BioMEMS and Microfluidics
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Lecture - 33

Hello and welcome back to this lecture 33 of Bio Micro Electrical Mechanical Systems would like to briefly review what happen in last lecture.

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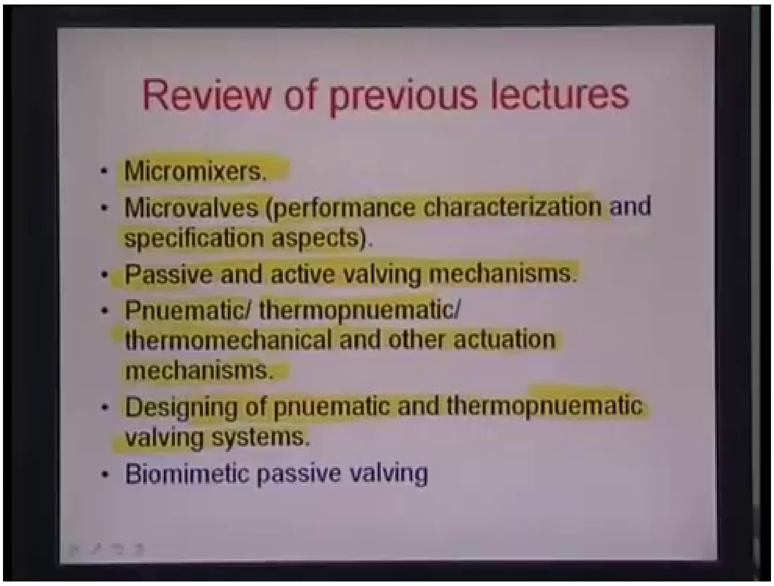

We talked about micro mixers in details parallel and sequential lamination mixers, as passive mixers or active mixers there would be either are some kind of piece of vibration. So, that there is cavitation or there is some active energy pumping into the system and there is mixing of two or more phases. We then detailed about micro valves essentially try to study some basics about their actuation mechanisms the performance characterization and also specifications.

So, some of the aspects like valve capacity, the leakage ratio, the power requirements, the other aspects like material selection, biocompatibility, etcetera when discussed for designing micro valves or micro valving systems. Now, for the categorize valving in to passive and active valving mechanisms and now we discussed different kind of actuation mechanisms like pneumatic, thermo pnuematic, thermo mechanical, electrical kinetic some other actuation mechanisms.

So, we also tried to designing some of these pneumatic and thermo pnuematic valving systems and saw that specially design after we made in manner with the micro scale and it kind of makes an area ratio between the inlet and the valve seat. So, that the amount of forces that I needed for actuating the valve member is small. So, because we talking about micro fluidic systems or micro flow systems the inlet area is typically a small which makes automatically the actuation forces very, very small as you saw the example about designing the pneumatic systems.

We further can amount of cylinder and use same kind of distributed load by means of pneumatically sealing the cylinder and adding temperature. So, that the system as PDV work and there applies pressure in the valves the effectively a force, because of the heating effect. We also talked about bio pneumatic passive valving mechanisms and try to discuss about what happens to the human body particularly in the vasculature with the pressure gradient and the way that the valves close and open.

Now, we talked about hydrogen valves here particularly, where which essentially to pH and swells and blocks or de swells and unblocks a certain flow and flow rates can be calculated to the pH values respectively. Today we will we talking a little more on that line about as some other non conventional valving mechanisms and one of the most popular in the category also electro chemical valving mechanism.

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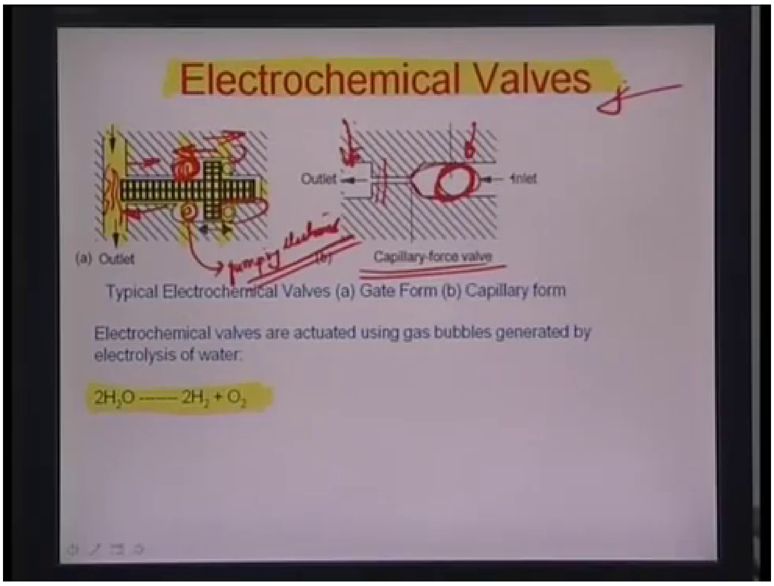

So, let us see what electrochemical valves really are essentially a very simple system of a reaction as can be seen here H_2O is electro chemically converted in to hydrogen and oxygen. And basically if you look at the overall architecture of these systems this is basically the outlet of micro pipe and this is a gating device here. And essentially there are four electrodes in this region, this region, this region and this region and the electrodes pump in electron, so that bubble gets formulated.

So, if you really control the differential of a size between bubble one here and bubble two here, you can make this gate mechanism move back and forth. Suppose, this is bigger and this is smaller the gate will push back vice versa this is smaller and that is bigger in the gate will push forward. And so therefore, the flow path here is kind of blocked because of this mechanism; however, this is an electro chemical valve, because hydrogen, oxygen bubbles here at produced just by venture of pumping electrons.

And so therefore, a valve is really actuated electro chemically. Similarly, you could have blocking mechanism, where in this the bubble which is generated by electrode is may be and the bubble is too big and blocks this code after awhile and cuts of the flow from the inlet sight to the outlet sight. So, that is again call capillary force valve then may be the tendency of the bubble to squeezes past and go to the other direction.

And ensure the pressure gradient between these two points, so that the valve kind of keeps here and protects the flow from going inlet to the outlet side of tops 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 thermal set of which would generate the same bubble and the electrical set of which will generate same bubble.

You find that there is law difference in the valving efficiencies and that is exactly why conventional means not very well soon an micro scale and rather you prefer doing something which is non conventional like let say electro chemistry based or magnetic based or electrical field based to prevent this extra amount of work which needs to be a certain for translating into the micro scale. So, therefore, we always fetch for rather non conventional systems for doing actuations in this scale.

