Chemical Process Intensification
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Lecture 16
Introduction and Mechanism of Cavitation-based PI

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So welcome to massive open online course on Chemical Process Intensification. So here we will start this module 6 for this process intensification. In this module we will discuss the process intensification by cavitation and in this lecture of this module 6 we will discuss about mechanism of cavitation-based process intensification.

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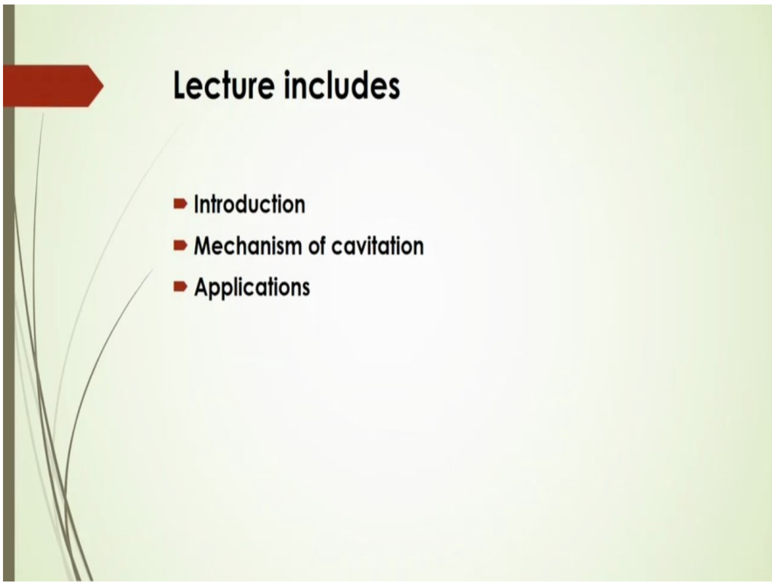

So this lecture includes introduction of cavitation and how cavitation is formed, what are the mechanisms and also some applications of this cavitation process which are very important for process intensification by this cavitation process.

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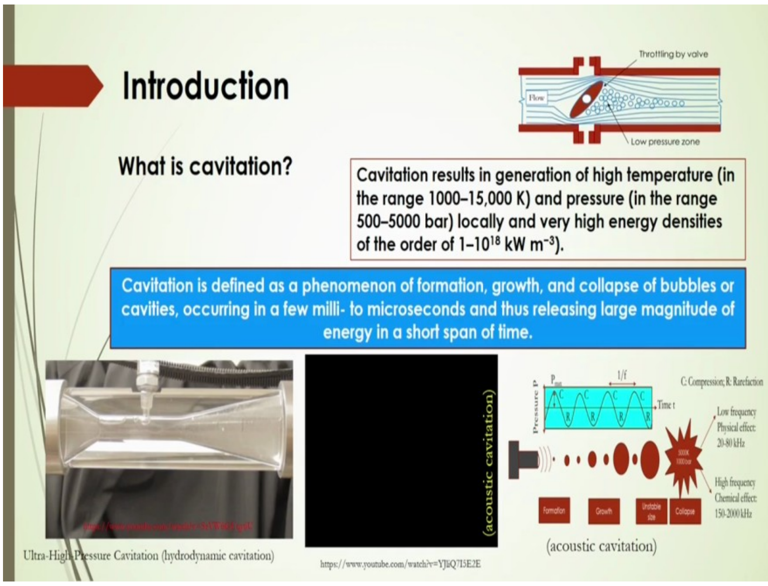

Now see, first of all you have to know what is that cavitation? The cavitation actually is a phenomena to form even to growth or to collapse of bubbles or cavities and during that occurrence of formation or growth or collapse of bubbles you see it will be forming within a milli or microseconds. And during that formation you will see that there will be a release of large magnitude of energy in a short period of time, that is why this cavitation can be defined as a phenomenon of formation, growth and collapse of bubbles or cavities occurring in a few milli to microseconds and thus releasing large magnitude of energy in a short span of time.

And this cavity is actually formation is happened by generation of high-temperature in the range of 1000 to 15,000 Kelvin and pressure in the range of 500 to 5000 bar locally and very high energy densities of the order of 1 to 10 to the power 18 kilo watt per meter cube. So in this you know slides, here we can see video of that cavitation, how it is forming like here one type of cavity formation, just watch this video first you will see how this you know that here this cavity is forming.

So this is one you know that eventually 5 here in this case you will see that how the cavity is forming here when liquid is flowing at a flow rate from this upstream to the downstream and based on that pressure difference there upstream and downstream there is a high-pressure difference. And here from this nozzle the gas is supplied so whenever liquid is flowing at a high velocity or high flow rate you will see that gas is how it will be forming a cavity there, and during that cavity you will see there will be some energy released here and formation of bubbles.

Now, you see there will be a certain range of size of that cavity that is formed in this you know release of that gas cavities by this venturi so it is called ultra-high-pressure cavitation and it is one type of cavitation which is called hydrodynamic cavitation. There are other several different types of you know that cavitations are there, we will be discussing.

