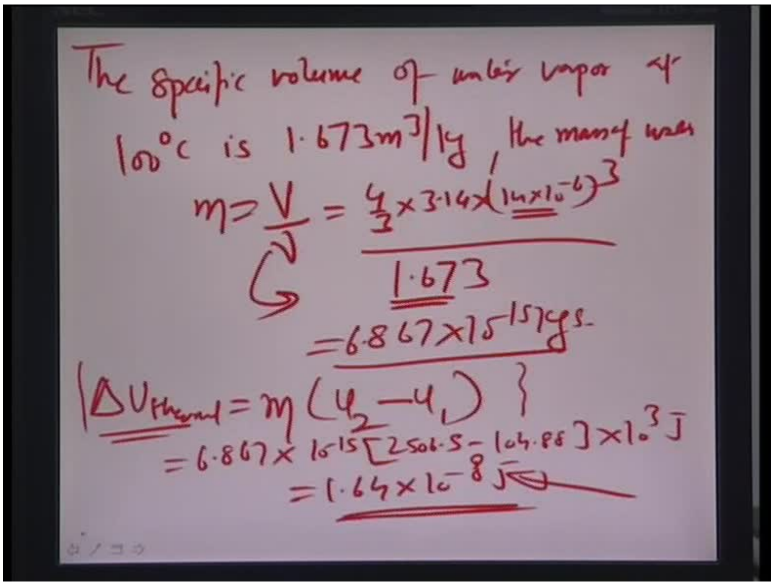

If you may compare this value with electro chemical energy which is needed, it is almost 4 order of magnitudes more in the electro chemical sense is about only 10 to power minus 12 joules, were is in the thermal sense is about 10 to the power minus 8 joules. The thermal means of course, is about 10 to the power 4 times more than the electro chemical means. So, definitely you can understand which one is better or you know more energy efficient process.

Let us also compare the efficiency by considering this bubble to have done a work of expansion and trying to compare that with the amount of energy that has been given into the system in terms of the work done and the internal energy change; the total energy which has been given to the system. If we do that we can get a comparative and we compare both cases the electro chemical as well as thermal and see which one has more energy efficient process in terms of what is going in and what is getting formulated, it is a result of it.

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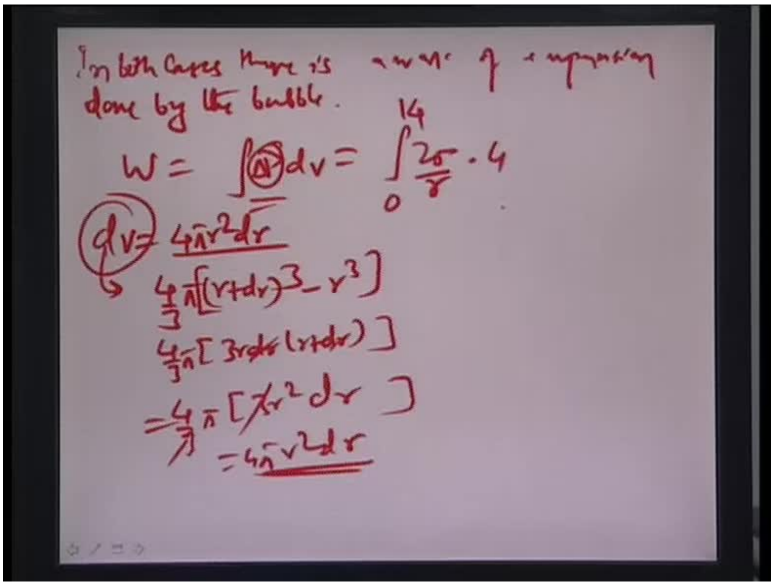

Let us say that in both cases there is a work of expansion which is done by the bubble and this work is essentially integral Pdv also this varies between 0 and 14 microns of course, and you have delta P here, the pressure differences is about 2 sigma by r times of the elemental volume as I had done way back before in case of spherical symmetry is given by 4 pi r square dr.

You can consider this by creating the volume between r plus dr and r elemental volume between these two components. So, r plus dr cube minus r cube this effectively boils down to r dr times of r plus dr the r cubes goes off, dr cube is too small and goes off, d r square here goes off and here only left with 4 by 3 pi times of 3 r square dr and that is essentially 4 pi r square dr. That is the elemental volume dv, I am just trying to recall, what we did earlier in one of the examples.

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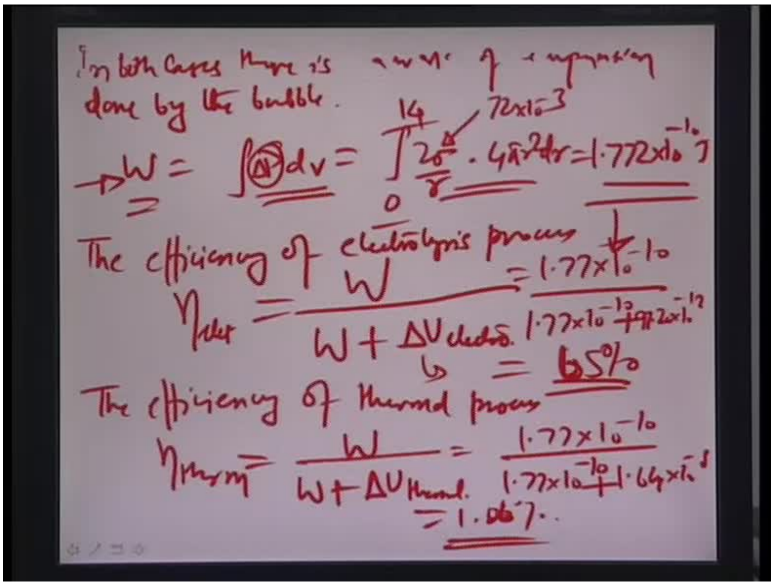

Let me just rub all this, before we start with the derivation of the total amount of work which is done. The work done in this case is of course, delta Pdv which is essentially equal to 2 sigma by r times of 4 pi r square dr and this varies between r between 0 and 14 microns. If you calculate this expression here with the sigma value which is already given in the a numerical problem as 72 into 10 to the power of minus 3 Newton per meter, you are left with a total amount of energy or work done as 1.772 times 10 to the power of minus 10 joules. That is how this total work done would translate into; this is the Pdv work, mind you as the bubble is expanding against an internal pressure of 2 sigma by r. We assume the r to be variable here, the amount of work that the bubble would do in the process of expanding against that pressure or expanding against the delta P is essentially delta P times of dv the change in volume.