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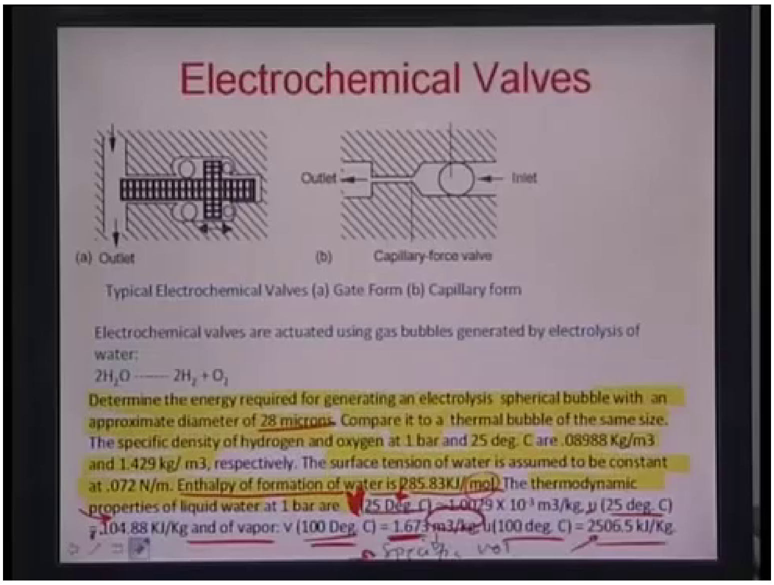

So, let us do this example here we have an electro chemical valve as which is described above which is based on the principle of electrolysis of water. And essentially here if we look in to we have to determine the energy required for generating an electrolysis spherical bubble with in approximation of diameter 28 microns and we have to compare it to similar bubble generating thermal mechanism with generates by evaporation of water of the same size, some parameters given of the specific density of a hydrogen and oxygen at one bar pressure and 25 degree Celsius it 0.08988 Kg/m^3 and 1.429 Kg/m^3 respectively the surface tension of water is assume to be constant and that is taken as 0.072 N/m.

And the enthalpy of formation of water is about 285.83 kilo joule per mole and some other thermo dynamic properties of the liquid water like a 1 bar pressure like for example, the u or the internal energy at 25 degree Celsius that at 100 degrees Celsius, this is the value, this is specific volume. So, very specific volume at 25 degree Celsius internal energy at 25 degree Celsius. And similarly this specific value at 100 degree Celsius and internal energy at 100 degree Celsius are given and basically specific volume again let me retreat as a unit here indicate the value per rate mass.

So, you have say 1 Kg of mass of both hydrogen, oxygen or other gases you really find out how this 1 Kg would be able to occupy in terms volumes. So, that is why I kind of make a common base or a common denominator and see a volume comparison based on that is called specific volume, it is different than the normal volume is prominent mass or prominent wave. So, let us see what the differences really are in terms of energy requirements and whether they are any different if it is thermal as suppose to electro chemical. So, let us first do the thermal the electro chemical part.

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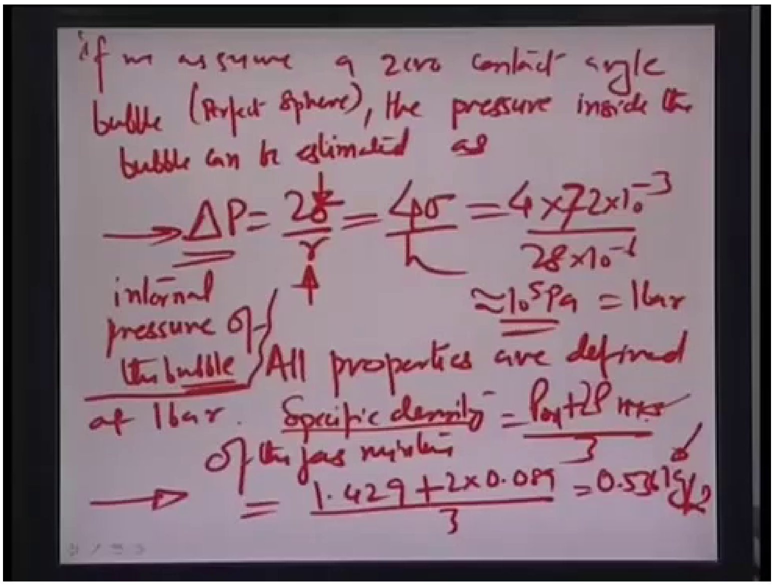

$$\Delta P = \frac{2\sigma}{r} = \frac{4\sigma}{h} = \frac{4 \times 72 \times 10^{-3}}{28 \times 10^{-6}}$$

So, if we assume zero contact angle bubble, let say a prefect 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 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 really and as we know from the example here the diameter of the bubble is approximately 28 microns, which makes the radius about 14 microns.

So, here the surface tension force as we know is about close to 0.072 Newton per meter for water molecules and 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, so this comes out to be about 10 to the power 5 Pascal's or 1 bar pressure.

So, all the properties are really defined at 1 bar, so therefore, we can find out specific density of the electrolysis gas mixer hydrogen and oxygen at 1 bar pressure. So, let us go ahead and do that, so all properties are defined at 1 bar. So, the specific density of the mixer of gases can be obtained as specific density of oxygen at 1 bar pressure and 25 degrees Celsius times of specific density in to 2 of hydrogen divided by 3. So, this comes out to be equal to 1.429 Kg/m^3 plus 2 times 0.089 Kg/m^3 by 3 which further about 0.536 Kg/m^3. So, that is what specific density of the gases mixer is in this particular case.

So, 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 a continuity between the two phases would have to be essentially decomposed in order to create a equal volume of a gas mixer H_2 and O_2 which would formulate a bubble. So, let just write this presumption again here.

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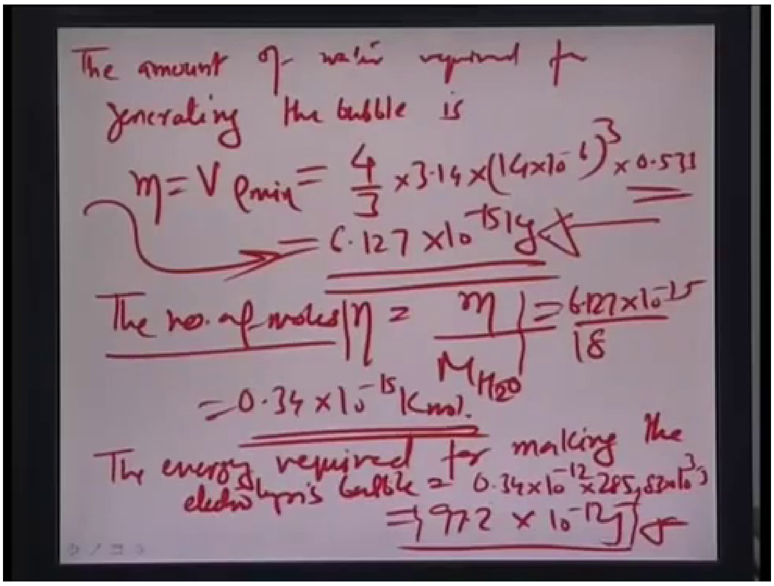

$$m = V\rho_{min} = \frac{4}{3} \times 3.14 \times \left(14 \times 10^{-6}\right)^3 \times 0.533$$

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 time of 0.536 which is the density at this particular density at this particular pressure and temperature. So, this comes out to be equal to about 6.127×10^{-15} kg. So, effectively you are actually electrochemically converting about 6.1 to 7 femtograms of mass in order to get a bubble which would have a pressure differential of about close to 1 bar.