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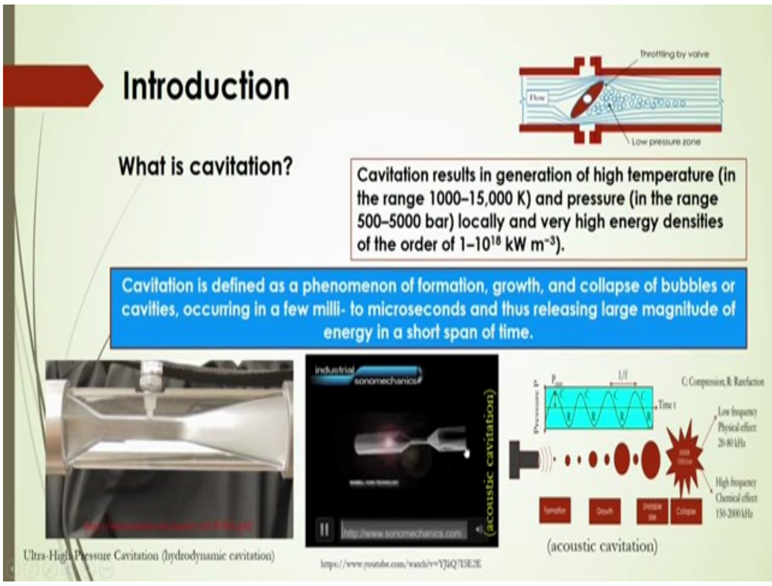

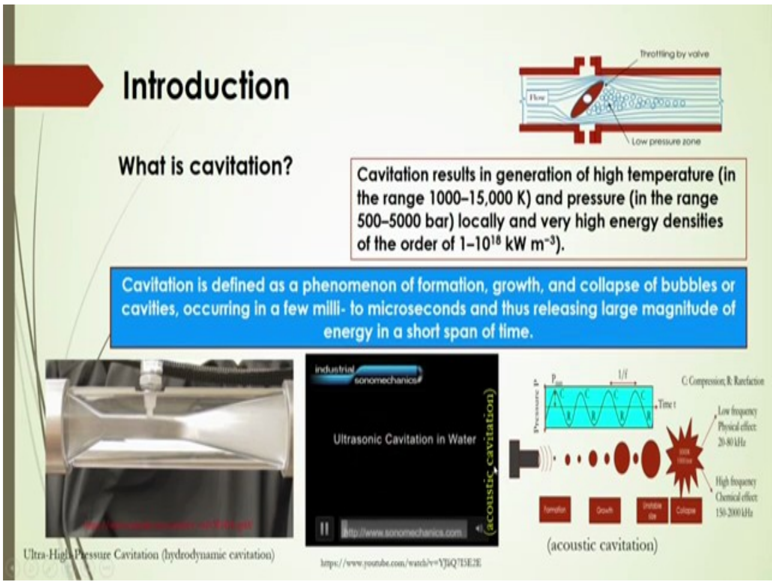

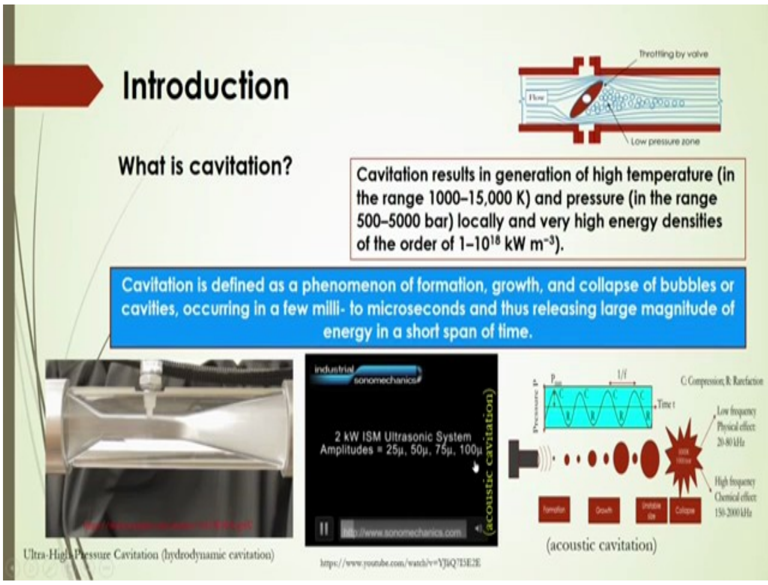

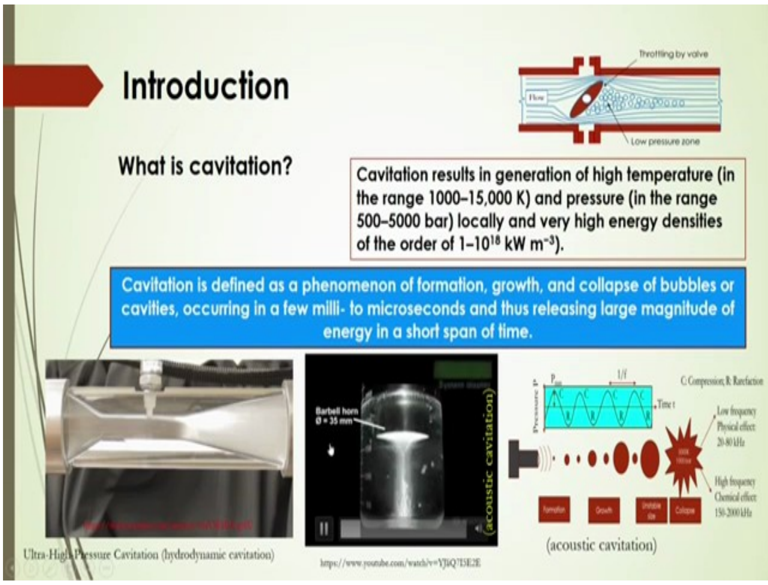

Another important cavitation is called acoustic cavitation, so here in this video if you watch that how this acoustic cavitation is formed here in this case some ultrasonic cavitation will be there in the water. In this case you know 2 kilowatt ultrasonic you know that energy will be supplied and then there will be a formation of cavity there.