Let us assume that the efficiency of electro chemical production of the bubble process, so electrolysis process in terms of bubble growth is essentially, let us call it n, let the W work done divided by W plus delta U electro chemical, which was in the range of 10 to the power of minus 12 joules as if you may remember.

So, this comes out to be equal to 1.77 10 to the power minus 10 divided by 1.77 into 10 to the power minus 10 plus 97.2 into 10 to the power of minus 12. We write this in little better manner, so it is 97.2 times 10 to the power of minus 12. So, this efficiency comes out to be roughly 65 percent, if you just do this calculation here.

However, if you look at the thermal efficiency in generating the bubble - let us call it n therm - is equal to work done divided by work done by of the small sphere times of the internal energy change by thermal means required for generating that amount of or size of gases which can cause the bubble to be about 14 microns in diameter. This would come out to be equal to 1.77 into 10 to the power minus 10 this does not change the work does not change in both cases plus divided by 1.77 into 10 to the power minus 10 plus 1.64 times 10 to the power minus 8 and this comes out be equal to about 1.06 percent. This almost 60 times change in terms of percentage efficiency, when you talk about the difference between electro chemical and the thermal processes. Definitely, electro chemical processes are much more efficient than the corresponding thermal processes.

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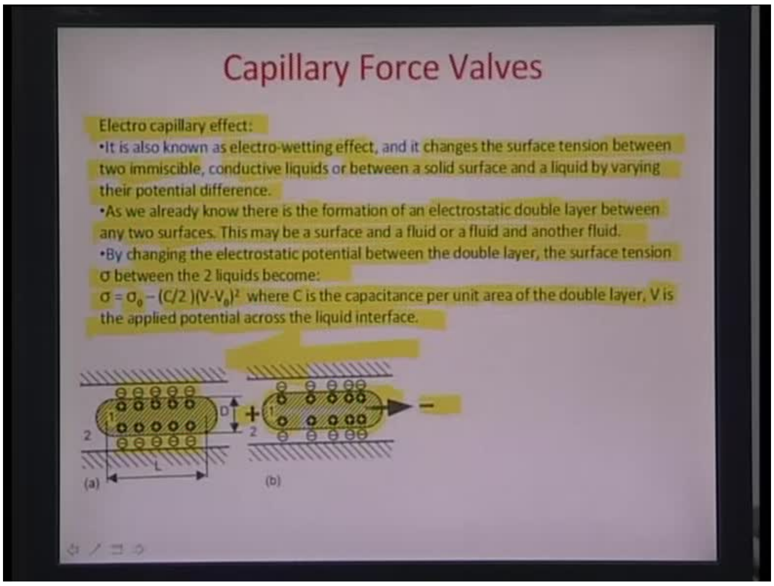

Let us look into another form of valves which is also known as the capillary force valves in the next example, here this effect is called the electro capillary effect. You have to really understand what that is, you can call it several other names like electro wetting effect and essentially, it happens because the surface tension changes between two immiscible, conducting liquids or between a solid surface and liquid just by varying the potential difference between these.

Here, has you are seeing this is uniformly distributed bubble with a double layer across it, you have some positive charges coming here, some negative charges outside this bubble here. If you just apply a potential difference along this direction may be, this is the negative end this is a positive end. There is a tendency of the charges to redistribute in the surfaces suddenly come in more attention or unless tension depending on which side it is facing. In this particular case as you see, the positive charges go back like this.

Therefore, there is more surface tension suddenly which comes in this particular domain here and it be negative charge inside surface tension would have coming in the opposite domain here, because of that there is a tendency of this bubble to move forward and backward just because of the change in the surface tension. Now, this can be done electrically and this can also be done thermally, as I will show in the next illustration where we are talking about a thermo capillary effects.

What will happen here is that as we already know that there is a formation of an electrostatic double layer between any two surfaces. Now, this may be a surface a fluid or a fluid and other fluid and surface. If you change the electrostatic potential in this case between the double layers the surface tension between the two liquids would become sigma new value which is equal to sigma old minus the amount of capacitative energy that you are pumping into the system half cv minus v 0 square; v 0 is the initial value of the voltage at which the double layer and v minus v 0 is the differential change in the voltage which causes this non-homogeneous charge distribution across surface causing a differential tension. C of course, is the capacitance per unit area of the double layer and v is the applied potential across liquid interface.

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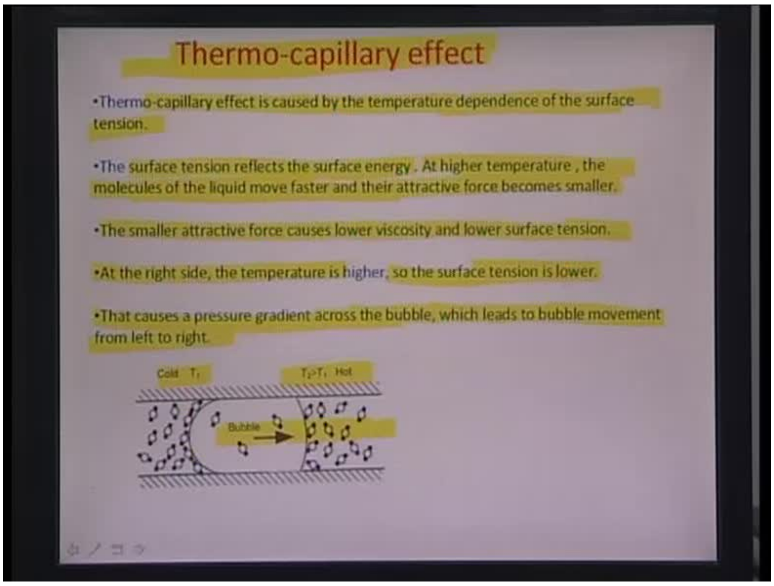

As a result of which there is a movement of this particular effect possible and suppose, this is going to block a capillary, you just need to a certain that you apply a field in the direction of the capitalist, so that the bubble goes and blocks capillary opening. If you reverse the field the bubble comes out and lets the flow go out. This is essentially how capillary force valves would work with. Another very interesting example is thermo capillary effect as you can see here, the same effect that has been done with an external field can also be done with temperatures.