And at that particular gas mixer density at 1 bar pressure or about room temperature 25 degree Celsius also. So, with this it is convenient to assume in terms of number of moles how many moles of water would be needed of so many Kg of water that has been generated here to electrolyze for creating the bubble. So, the number of moles this case n will be equal to mass by mass of H_2O which is 6.127 times of 10 to the power minus 15 by 18 or about 0.34 10 to the power minus 15 kilo moles that is how number of moles of H2 molecules would be needed to make a volume which would support a pressure differential if about 1 bar.

So, as we also know from the question here the enthalpy a formation of water, if you see in this region and this is actually electro chemical enthalpy of formation is actually 285.83 kilo joule per mole of material and you 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.

And so therefore, if we write that down have the energy require for making the electrolysis bubble is essentially equal to 0.34 $*10^{-12}$ moles times of 285.83 * 10 to the power of minus or 10 to the power of 3 joules which is also 97.2 $*10^{-12}$ joules. So, effect if this much amount of energy is needed to realize the total volume of the gas mixer in form of an electro chemical bubble.

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

So, therefore, if we compare the specific volume of water vapor that 100 degree 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, how should be able to have a comparative between the total energy is in both cases.

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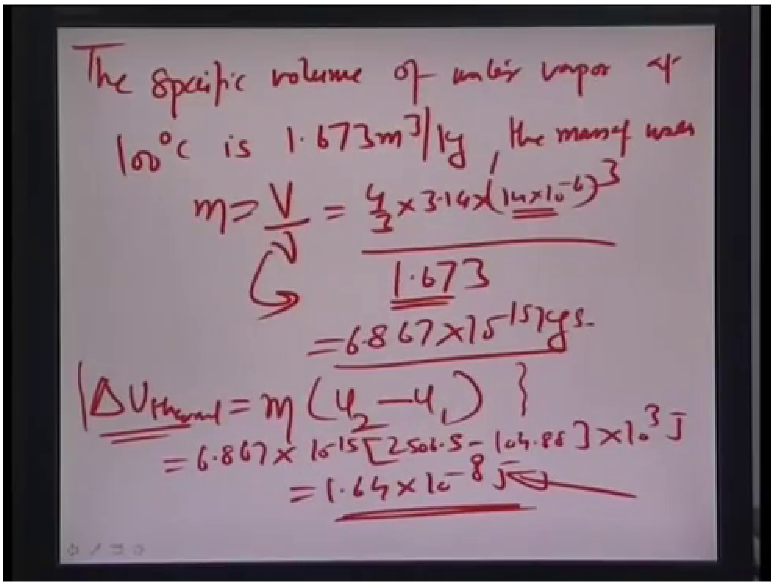

$$m = \frac{V}{v} = \frac{4}{3} \times 3.14 \times \left(14 \times 10^{-6}\right)^3$$

$$\Delta U_{therm} = m\left(u_2 - u_1\right)$$

So, let us say that the specific volume of water vapor at 100 degree Celsius is about 1.673 meter cube per Kg and mass of water therefore, m is also known is also given by V by nu the specific volume is essentially 4 by 3 times 3.14 times 14 times 10 to the power minus 6 by 3 this is essentially the volume of this sphere half radius 14 microns diameter 28 microns, which is the size of the bubble divided by the new value which is 1.673 this is essentially this specific volume of water vapor, which is actually given in the numerical example the question at the very beginning.

So, as you see here specific volume of the water vapor at 100 degree Celsius is given to be 1.673 meter cube per Kg mind you in thermodynamics state 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 and we need to formulate the vapor in order to realize the bubble. So, therefore, all specific volume is etcetera which are considered really are at 100 degree Celsius.

So, let us try to look at that figure here and see what the mass would effectively be, so in this case the mass comes out to about $6.867 * 10^{-15}$ Kg's and essentially if you ignore the heat loses from the system we assume that this system is we can find out the energy required, the thermal energy required for formulating this amount of water vapor mass $6.867 * 10^{-15}$ Kg's of water vapor mass.

So, how do we do that we know the delta U thermal, the amount of internal energy that needs to be supply 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 Kg's divided by the internal energy at 100 degrees minus internal energy at 25 degrees Celsius. And if you look back in the example both these values are given here as internal energy at 100 degrees is about 2506.5 joules and that at 25 degrees is about 104.88 kilo joules per Kg.

And so we are multiplying the mass and Kg's, so we are left with this equation which is in kilo joules of energy. So, we reduce this to $6.867 * 10^{-15}$ times of 2506.5 minus 104.88 times 10 to the power of 3 joules. So, it comes out to be $1.64 * 10^{-8}$ joules. And so essentially that is the amount of thermal work that is needed to be done for creating this particular bubble in this example.

If you make compare this value with the electro chemical energy which is needed, it is almost four order of magnitudes more in the electro chemicals sense it is about only 10 to the power of minus 12 joules, whereas and the thermal sense it is about 10 to the power minus 8 joules. So, the thermal means always of course, is about 10 to the power 4 time more than the electro chemical means and so definitely you can understand which one is a better for you know more energy efficient process.

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

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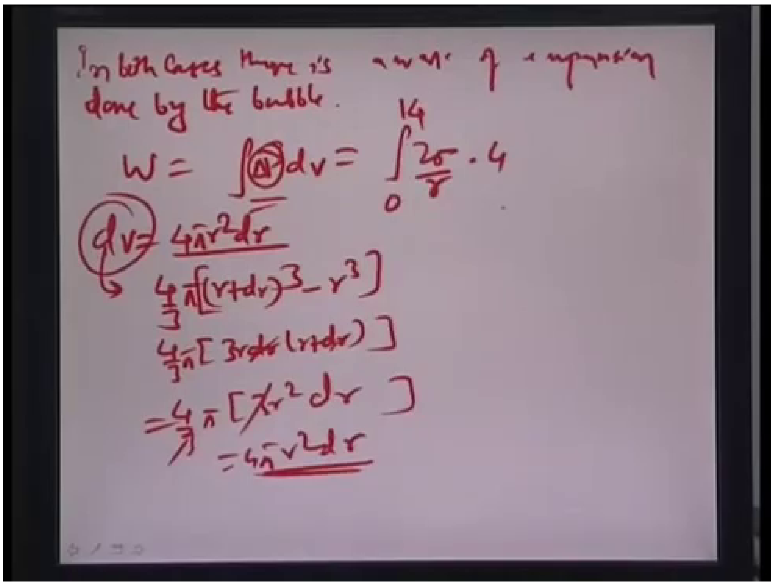

$$W = \int dV = \int_0^{14} \frac{2\sigma}{r} . 4\pi r^2 dr$$

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So, let say that in both cases and there is a work of expansion which is done by the bubble and this work is essentially integral p dv also this various between 0 and 14 microns of course, and you have a delta p here, the pressure deference is about 2 sigma by r times of the elemental volume as I had done way back before in case of spherical symmetries 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, you have r plus dr cube minus r cube this effectively down to 3 r dr times of r plus dr the r cube goes of dr cube is too small goes of dr squared here goes off we are only left with 4 by 3 pi times of 3 r square dr and that is essentially 4 pi r squared dr. So, that is the elemental volume dv. I am just trying to recall what we did earlier in one of the examples earlier.