Here in this case you will see whenever the ultrasonic wave will be supplied or you know generated then you will see there will be some wave formation and for which that wave of that compression and rare fraction of that wave. There will be simultaneous you know formation growth and also you can say that there will be an unstable formation of bubbles.

And after that at a certain you know that pressure there will be a you know collapse of that bubbles there and that collapse will happen at a certain frequency, some it will be maybe low frequency of 20 to 80 kilo hertz whereas, at high frequency that also will be happened that will be at you know 150 to 2000 kilo hertz. So based on this frequency, this ultrasonic cavitation will be applied in physical as well as chemical applications, chemical processes, so here we will see how you know that ultrasonic wave is supplied and then how this cavity is forming.

So this is one you know that mechanism of formation of cavity, so this is called acoustic cavitation and this is called you know that hydrodynamic cavitation. And during this hydrodynamic cavitation at different types there, we will say sometimes it will be formed by floating valve or by you know that vena contracto or some other mechanism so we now say that how actually this cavity is formed there.

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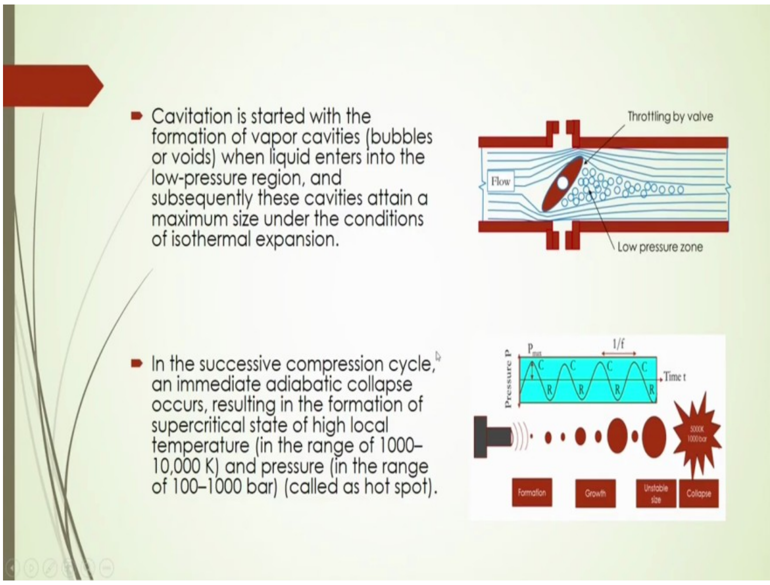

After then we can say that that cavity or cavitation process is started with formation of vapour cavities is that is called bubbles or voids or cavities sometimes it will be named, when liquid enters into the low-pressure region and subsequently these cavities attain a maximum size under that condition of isothermal condition or isothermal expansion.

In the successive you know that compression in acoustic cavitation process that an immediate adiabatic collapse will occur which will result in the formation of supercritical state of high local temperature in the range of 1000 to 10,000 Kelvin temperature and in the range of 10 to 1000 bar also in pressure that is sometimes called that hotspot formation.

So that is why this acoustic cavitation will happen successive for compression as well as a rare fraction, here in the figure it is shown that C is for compression, R is for rare fraction, so this is the wave and during this wave formation how this wave will be there and according to the pressure how this wave you know amplitude will be changing with respect to time and this is your maximum pressure at this you know that here magnitude, then even this to this is called frequency.

So because of this you know compression rare fraction there will be formation of bubble and it will grow and also after that whenever it will be a certain range, when it will be unstable and then it will collapse and it will be collapsing into a very finer bubbles there.

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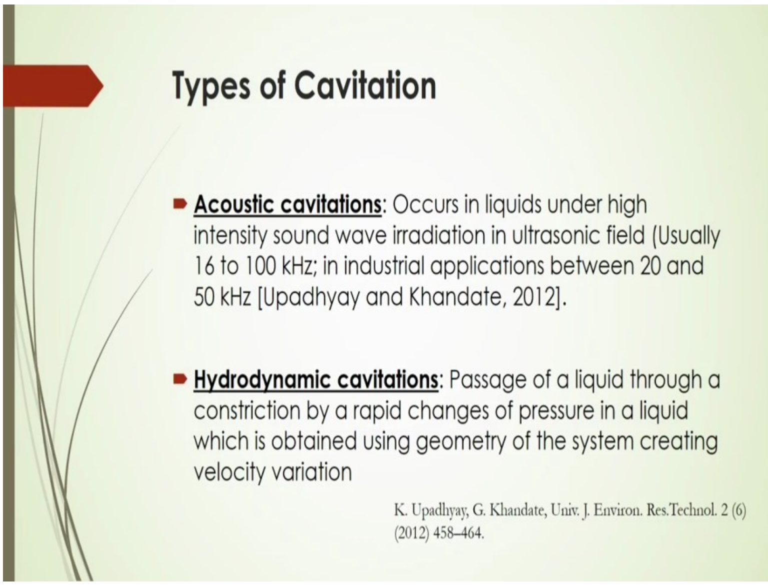