In this effect there is a temperature dependence of surface tension which is utilized for moving the fluid around or fluid the valve around, which is essentially a bubble. Surface tension really reflects the true state of surface energy of a particular structure maybe a bubble or an air bubble or water bubble and oil etcetera. At a higher temperature the molecules of the liquid moves faster and their attractive forces become smaller, because there is less boundation because of more kinetic energies.

Therefore, the surface tension definitely gets affected and becomes lower when the temperature is higher. There is a difference of the gradient in surface tension which would cause the bubble to move towards the lower surface tension. The smaller attractive force causes lower viscosity, lower surface tension. At the right side in this particular instance say, the temperature is hot as you can see, so this T 2 here is much more than T 1 which is the colder side. The surface tension is low here.

That causes a pressure gradient across the bubble, which leads the bubble to move from left to right, so the bubble actually starts moving in this direction towards the hotter side because of the low surface tension. In any case or anybody, in this universe as always prefers to go from high energy content to low energy content. Surface tension is a surface energy parameter, so if the surface tension is lesser the bubble would definitely try to go towards the lesser surface tension which is given by this temperature gradient between T 1 and T 2.

Very interesting affects in fact, this group tenuous which works in making these bubbles to flow around in micro fluidics based on these differentials heating. However, one constraint that such thermo capillary effect - although it is an immensely useful effect in almost all situations but - particularly in the bioassays the problem comes because the time kind of temperatures that you are talking about for a changing surface tension are pretty high in the range of about 90 plus. Most of the biological entities do not survive this kind of temperature. Therefore, especially for biological applications thermo capillary effect may not be that prominently used. However, the electro capillary effect or electro wetting is definitely a very widely used area for BIOMEMS based applications.

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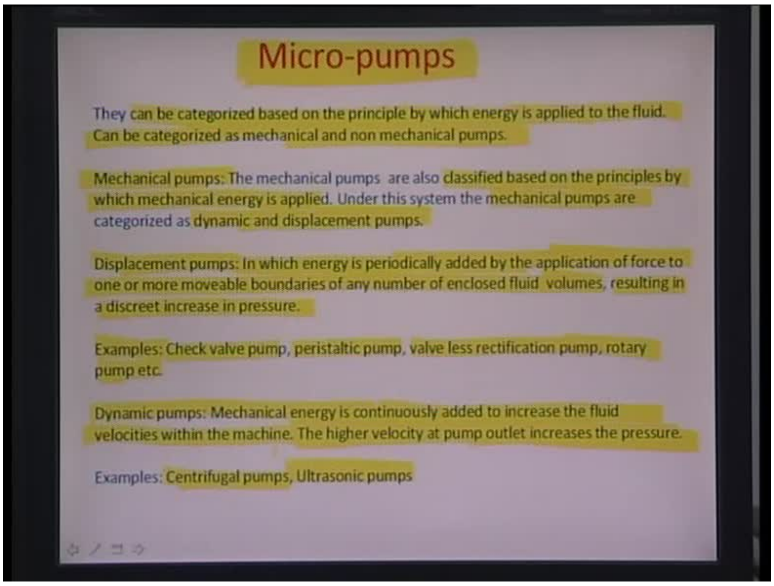

Let us look at a different paradigm altogether which is the world of micro pumps. Essentially, I would like to describe here some of the basic definitions about, what micro pumping is. I would like to categorize into different mechanisms again, there are passive and active micro pumps, there on mechanical non-mechanical pumps essentially. Of course, there up actuation principles or operation principles are based on totally different physical properties or physical effects.

Therefore, one important point to mention here is that whatever the technology has been develop for micro valving mechanisms can very well translated directly to micro pumping. The idea is that if you have some kind of peristaltic motion where you have a travelling contractile. You would discretize that and make a set of 3 valves to do identically in a particular sequence this blocking action of flow at different points to build up a pressure, move along that pressure and release that pressure, against and billing that pressure on a small channel.

Whatever mechanism we have done for valving can be sequenced in a manner, so that you can make those mechanisms to flow fluids around. Micro pumps can be categorized based on the principles by which energy is applied to the fluids. They can be categorized as mechanical and non-mechanical. Mechanical pumps include classification is based on the principles by which mechanical energy is applied.

All mechanical pumps however, either categorize the dynamic pumps or displacement base pumps. There is some moving membrane which is in close proximity to the fluid that you are moving. So, that is why they are dynamic and displacement pumps. A displacement pump again is that when the energy is periodically added to the application of force to one or more movable boundaries of any number of enclosed fluid volumes. This result in actually discreet increase in pressure along the direction of valving close and the fluids keeps moving that particular direction.

Examples could be check valve pump, peristaltic pumps, valve less rectification pumps and I am going to go into detail principles of all these pumps just about little bit, rotary pumps etcetera, these are some of the examples. Dynamic pumps on the other hand are mechanical energy continuously added to increase the fluid velocities within the machine. The higher velocity at pump outlet increases the pressure and therefore, there is a backpressure concept which comes out in this kind of pumping mechanisms. Such mechanisms can be categorized into centrifugal pumps ultrasonic pumps etcetera.