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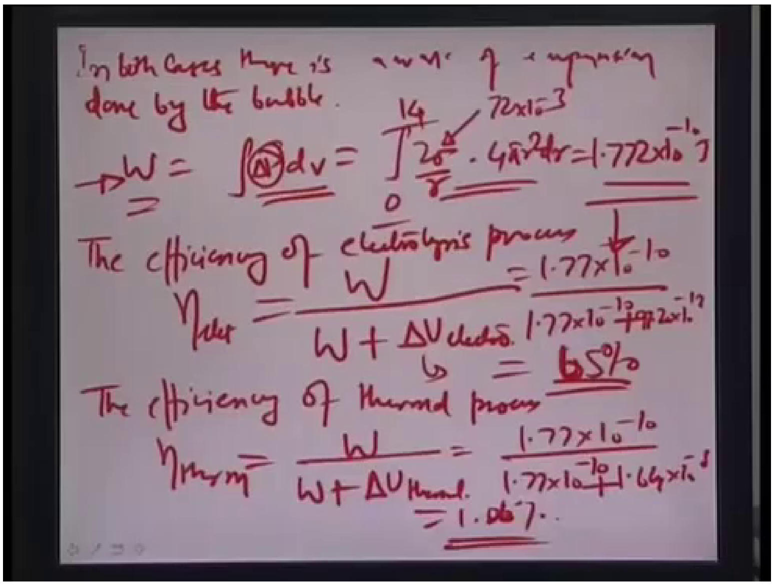

$$W = \int dV = \int_{0}^{14} \frac{2\sigma}{r} .4\pi r^2 dr$$

$$\eta_{\square} = \frac{W}{W + \Delta U}$$

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So, let me just rub all these before we start with the derivation of the total amount of work which is done. So, the work done in this case is of course, delta p dv which is essentially equal to 2 sigma by r times of 4 pi r squared dr and this where is between r between 0 and 14 microns and if you calculate this expression here with the sigma value which is already given in the numerical problem as 72 * 10^{-3} Newton per meter, you are left with a total amount of energy or work done as 1.772 * 10^{-10} joules that is how this total work done would translate into this the p dv work mind you as the publish expanding against internal pressure of 2 sigma by r and we assume that to be variable here, the amount of work that the bubble would do in the process of expanding against that pressure or expanding again the delta p is essentially it delta p times of dv the changing volume.

And so let us assume that the efficiency of electoral chemical production of the bubble process. So, electrolytes process in times of bubble growth is essentially let us call it the w work done divided by w plus delta u electro chemical which was in the range of 10 to the power minus 12 joule as if you remember. So, this comes out to be equal to 1.77 times 10 to the power minus 10 divided by 1.77 times 10 to the power minus 10 plus 97.2 times 10 to the power of minus 12 and let me write this little better manner. So, it is 97.2 times 10 to the power of minus 12 and so this is sufficient comes out to be roughly 65 percent, so if we just do this calculation here.

However, if you look at the thermal efficiency in generating the bubble let us call it n term is equal to work done divided by work done by the small sphere times of the internal energy change by thermal means required for generating that amount of or sizes of gases which can calls the bubbles to be about 14 microns in diameter. So, this would come out to be equal to essentially 1.77 times 10 to the power minus 10 this does not change the work does not change in both cases plus divided by 1.77 times 10 to the power minus 10 plus 1.64 times 10 to the power of minus 8 and this comes out to be equal to about 1.06 percent.

So, this almost a 60 times change in terms of percent efficiency, percentage efficiency when you talk about the difference between electro chemical and the thermal processes. So, definitely electro chemical process are much more efficient then the corresponding thermal processes. So, let us look in to 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 and you have to really understand there is.

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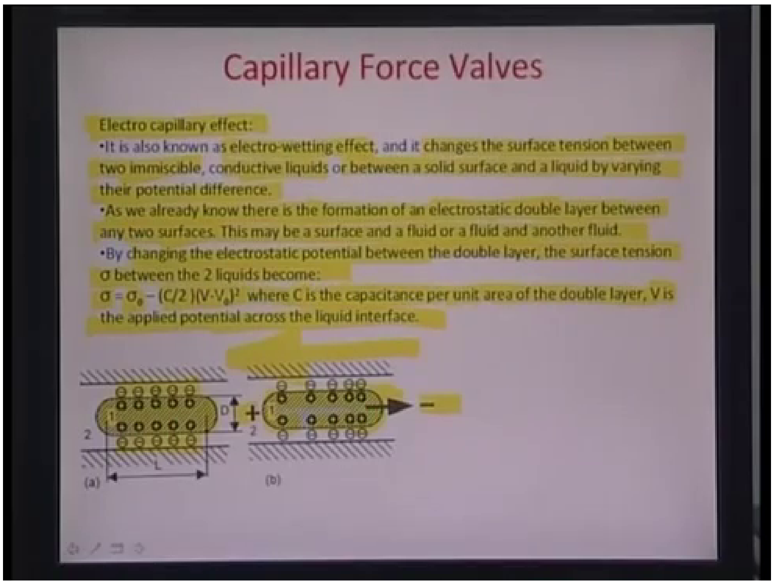

So, you can call it several other names like electro wetting effect and essentially it happens, because the surface tension essentially changes between two immiscible conductive liquids between in a sold surface and liquid just by varying the potential difference between these. So, here as you are seeing this is a uniformly distributed bubble with double layer across at you have some positive charge coming here, some negative charges outside this bubble here.

So, if we just apply a potential difference along this direction may be this is the negative end, this is the positive end, there is a tendency of the charges to kind of redistribute and the surfaces certainly come in more tension or less tension depending on which side it is facing in this particular case as you see the charges kind of positive charges kind of go back like this. And so therefore, there is a more surface tension suddenly which comes in this particular domain here and it be negative charge inside the surface tension would have come in the opposite domain here.

So, because of that there is a tendency of this bubble to move forward and backward, it just because of change in surface tension. Now, this can be done electrically, this can also be done thermally as I will show in the next illustration when we are talking about thermo capillary effect. So, what will happen here is that as we already know that there is formation of electrostatic double layer between any two surfaces, now this may be a surfaces of a fluid or a fluid and other fluid and surface.

And if you change the electro static 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 capacitors energy that you are pumping into the system half c b minus v0 squared, v0 is the initial value of the voltage at which the layer exist and v minus v0 is the differential change in the voltage, which casus this non homogenous charge distribution across the surface casing a differential tension.