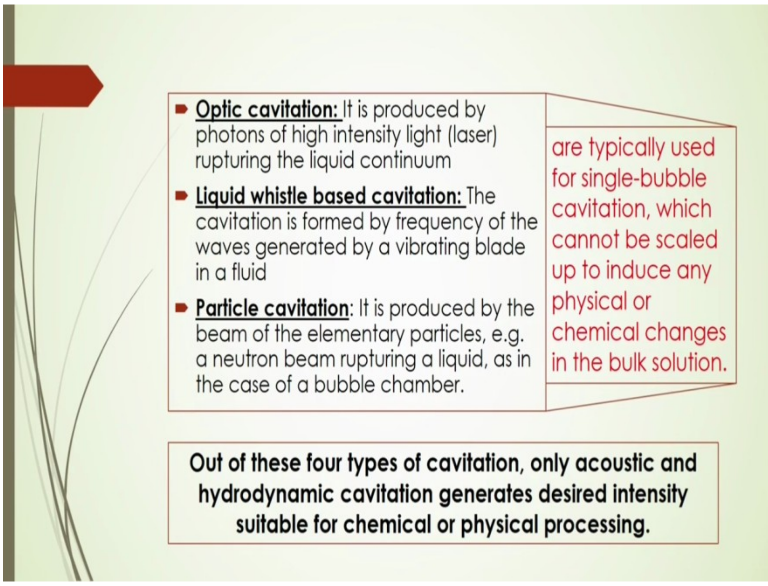

Now what are the different types of cavitation? We will see there are different types of cavitation like it is called acoustic cavitation, hydrodynamic cavitation, even you know that optic cavitation, liquid whistle-based cavitation, particle cavitation, so there are different types of cavitation are there.

So acoustic cavitation generally occurs in liquids under high-intensity sound wave irradiation in ultrasonic field that is usually 16 to 100 kilohertz, in industrial applications between 20 to 50 kilohertz and, whereas hydrodynamic cavitation, it is actually processed by passage of a liquid through a constriction by a rapid changes of pressure in a liquid which you know that is obtained by using geometry of the system creating velocity variations.

So this hydrodynamic cavitation is nothing but the thus the flow of liquid to a constriction in a certain geometry of the use know that five and through which there will be a variation of velocity and because of which there will be a change of pressure in the liquid and that change of pressure will give you the formation of cavity.

Optic cavitation it is generally produced by photons of high-intensity light it is called laser rupturing the liquid Continuum. And also liquid whistle-based cavitation also are important hydrodynamic cavitation, it is called that whistle-based cavitation. In this case the cavitation is formed by the frequency of the waves generated by vibrating blade in a fluid.

And particle cavitation it is produced by the beam of the elementary particles that is as an example a neutron beam by rupturing a liquid as in the case of you know that bubble chamber. So these are the various different types of cavitation and this optic cavitation, liquid whistle-based cavitation, particle cavitation are typically used for single bubble cavitation which cannot be scaled up to induce any physical or chemical changes in the bulk solution.

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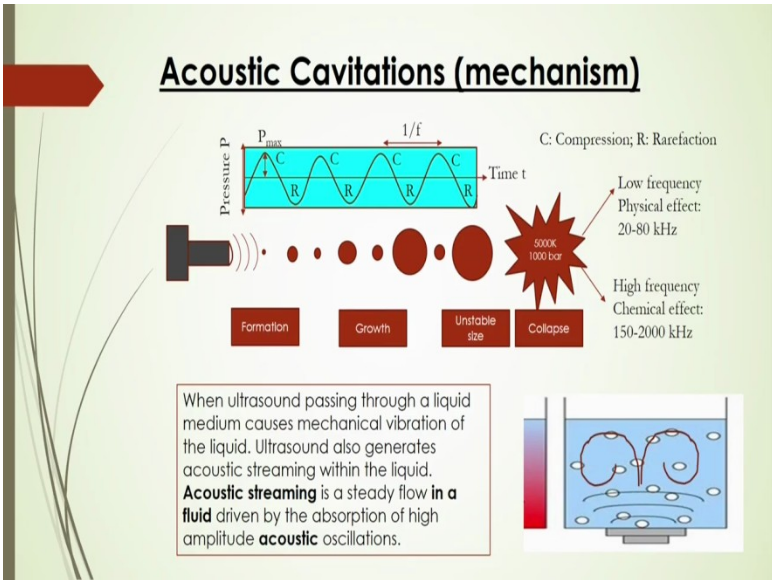

Now out of these you know that 4 or 5 types of cavitation, only acoustic and hydrodynamic cavitation generates desire intensity that will be suitable for a chemical or physical processes. Now, let us have the mechanism of this acoustic cavitation here in this slides the you know the picture is shown that mechanism when ultrasound passing through a liquid medium that will cause the mechanical vibration of the liquid and because of which there will be a formation of cavity or bubbles that is fine bubbles when you know micro or nano bubbles will be forming and in this case you will see just by you know that growing and becoming unstable size and then collapsing at a certain temperature and pressure to give you that very finer or micro or nano bubbles.