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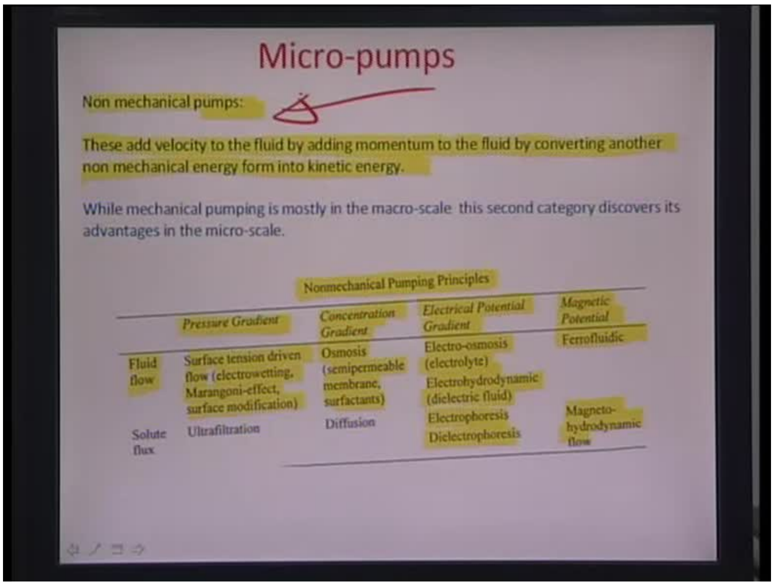

Now, let us describe some of the non-mechanical pumps or types of pumps. Essentially, as I told you before, these really add velocity to the fluid by adding momentum to the fluids by means of converting another non-mechanical energy form into kinetic energy. While mechanical pumping is mostly in the macro scale the second category discovers these advantages of the micro scale.

The various principles of non-mechanical pumping could be a pressure gradient driven flow as an surface tension driven flows, electro wetting, the marongani-effect, which I showed in case of thermo capillary valves about sometime back. Also, the pressure gradient created by surface modification, you can create a hydrophobicity gradient and that could help in transporting water towards the hydrophilic side from the hydrophobic side. So, that is one of the non-mechanical pumping mechanisms.

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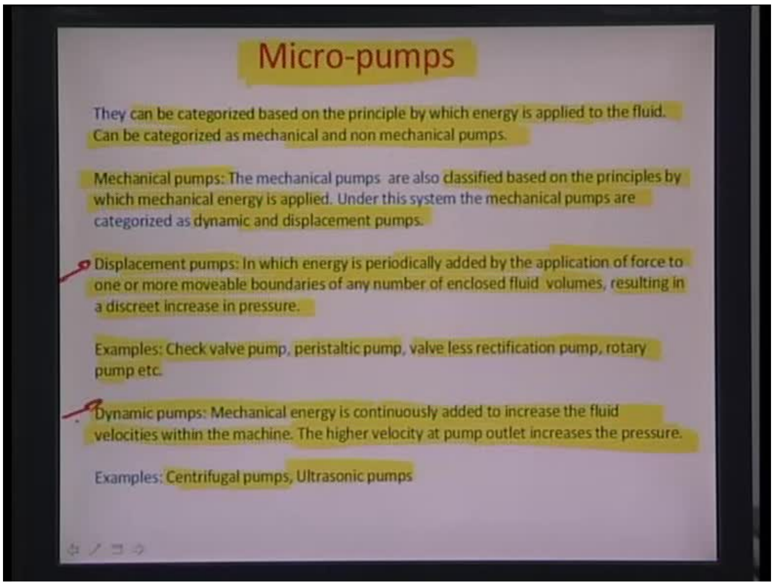

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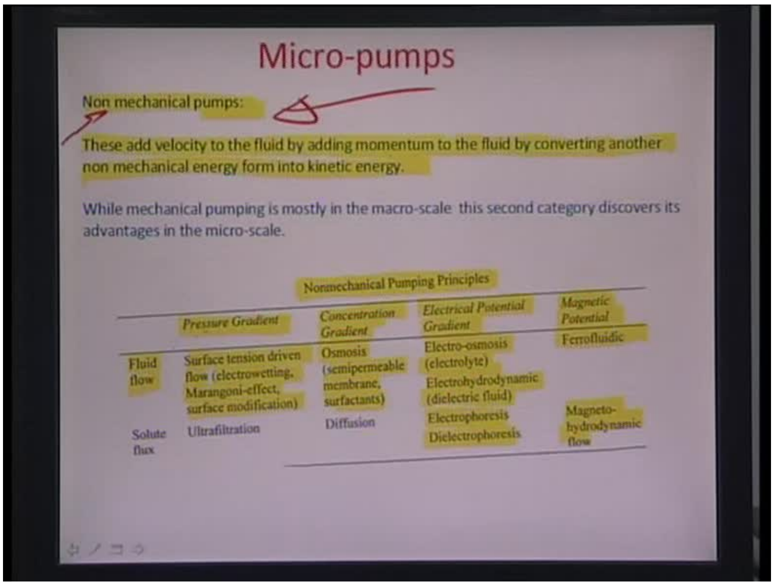

Another is concentration gradient driven mechanisms like osmosis, if you have a charged concentration and you have seen the details of such kind of pumping mechanisms before while doing the chemistry. Essentially, semi-permeable membrane surfactants they would cause this kind of charged double layer along the surface in the solution and diffused layer. This layer can help you to move ahead the flow of fluids is a plug through channels.

There is some other ways and means of non-mechanical pumping; electrical potential gradient is one of them, so you have electro osmosis, electro hydrodynamic flows, electrophoresis, these are all mechanisms were electrical potential gradient would be used for non-mechanical pumping. Then, you have magnetic potential driven micro pumps like ferrofluidic pumps or magneto hydrodynamic pumps.

Essentially, here you later see, it is an oil emulsion of ferrous particles, which act as a plug and can be moved as a piston for driving ahead the meniscus of fluid. The magnetic assembly is moved back and forth by using external magnet sequentially fired in a manner, so that it can move the magnetic plug back and forth. These are some of the non-mechanical basis of micro pumps. You have now categorized pumps into displacement types, dynamic types. These are the two mechanical kinds of pumps and then, several other non-mechanical pumps based on varied pumping principles.