C of course, the capacity per unit area of the double layer and v is the applied potential across the liquid interface. So, 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 capillaries, So, that the bubble goes and blocks the capillary opening, if you reverse the feels the bubbles comes out and let us the flow go out. So, this is essentially how capillary force, valves would work on.

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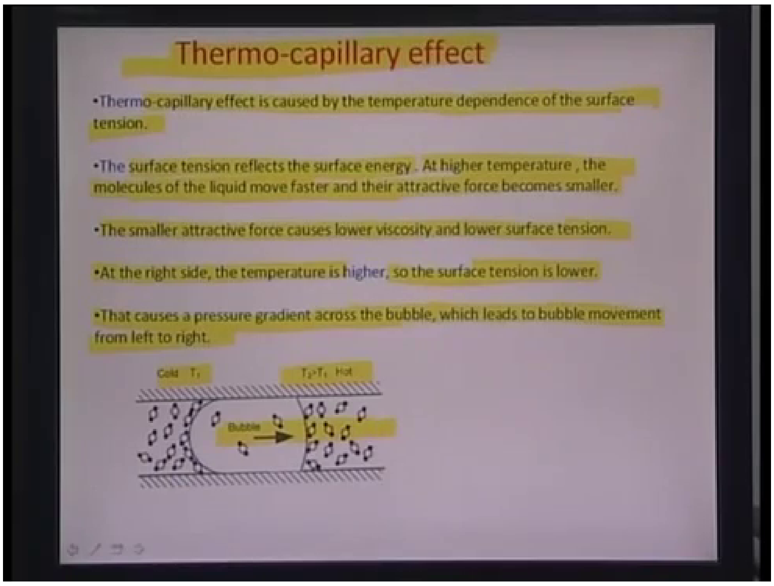

Another very interesting example is thermo capillary effect as you can see here, the same effect that has to be done with an external feel can also be done with temperatures. So, in this effect there is a temperature depends on surface tension which is utilized for moving the fluid around or fluid the valve around, which is essentially a bubble and surface tension really reflects the two state of surface energy of a particular structure may be a bubble or you know air bubble or a water bubble etcetera.

So, at a higher temperature the molecules of the liquid moves faster and there attractive forces becomes smaller. Because, there is less boundation because of more kinetic energies and therefore, the surface tension defiantly gets effected and becomes lower when the temperature is higher and 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 cases lower viscosity, lower surface tension at the right side in this particular instant say, the temperature is hard as you can see, so this T2 here is much, much more than T1 which is colder side.

So, the surface tension is lower here and this cause a pressure gradient across the bubble which leads the bubble to move from left to rights. So, the bubble actually touch moving in this direction towards the hotter side, because of the low surface tension many case anybody in this universes you know always prefers to go from a high energy content to a low energy content, surface tension is the surface energy parameter.

And so if the surface tension is lesser a bubble would defiantly try to go towards the lesser surface tension which is given by this temperature gradient between T 1 and T 2. So, very interesting effects in fact this group in US which works and making these bubbles to flow around in microfluidics based on these differential heating; however, one constraint that such thermo capillary effect although it is an immensely useful effect in almost all situations.

But, particularly in the by over says the problem comes, because you know the time kind of temperatures that you are talking about for changing surface tensions are pretty high in the range above 90 plus most of the biological entity is do not survive this kind of temperature. And therefore, especially for biological applications thermo capillary effect may not be that prominently used; however, the electro capillary effect is defiantly are electro getting is defiantly a very widely used area for BioMEMS based applications. So, let us look at now are different paradigm all together which is the world of micro pumps.

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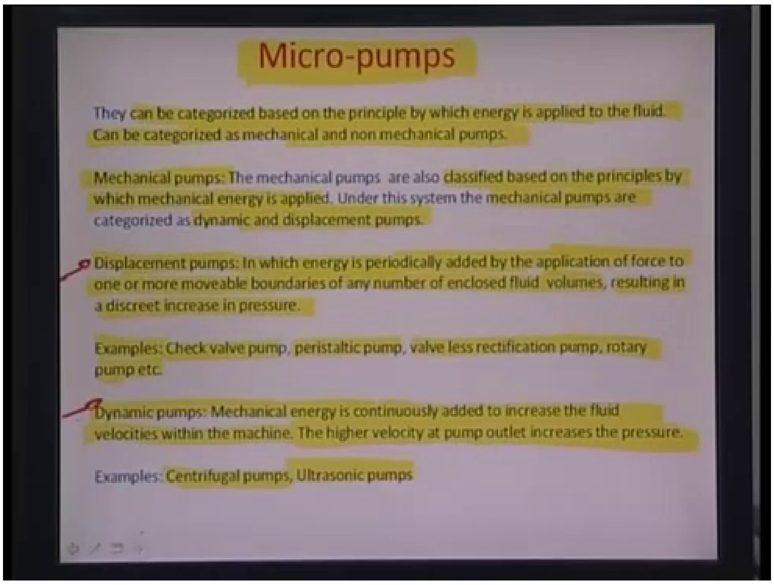

Essentially I would like to describe here some of the basic definitions about what micro pump is I would like to categories into different mechanisms again there are passive and active micro pumps there are mechanical, non mechanical pumps essentially. And of course, there actuation principles or operation principle are based on totally different physical properties or physical effects. And so therefore, one important point to mention here is that whatever technology has been developed for micro valving mechanisms can be very well translated directly to micro pumping.

The idea is that if you have some kind of motion, where you have a traveling contractile you could make a set of three valves to do identically in a particular sequence this blocking action of flow at different points at build up pressure, move along that pressure and release that pressure and again start willing that pressure a small channel. So, whatever mechanism you have done for a valving can be sequenced in a manner. So, that you can make those mechanisms to flow fluids around.

So, micro pumps can be categories based on the principles by which energy supplied to the fluids they can be categorized as mechanical and non mechanical and mechanical pumps include classifications based on the principles by which mechanical energies applied. So, all mechanical pumps however or either categories dynamic pumps or displacement pumps. So, there are some moving component, some moving member, some moving numbering which is enclose proximate to the fluid that you are moving. So, that is why they are dynamic and displacement pumps, displacement pumps again is start when the energy is periodically added to application of force to one or more moveable boundaries of any number of enclosed fluid volumes and this results an actually discrete increase in pressure along the direction of valve enclose and the fluids keep moving that particular direction.

So, examples could be check valve pumps, peristaltic pumps, valve less rectification pumps and I am going to detailed principles of all these pumps just an about little bit rotary pump etcetera this is the some of the examples. The dynamic pumps on the other hand are where mechanical energy is continuously added to increase the fluid velocity within the machine and the higher velocity at pump outlet increases the pressure and there is a back pressure concept which comes out in these kind of pumping mechanisms, such mechanisms can be categories into centrifugal pumps, ultrasonic pumps etcetera.