Now, during this acoustic cavitation not only you will have this fine bubbles they are formation of cavity, here as well as you will see there will be mixing of the fluid elements will be there inside the reactor. In that case this ultrasound generator acoustic streaming within the liquid and it is a steady flow in a fluid which will be driven by the absorption of high amplitude acoustic oscillation.

So because of this there will be a streaming of liquid inside the liquid so that streaming will also give you the mixing of the fluid element inside the reactor which will give you the better chemical processes there.

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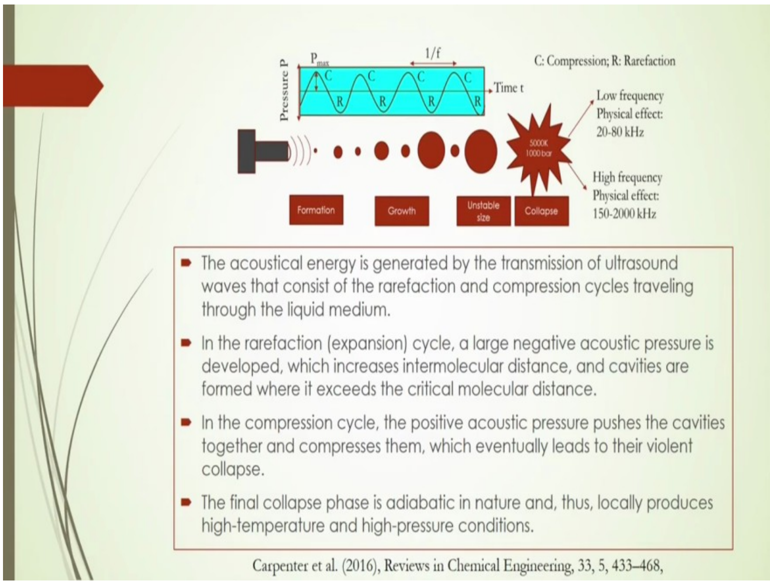

And in this case you will see acoustical energy is generated by the transmission of ultrasound waves that consist of rare fraction and compression cycles that travelling through the liquid medium. Now, in the case of rare fraction it is called sometimes expansion and in this cycle a large negative acoustic pressure will be developed which increases intermolecular you know distance and cavities are formed where it exceeds this critical molecular distance there.

So in the compression cycle the positive acoustic pressure that will push the cavities together and compresses them which eventually leads to their violent collapse. So that is why there will be you know that formation of minor bubbles during this you acoustic pressure push and during this you know that violent collapse there will be a formation of finer and micro and nano bubbles there.

And then final collapse phase is adiabatic will be there in nature and thus locally produces high temperature and high pressure conditions. So this is the way how actually that acoustic cavitation can happen.

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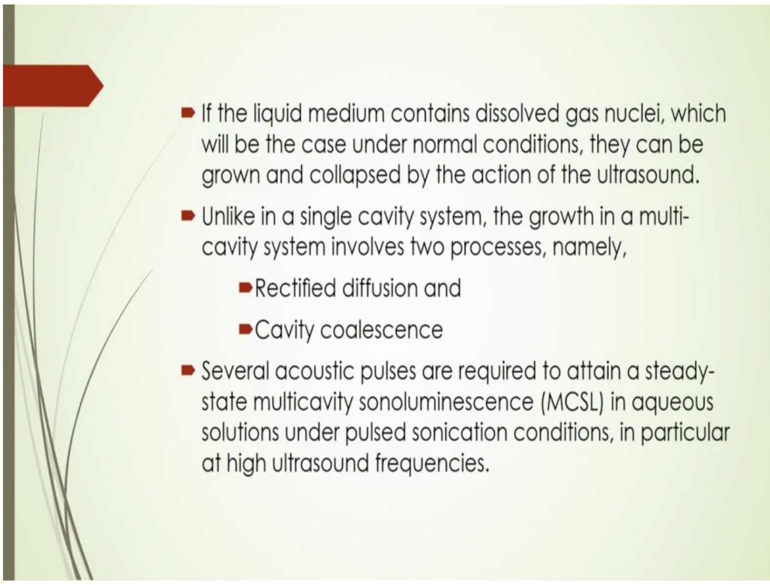

Now, if the liquid medium where this acoustic cavitation will be you know taken place if that liquid medium contains dissolved gas nuclei which will be the case under normal conditions there, they can be grown and collapsed by the action of the ultrasound. So unlike in a single cavity system the growth in a multi-cavity system involves 2 processes; namely rectified diffusion and also cavity coalescence.

Now, several acoustic pulses are you know required to attain this steady-state multi-cavity phenomena it is called that sonoluminescence in aqueous solutions under pulsed sonication conditions, in particular at high ultrasound frequencies. So at that high ultrasound frequencies of there will be formation of multicavity sonoluminescence because of that you know transfer of that you know that ultrasound energy by that way formation.