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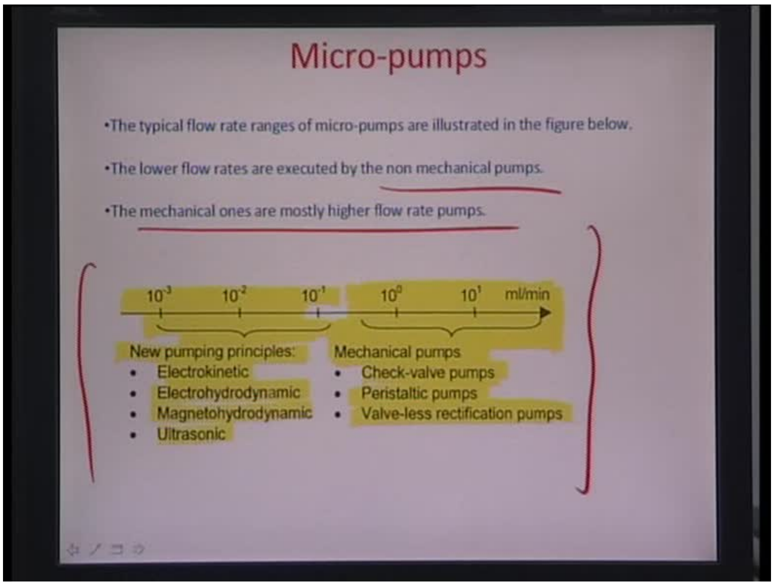

Let us look at some of the comparative flow rates of these micro pumps as illustrated in the figure below here. Typically, mechanical ones are the most flow rate ones; you have a higher flow rate definitely in mechanical pumps. Non-mechanical pumps are actually low on the flow rate characteristics that is because the amount of energy density that you may have to add per unit displacement or per unit volume or per unit volume displacement of fluid is comparatively energy requirement is higher in this case.

If you look at in terms of flow rates of different pumps, the mechanical ones are categorized here onto the right side of this particular scale, this could include check valve based peristaltic micro pumps, valve less rectification pumps and I am going to describe these just about little bit. They are more based on the 10 to 1 micro liter or mille liter per minute range, high flow rate range. The other hand, new pumping principles which are non-mechanical like electro kinetic pumps, electro hydrodynamic pumps, magneto hydrodynamic pumps and ultrasonic pumps, they are more towards the left of this figure starts from about 1000 th of a ml per minute to all the way to about 10 th's of ml per minute or so.

Definitely, as you see here, the mechanical pumps are much more in terms of flow rates, so they can couple the energy or they can put really high energy density for a flow rate to be higher. The novel effects however have low amount of density that you can pack it may be an efficient process but, at a time you may not be able to pump that much density because of limitations related to the properties of the materials which were flowing or fluids that you are flowing. So, that is in a nutshell what the categorization is in terms of flow rates.

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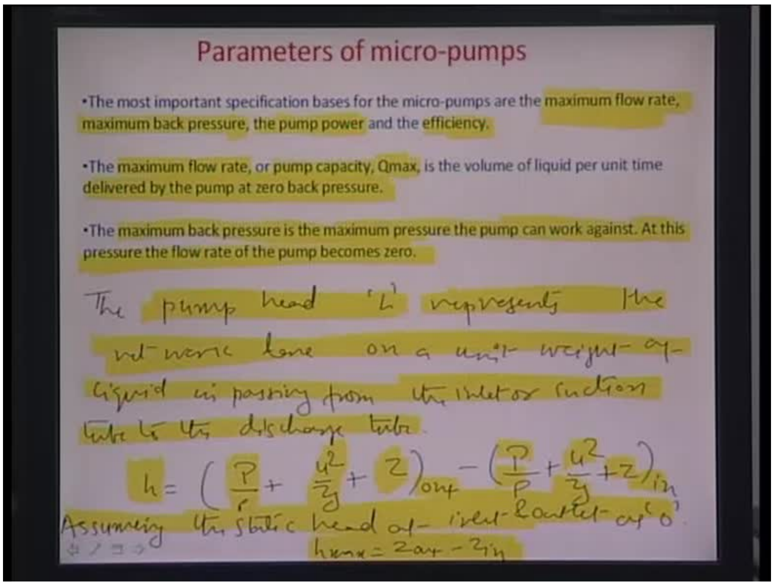

The parameters which are most important to define specifications of micro pumps are essentially the maximum flow rate and quantities like maximum backpressure. Mind you, the backpressure is developed because you are constricting the forward flow into very small venture or is a very small outlet. Definitely, it is going to take some work for the pump to do for pushing the fluid through the small outlet that generates a backpressure on to the system. Essentially, whatever the pumping mechanism be it has to overcome this backpressure by the application of mechanical or non-mechanical energy and only the pump can be forward directional working micro pump.

Specifications would include maximum backpressure, the pump power is very critical and also pumping efficiency is very critical, as you saw in the electro chemical case in case of valves. The electro chemical valve has more efficiency about 65 percent in comparison to thermal which is only about close to 2 percent. Some other parameters for pumps are maximum flow rates that the pump can accommodate which is also known as pump capacity. So, it is essentially the maximum discharge volume Q max, in terms of a centimeter cube per unit time delivered by the pump assuming that there is a 0 backpressure. If you just letting the fluid go into an open atmosphere then, whatever amount of flow rate can be generated is really the maximum flow rate that the pump can generate. You can also categorize the pumps in terms of the maximum backpressure; it is also the maximum pressure that the pump can work against. It can still keep working if you keep on increasing the max in the backpressure, at certain pressure it can fail to work or deliver fluid any more. So, that is essentially the maximum backpressure that the pump can sustain. At this pressure the rate of flow becomes equal to 0.