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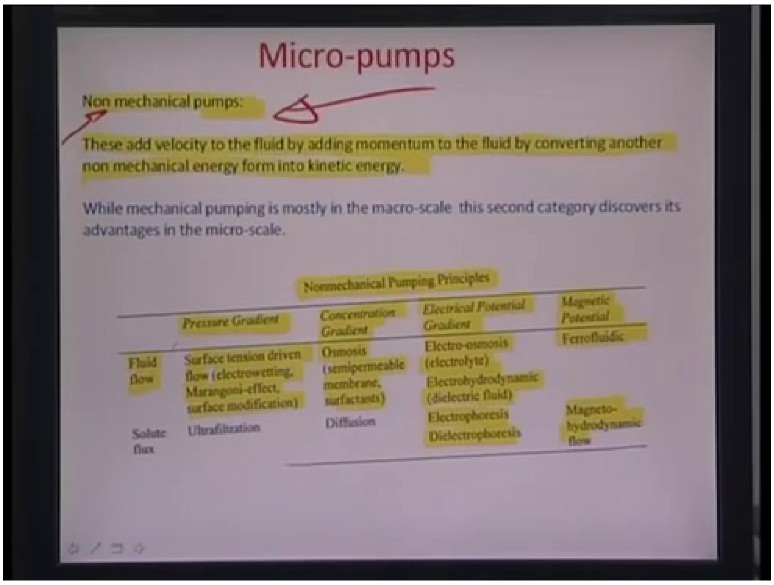

So, now, let us describe some of the non mechanical pumps a types of pumps. So, essentially as I told you before these really add velocity to the fluid by adding momentum to the fluid I means a converting another non mechanical energy form into kinetic energy. So, while mechanical pumping is mostly in the macro scale, the second category discovers is advantages in the micro scale. The various forms of non mechanical pumping various principles of non mechanical pumping could be a pressure gradient driven flow as in surface tension driven flows electro wetting the effect which I showed in case of thermo capillary valves about sometime back.

And also in pressure gradient created by surface modification you can create a hydro gradient and that could help in transporting water towards the hydrophilic side from the hydrophobic side. So, that is one of the mechanisms, non mechanical pumping mechanisms, rather is concentration gradient driven mechanisms like osmosis, if you have a charge concentration and you have detail, you have seen the details of such kind of pumping mechanisms before while do an electrochemistry.

So, essentially semi permeable membranes, surfactants they would cause this kind of charged double layer along the surface in the solution and a diffused layer. And this layer can help you to kind of a move ahead the flow of fluids is a plug through channels and there some other ways means of non mechanical pumping, electrical potential gradient is one of them. So, you have electric osmosis electro hydrodynamic flows like electrophoresis, the electrophoresis these are all mechanisms, where electrical potential gradient would be used for non mechanical pumping.

Then, you have magnetic potential driven micro pumps like Ferro fluidic pumps or magneto hydrodynamic pumps, essentially here as you will later see is there is an oil immersion of which act is a plug and can be moved as a piston for driving a head the fluid the magnetic assembly is move back and forth by using external magnet sequential if I in a manor. So, that it can move the magnetic plug back and forth, these are some of the non mechanical bases of micro pumps. So, you have now categories pumps into displacement types, dynamic types these are the two mechanical kind of pumps and then several other non mechanical pumps based on varied pumping principle.

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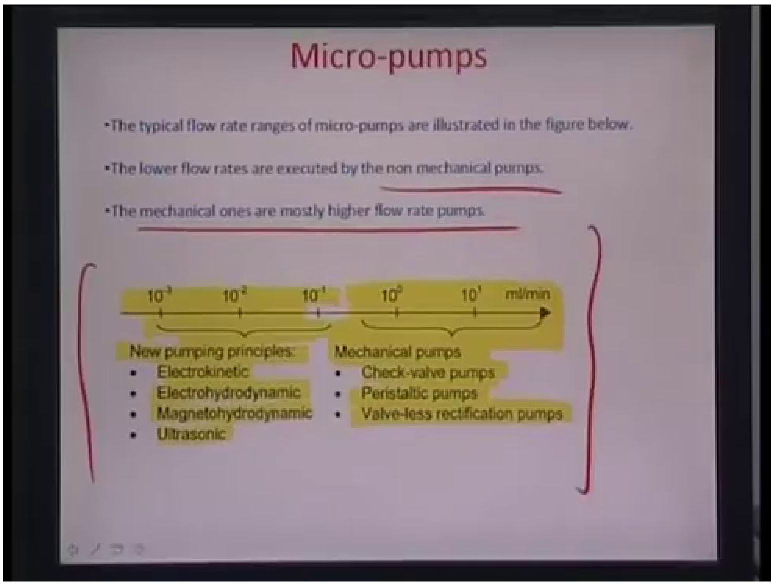

Let us look at some of the comparative flow rates of these micro pumps as illustrated in the figure below here, typically mechanical ones are the most flow rate ones, you have a higher flow rate definitely in mechanical pumps, non mechanical pumps are actually low on the flow rate characteristics that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

So, if you look at in terms of ml per minute, in terms of flow rates of different pumps the mechanical ones are categories here on to the right side of this particular scale is could include check valve based peristaltic micro pumps, valve less rectification pumps and I am going to describe these just about little bit. So, they are more based on the 10 to the 1 millimeter per unit range, high flow rate range.

The other hand new pumping principles which are non mechanical like a electro kinetic pumps, electro hydrodynamic pumps, magneto hydrodynamic pumps and ultrasonic pumps they are more towards the left of this figure and start from about 1000 of a ml per minute to all the way to about 10's of ml per minute or so. So, definitely as you see here the mechanical pumps are much more in terms of flow rates, the silicon couple the energy or they can put really high energy density to the flow or a flow rate to be higher.

The novel effects however have lower amount of density that you can part, it may be an efficient forces, but at a time you may not be able to pump that density, because of limitations related to properties of the materials which we are flowing essentially the fluids you are flowing. So, that is in a nutshell what into categorization is in terms of flow rates. So, the parameters which are most important to define specification as micro pumps are essentially the maximum flow rate and quantities like maximum back pressure.

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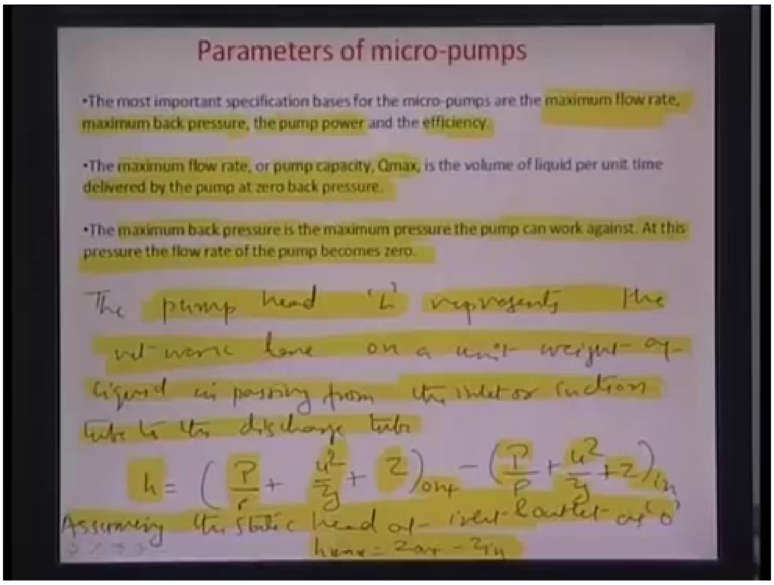

$$h=\left(\frac{P}{\rho}+\frac{u^2}{2g}+z\right)_{out}+\left(\frac{P}{\rho}+\frac{u^2}{2g}+z\right)_{\square}$$

Mind you the back pressure is develop, because you are constricting the forward flow go to in a very small maturing are very small out let and definitely it is going to take the some work for the pump to do for pushing the flow it through this small out let that generates back pressure on to the system. And essentially whatever the pumping mechanism beat it has to overcome this back pressure by the application of mechanical or non mechanical energy and only then the pump can be a forward directional working micro pump.