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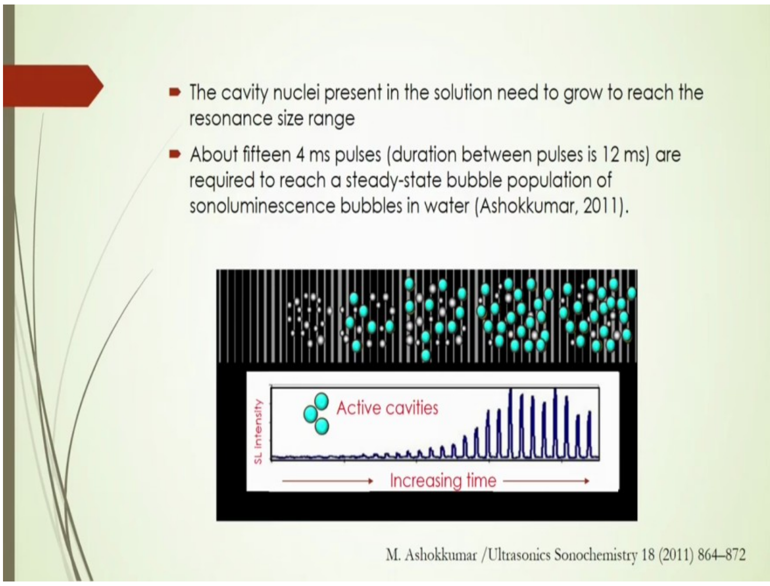

Now this cavity nuclei present in the solution need to grow to reach the resonance size range there. Here in this figure it is given as per that you know that paper of AshokKumar, it is published in ultrasonic sonochemistry in 2011. He has described this you know that cavity nuclei that will be present in the solution need to grow to reach the resonance size range.

Now this about, he told that fifteen 4 millisecond pulses (duration between pulses is 12 millisecond) are generally required to reach a steady-state bubble population of sonoluminescence bubbles in water. So here it is shown that how this you know that sonoluminescence intensity are changing with respect to including time and formation of bubbles there.

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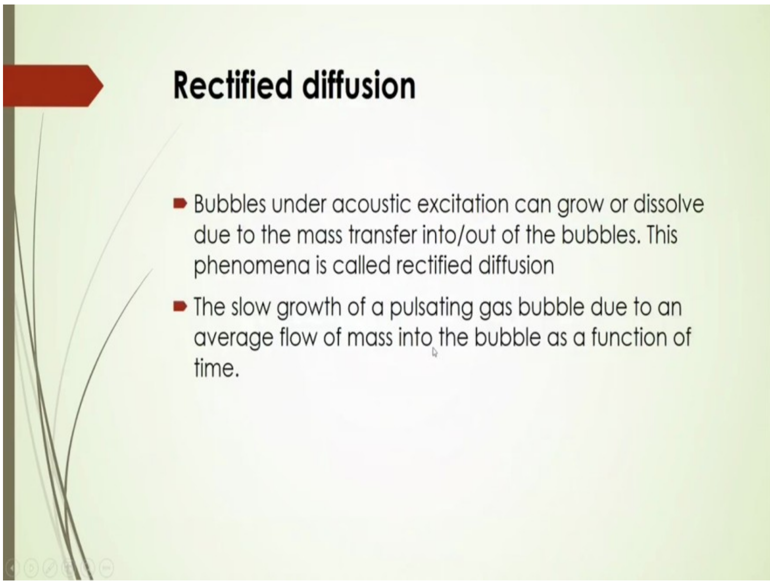

Now, according to his observation he explained that bubbles under will be acoustic excitation which can grow or dissolve due to the mass transfer into or out of the bubbles and this phenomena is called as rectified diffusion and the slow growth of that pulsating gas bubbles due to an average flow of mass into the bubble as a function of time so that will happen during that growth of pulsating gas bubbles.

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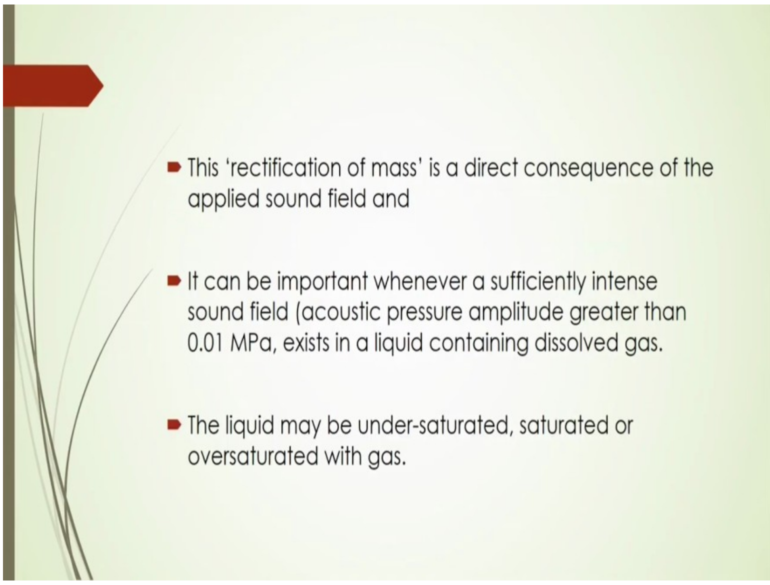

Now, you will see that this rectification of mass transfer is actually direct consequence of the applied sound field. And also it can be important whenever a sufficiently intense sound field that is acoustic pressure amplitude that will be greater than that you know he explained that it will be greater than 0.01 mega Pascal and it will exist in a liquid that will containing a that dissolving gas. And in that case that liquid maybe you know that under saturated, saturated or even oversaturated with the gas.