Let us do some mathematical representation of how you can calculate these efficiency factors. The best factor that is used here is the pumping head in terms of the pressure head that is deliverable by the micro pumps. Let us say, the pump head h represents the net work done on unit weight of liquid on passing from inlet to the outlet of the discharge tube. So, the h here is given by the Bernoulli's equation as the height due to the pressure that is p by rho. The height due to the kinetic energy u square by 2 g and the potential functions z in the outlet site minus the same quantities here on inlet side. So, this essentially the difference in the inlet and outlet pressure heads and that should come somehow as h, outlet pressure being more, so this is the pressure delivered by the pumps.

If you are delivering an outlet pressure will more than the inlet pressure definitely it is a head addition, while the flow is going into the pumps. Assuming static head at inlet and outlet as 0, which means that you assume that the pressures on both sides are at prosperous pressures and the velocity is really are similar on both sides; you do not assume a velocity gradient.

In that case, the max height that this particular configuration can accumulate or the pressure head that it can give maximum is equal to the potential at the output side minus the potential at the input side due the position. If a pump is kept like an incline and output is more than z inputs, so there will be a definite head which comes because of that. That is essentially some of the parameters of micro-pumps which are considered for designing such systems.

Based on the maximum flow rate of the micro pump, the maximum backpressure p or the maximum pump head h max, you can really calculate the maximum power that the pump can deliver. As you know, power is essentially nothing but pressure times of discharge by 2. This is the average power because, if we assume the discharge to be 0 and after application of the pressure head P by the pump, the maximum discharge to be Q max the average flow rate really is 0 plus Q max by 2. So, pressure times of the average flow rate are nothing but the work done per unit time. You may remember that pressure into volume or P dv is the work done in joules. Q is essentially volume per unit time, so this is power, the work done per unit time.

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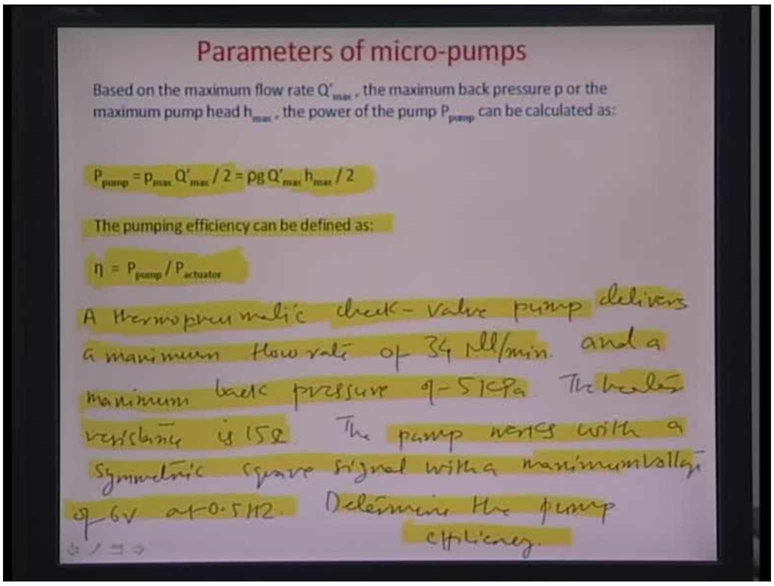

The power of a pump here assuming P max to be the maximum pressure, Q max dash to be the maximum flow rate and assuming that the flow rate starts from 0 and gets this height as the fluid passes through the whole pumping chambers or the pumping system. So, Q max by 2 effectively is the average flow rate. P max into Q dash max by 2 makes the power. We know that the pressure max is also represented by this height max into rho into g, so rho g h max q dash max by 2 is what the pumping power is.

Based on these power equations, we can define pumping efficiency as the power that the pump actually generates in terms of flows by the power that it takes in terms of actuation. If you have certain power delivered inside a certain energy which is delivered per unit time inside the pump, which causes the mechanical or non-mechanical actuation of the fluid. Then, it results in certain work done by the fluid flow against the pressure heads etcetera. So, these two are essentially the ratio between them to determine what is the pumping efficiency, as to how much amount of energy which are packing in is densified as energy applied for flow inside the pump.

Here is an example that I would like to illustrate, so you have a thermo pneumatic system of check valve pump which delivers a maximum flow rate of 34 micro liters per minute. There is maximum backpressure of a 5 kilo Pascal's which is generated and because this thermo pneumatic you are essentially heating the fluids. The heater resistor here is about 15 ohms and the pump works with a symmetric square signal will maximum voltage of 6 volts at point 0.5 hertz, so you have to determine the pump efficiency.

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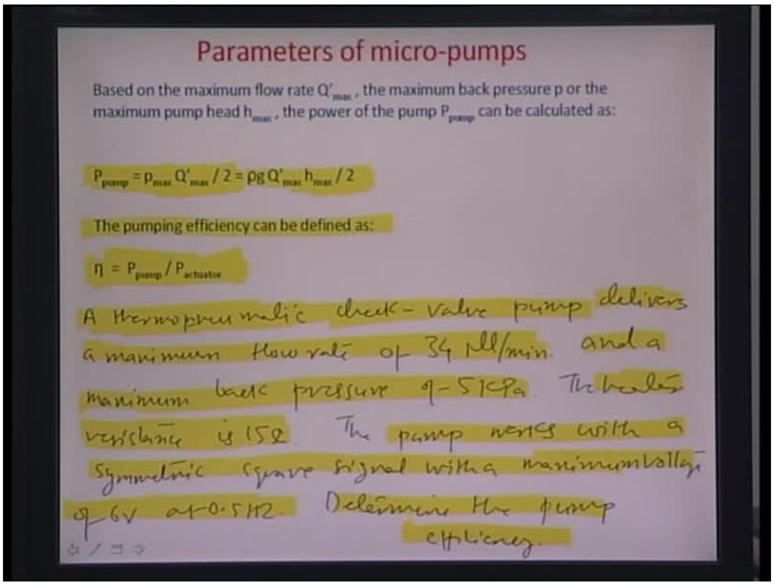

Let us go and solve this particular example, first we calculate the pumping power. The power of the pump is really equal to P max times of Q dot max by 2, P max here is about 5 kilo Pascal's - the total maximum backpressure against it is a flow rate has to be working. So, 5 into 10 to the power 3 Pascal's is what the P max is. Q dot max is the maximum flow rate which is about 34 micro liters per minute. So, I can write that as 34 into 10 to the power minus 9 meter cube divided by 60 for per second into 2. This comes out to be equal to about 1.42 into 10 into the power minus 6 watts that is what the power of the pump is.