So, specification of course, you would include maximum back pressure and the pump power is very critical and also the pumping efficiency is very critical as you saw in the electrochemical case and in case of valves the electrochemical valve as more efficiency is 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 centimeter Q per minute upper unit time delivered by the pump assuming that there is a 0 back pressure. So, if you are just letting the fluid going to an open atmosphere, then whatever amount of flow rate can be generated is really a maximum flow rate that the pumping can generate, you can also categories the pumps in terms of the maximum back pressure it is also the maximum pressure that the pump can work against, it can still keep working if you keep on increase the back pressure at a certain pressure it can failed to occur delivered fluid any more. So, that is essentially the maximum back pressure that pump can sustain.

So, at this pressure the rate of flow become equal to zero. So, let us do some mathematical representation of how you can calculate this efficiency factor. So, the best factor that issues here is a pumping head in terms of the pressure head that is deliverable by the micro pumps. So, let say the pump head h represents the network done on unit weight of liquid in passing from inlet to the outlet the discharge tube. So, the h here is given by the equation has the high due to the pressure that is p by rho, the high due to the kinetic energy u square by 2g and the potential of function z.

In the outlet side minus the same quantities here on inlet side, so this is essentially the difference in the inlet and outlet pressure heads and that should comes and how as h the outlet pressure being more. So, this is the pressure deliver by the pumps, so if you are delivering in a outlet pressure which is more than the inlet pressure definitely that is a head edition while the flows going in to the pumps. So, assuming statics head at inlet and outlet as 0 really which means that you are you know you assume that the pressures on both sides are at atmosphere pressures and the velocity is really a similar on both sides you do not assume velocity gradient.

So, in that case the maximum height to that this particulars configuration can accumulate at the pressure head that it can give maximum is equal to the potential act the output side minus the potential at the input side due to the pressure in did the position. So, if a pump is kept like inclined and z input are more than z output, output is more than the z inputs. So, there will be a definite head which comes because of that.

So, that essentially some of the parameters of the micro pumps which are considered for designing and subsystems. So, based on the maximum flow rate of the micro pump, the maximum back pressure p are the maximum pump head h max, you can really calculate the power the maximum power that the pump can deliver. And as you know power is essentially nothing but, pressure times of discharge by 2 this is the average power.

Because, if you assume the discharge to be 0 and after application of the pressure head p by the pump the discharge maximum discharge to be q max, the average flow rate really is 0 plus q max by 2 and so pressure times of the average flow rate is essentially nothing but, the work done per unit time you may remember that pressure into volume at p dv is the work done in Jules and q is essentially volume per unit time. So, essentially this is power the work done per unit time.

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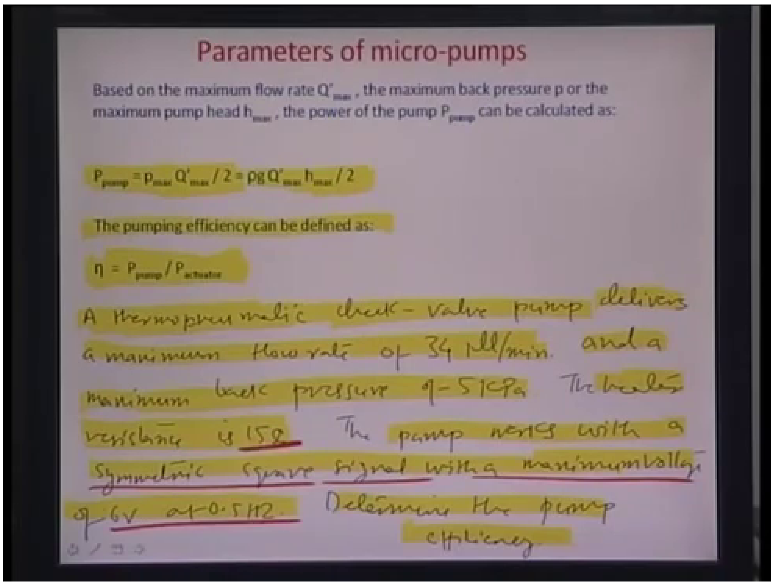

So, the power of a pump here assuming p max to be the maximum pressure q max dash to be the maximum flow rate assuming that the flow rates start from 0 and gets this height as the fluid passes through the whole pumping champers the pumping system. So, q max by 2 effectively is the average flow rate. So, p max into q dash max by 2 essentially is what mix the power and we know that the pressure max is also represented by this height max into rho into g. So, whole g h max q dash max by 2 is what the pumping power is.

So, based on this power equations we can define the pumping efficiency as the power that the pump actually generates in terms of flows by the power that it takes in terms of actuation. So, if you have certain powered delivered inside a certain energy which is deliver per unit time inside the pump, which causes the mechanical or the non mechanical actuation of the fluid and then it result in certain work done by the fluid flow against the pressure head etcetera.

So, these two essentially the ratio between them would determine what is the pumping efficiency has to how much amount of energy which you are packing in is dentensified as energy applied for flow inside the pump. Now, here is an example there are would like to illustrate, so you have a thermo pneumatic system of check where pump I will deliver some maximum flow rate of 34 micro liters per minute, there is a maximum back pressure of 5 kilo Pascal's, which is generated. And because this thermo pneumatic you are essentially heating the fluid, the heater resistance here is about an 15 ohms and the pump works with the symmetric square signal with the maximum voltage of 6 volts at 0.5 volt. So, you have to determine the pump efficiency. Solve this particular example and so we assume first are we calculate the pumping power.