So in this rectification of mass by the applied sound field that depends on that you know intensity of the sound field and that also there will be a certain limit of that and in that case acoustic pressure amplitude should not be you know that less than 0.01 mega Pascal and in that case if you are getting the dissolved gas and that liquid may be you know that under saturated, saturated or oversaturated with that with you know that gas.

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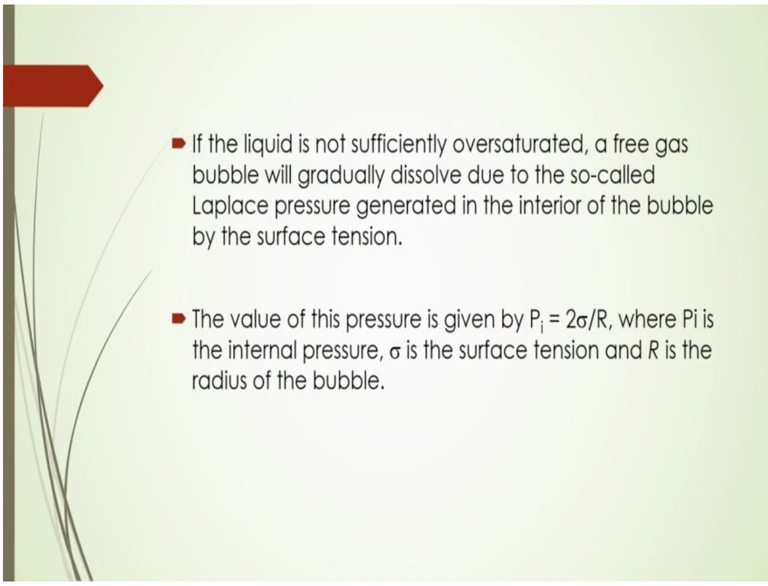

So if the liquid is not you know sufficiently over saturated that is in that case you will see there will be a free gas bubble will you know gradually dissolve due to the so-called Laplace you know pressure generated in the interior of the bubble by the surface tension. So according to that Laplace theory that you know internal pressure of that bubble should be is equal to you know that 2 Sigma by R, where Sigma would be is equal to surface tension and R is the radius of the bubble or cavity.

So the value of this pressure you know is called internal pressure and due to this you know that if you will see that if the liquid is not sufficiently over saturated if a free gas bubble will be gradually dissolving based on this you know Laplace pressure that is generated in the interior of the bubbles by the surface tension.

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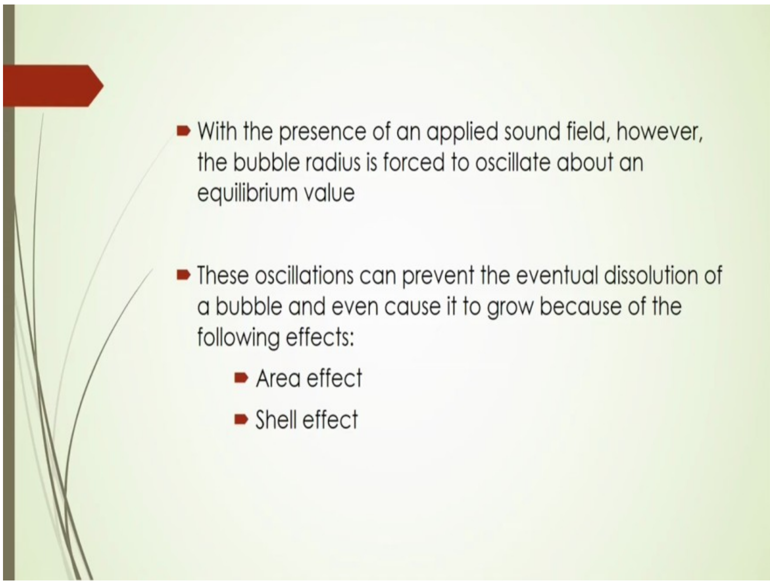

Now, if we consider that if the presence of applied sound field you will see that at an equilibrium value then there will be an oscillation which can prevent the eventual dissolution of the bubble and even it will cause to you know that grow because of the following aspects like you know area effect, shell effect, like this.