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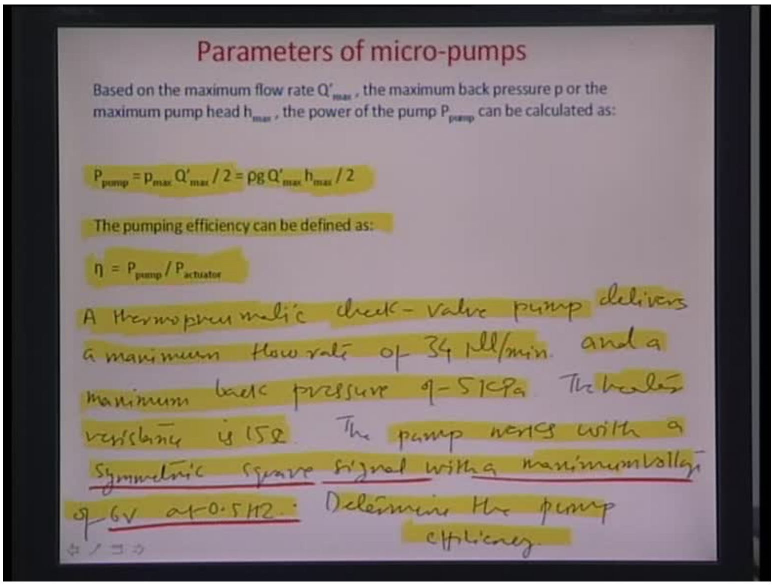

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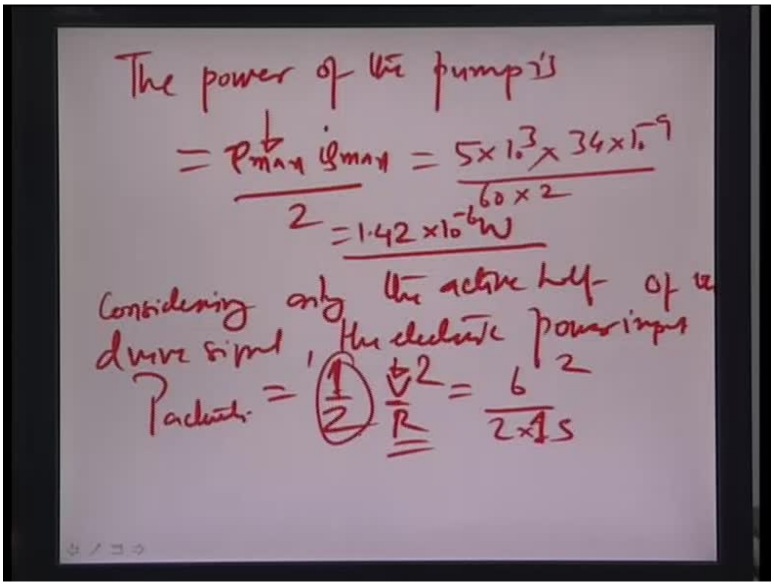

Considering only the active half of the drive signal the dielectric power, basically if you see here, what he saying is that you have a square wave or a square signal to operate the max voltage of 6 volts at point 0.5 hertz, which means that for the other half cycle the power is switched off to 0, so is between 0 and 6 volts. Effectively, the power cycle is only about half the times and the total amount of voltage given as 6 volts in that case. The remaining half is about 0 volts, it is just a square pulse or square wave which is given to control the heaters for the pressure rise of thermo pneumatic force which would close and open the particular valve.

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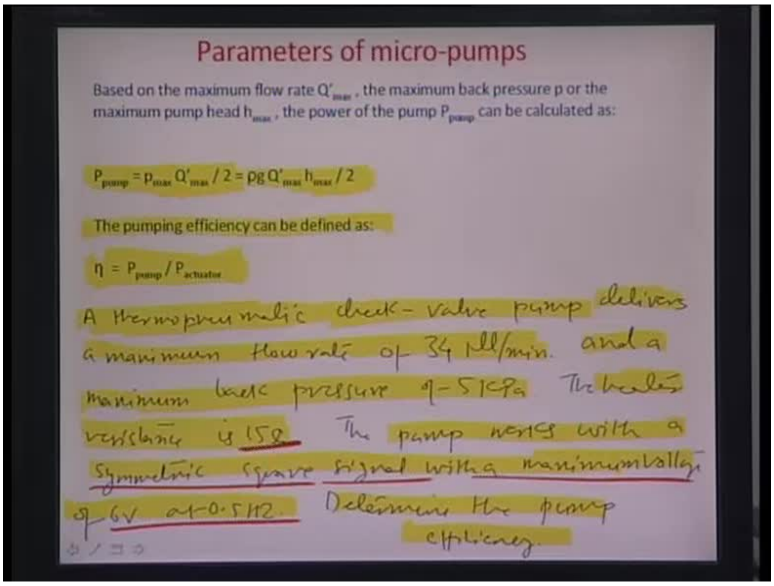

The electric power input here which causes the actuator power is half V square by R; V is 6 volts half because the half cycle is only the power cycle. The remaining half cycles are 0 volts, there is no power delivered from the source into the thermo pneumatic chamber. So, this comes out to be equal to square of 6 times by 2 times 15, the resistance is about 15 ohms as has been illustrated in the example here. This comes out to be about 1.2 watts, so that is what the actuation power is.