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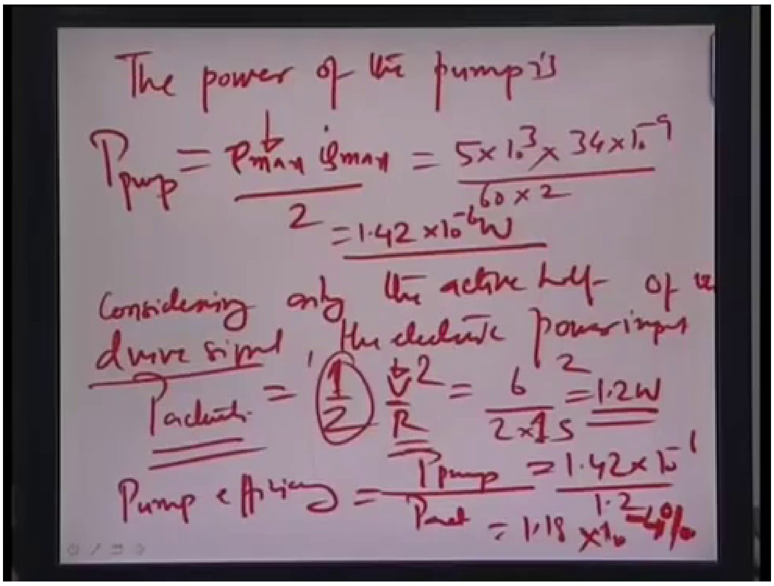

$$P_{pump} = \frac{p_{max} \acute{Q}_{max}}{2} = \frac{5 \times 10^{3} \times 34 \times 10^{-9}}{120} = 1.42 \times 10^{-6} W$$

$$P_{actual} = \frac{1}{2} \frac{V^{2}}{R} = 1.2 W$$

$$P_{pump} eff. = \frac{P_{pump}}{P_{actual}}$$

So, 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 back pressure against fluid has to be working. So, 5 times 10 to the power 3 Pascal's is what the p maxes q dot max is essentially the maximum flow rate, which is about 34 micro liters per minutes you can write that as 34 times 10 to the power of minus 9 meter cube and divided by 60 for the per second into 2, so this comes out to be equal to about 1.42 times 10 to the power minus 6 Watts that is what the power of the pump is.

So, considering only the active half the drive signal, the direct pass, so basically if you see here what he saying is that you have a square wave or a square signaled to operate the maximum voltage of 6 volts at 0.5 hertz, which means that for the other half cycle the power is switch off to 0. So, it is between 0 and 6 volts, so effectively the power cycle is only about half the times and the total amount of voltage given as 6 volts in that case, in the other half which is about the remaining half is about 0 volts. So, it is a just a square pulse at a square wave which is given to control the heaters for the pressure rise thermodynamic force which would close and open the particular valve.

So, the electric power input here which causes the actuator power is half v square r, v is 6 volts, half because the half cycle is only the power cycle, the remaining half cycles are 0 volts that is no power delivered essentially from the source into the chamber, the numeric chamber, thermo numeric chamber. So, this comes out to be equal to square of 6 times 2 times 15 the resistance mind is about 15 ohms this has been illustrated in the example here, so this comes out to be about 1.2 volts.

So, that is what in the actuation power is, so pumping efficiency is defined earlier is essentially the by the power of the pump you should just calculated the top divided by power of the actuator is comes out to be 1.42 times 10 to the power minus 6 by 1.2 which is about 1.18 times 10 to the power of minus 4 percent. So, that is what the pump is efficiency is pretty low the pumping efficiency in this particular case, thermo numeric effects in fact do not really give a very lot of efficiency, because and also there half and half slow the response rate is very slow. So, let us now talk about the second kind of mechanism, which is peristaltic micro pumps and I would like to show some illustration station from one of the research modules that we have developed in our laboratory here.

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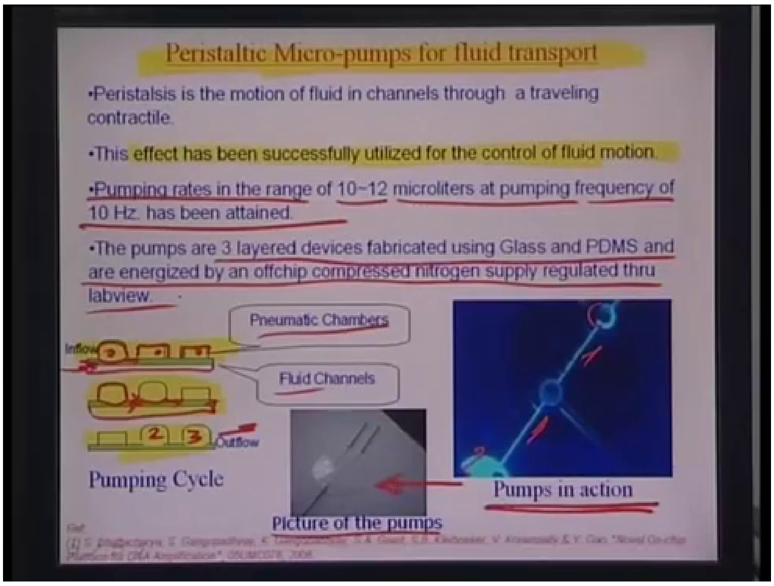

So, this right here is the example of what peristaltic pump would typically do for fluid transport. So, let me just rerate peristaltic is in the motion of a traveling contractor or fluid due to a traveling contractor. So, if you think that you have like a silicon tubing or something like a flexible rubber near pushing this rubber from both side and there is a fluid column in between, the fluid is almost are going to be squeezed on both sides.

Now, with this two 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 peristaltic, so traveling contractor similar mechanisms take place within the body, where intestine used to generate enough motion for pumping bile I would to human system. So, we can use this traveling contractor mode is a continuous one continues process or we can probably discritizing which is more suitable for the mems architecture.

So, what we have done here is that this effect has been successfully utilized to a control flow of a fluid motion and there has been done by discretizing the peristaltic action in this particular illustration here. So, the device made is the three layer device with the layer a bottom which you cannot see here, but it is 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 and this blister pockets are all connected through and here circuit which is controlled selectively using the solenoid motion.

And the idea is that you actually inflate and deflate these blisters in a sequence. So, that you can press say for example this region here which squeezed out the fluid in both directions and then after this forwards momentum is gathered you keep this closed for that the fluid cannot trace back and close on the second. So, you start compressing the channel on the second. So, here the fluid cannot where should this path is closed and the only forward direction momentum would be implied on to the fluid channel.

Mind you this green layer here indicates the fluid channel and that is the layer at the bottom here which is the base or the glass substrate and then you can have valve two and three operated and this sequence can keep on rotating. So, that the flow picks up from here and goes all the way up to the out flow, these are some coin like peristalsis pumps which have been developed, this an pneumatic chamber based pumps.

And essentially these kind of source of real picture of the fluid transport as you are seeing here, this valve is slowly getting fill by the fluid and this valve is slowly getting empty, because the fluid transports across this whole channel here through this blister pockets these are some of the pumps in actions. So, the pumping rate has been categorize in the range of above 10 to 12 micro liters at pumping frequency of 10 Hertz which has been attained and the pumps are essentially 3 layered devices fabricated using glass and PDMS pretty much in the manner that we had done blisters.

In this case of course, the orientation of these chambers for pumping peristalsis chambers for pumping a different and there energized by an off chip compressed nitrogen supply regulated thru lab view. So, this kind of brings as to end of this particular lecture.

Thank you.