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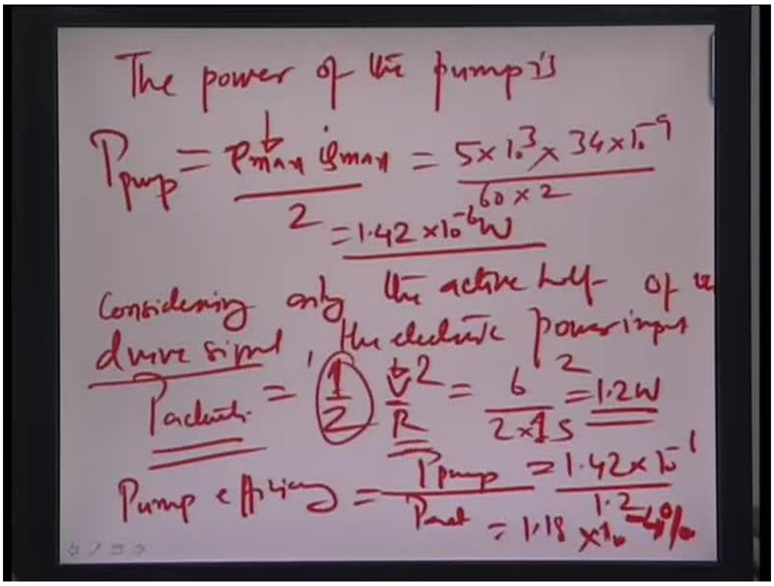

Pumping efficiency is defined earlier is essentially, the power of the pump which we just calculated in the top divided by power of the actuator comes out to be 1.42 times 10 to the power minus 6 by 1.2 which is about 1.18 into 10 to the power of minus 4 percent. So, that is what the pump efficiency is pretty low in this particular case. Thermo pneumatic effects in fact do not really give a lot of efficiency and also, there are awfully slow - the response rate is very slow.

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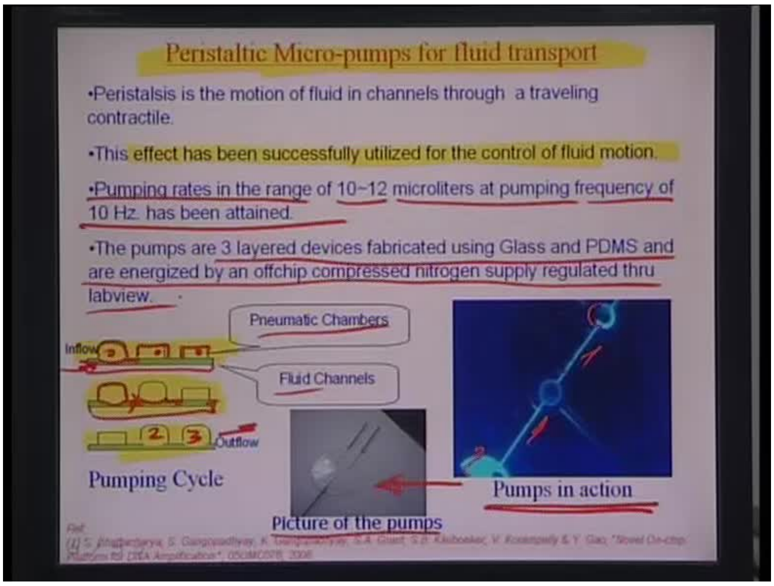

Let us talk about the second mechanism which is peristaltic micro pumps. I would like to show some illustration from one of the research modules that we have developed in our laboratory here. This right here is the example of what a peristaltic pump would typically do micro for fluid transport. Let me just retreat peristalsis in the motion of a travelling contract a fluid due to travelling contract.

If you think that you have, let us say, silicon tubing or something like a flexible rubber; pushing this rubber form both sides and there is a fluid column in between, the fluid is almost going to be squashed on both sides. Now, with this to pushed if you just go along the pipe you are pushing the fluid along the directions of the two pushers and that is what causes pumping to happen or pumping to occur, so that is called peristalsis - travelling contractile. Similar mechanisms take place within the human body where intestines are used to generate enough motion for pumping bile out of the human system.

We can use, this is travelling contractile mode is one continuous process; we can probably discretize it which is more suitable for the MEMS architecture. What we have here is that this effect has been successfully utilized to control flow of fluid motion and that has been done by discretizing the peristalsis action in this particular illustration here. The device made is a 3 layered device with a layer at the bottom, which we cannot see here but it exist, so there is a layer at the bottom, there is a channel layer on the top and then there is a blister pocket which is on the top of all this.

This blister pockets are all connected through an air circuit which is controlled selectively using solenoid motion and the idea is that you actually inflate and deflate these blisters in a sequence, so that you can press for example, this region here which squashes out the fluid in both directions. After this forward momentum is gathered you keep this closed, so that the fluid cannot rushed back and close on the second, so you start compressing the channel on the seconds.

Here the fluid cannot rush back, this path is closed and only the forward direction momentum would be implied onto the fluid channel. Mind you, this green layer here indicates the fluid channel and there is a layer of the bottom here, which is the base or the glass substrates. Then, you can have valve 2 and 3 operated, this sequence can keep on rotating, so that the flow picks up from here and goes all the way up to the outflow. These are some coin like peristaltic pumps which have been developed; these are pneumatic chamber based pumps. Essentially, this shows the real picture of a fluid transport as you are seeing here - this valve is slowly getting filled by the fluid. This valve is slowly getting empty because the fluid transports across this whole channel here through these blister pockets, these are some of the pumps in action.

The pumping rate has been categorizing the range of about 10 to 12 micro liters at pumping frequency of 10 hertz which has been attained. The pumps are essentially 3 layered devices fabricated using glass and PDMS pretty much in the manner that we had done blisters and in this case of course, the orientation of these peristalsis chambers for pumping at different. They are energized by an off chip compressed nitrogen supply regulated through lab view.

This brings us to an end of this particular lecture. Next time, I would like to analyze the peristalsis effects in a little more detail with numerical approach and try to see things like flow rates, backpressure, pressure heads which obtained by this peristaltic motion sequence. We will also look in to some of the other kind of passive pumps like valve less rectification pumps or centrifugal or some of the active pumps like centrifugal pumps etcetera. Then, we will try to go ahead and do some fabrication processes for realizing how these small scale devices can be realized using MEMS technology; thank you.