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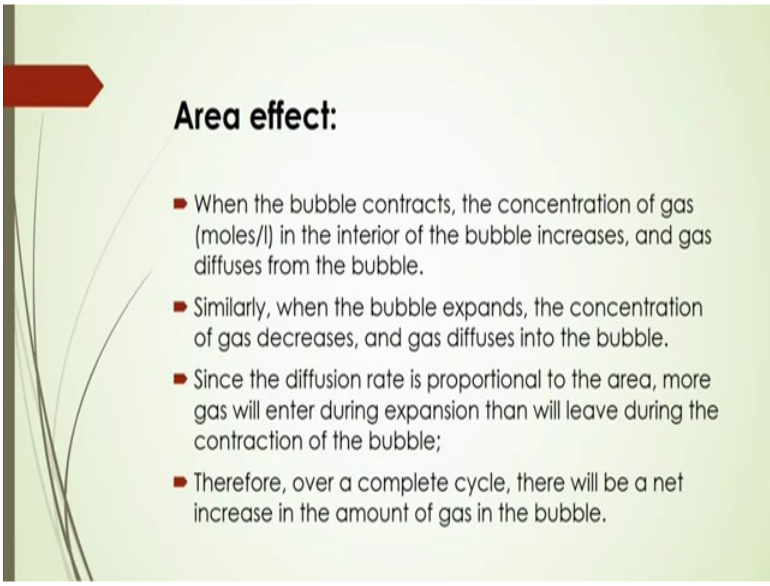

And what is that area effect that when the bubble contracts, the concentration of the gas moles per liter in the interior of the bubble that will increases and you know gas diffuses from the bubble. And when the bubble expands, the contraction of the gas decreases and then gas will diffuse into the bubble. And also because of the diffusion rate is proportional to the area, more gas may enter during the expansion then we leave during the contraction of the bubble.

So therefore, in that case a complete cycle will be a net increase in the you know amount of gas in the bubble so this is called area effect how it will be effect on that mass transfer and also you know that diffusion process of the gas molecules into and out of the liquid and also bubble.

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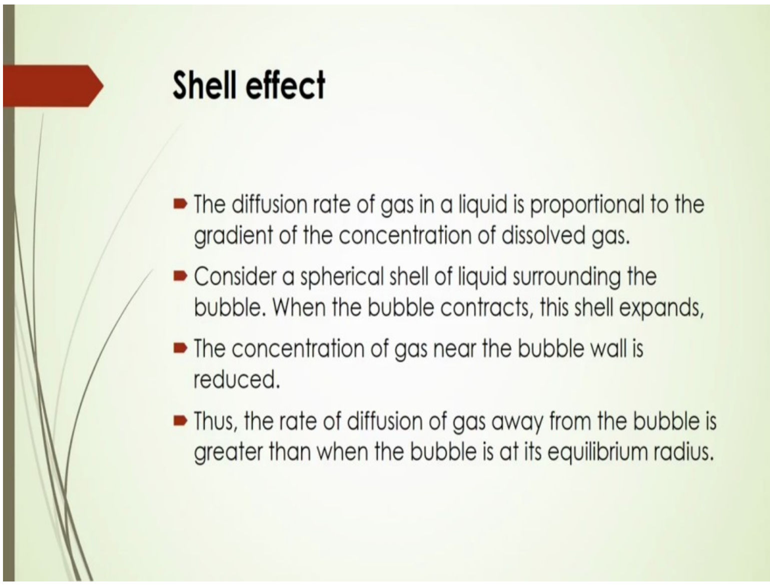

Then shell effect will be also important there, this is generally because of that very fine or micro bubbles formation, micro-cavity formation, so this diffusion rate of the gas in a liquid is proportional to the gradient of the concentration of the dissolved gas there. And consider a spherical shell of liquid that surrounding that bubble, when the bubble contracts this shell also will be you know expands. So the concentration of the gas near that bubble wall will be reduced and in that case you will see the rate of diffusion of the gas away from the bubble will be greater than when the bubble is at its equilibrium condition or equilibrium radius that is equilibrium size.

So we can say that there will be a shell effect on the diffusion rate and in that case how thickness of that shell affect also how it will be there if shell expands in that case you know that there will be a concentration gradient of the gas near the bubble wall and in that case the rate of diffusion of the gas will be changing according to that shelf size and also according to that size of the bubble.

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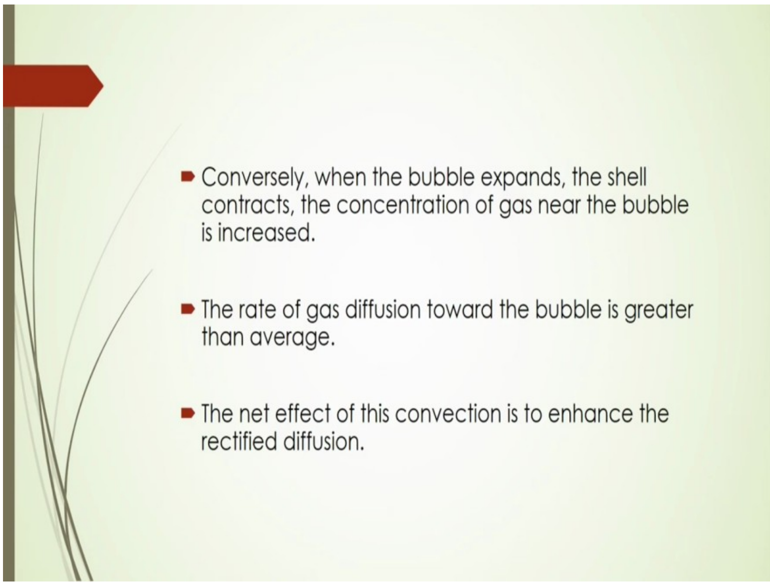

And when the bubble expands, you will see that the shell will contracts and the concentration of the gas near the bubble will be increased, and the rate of gas diffusion towards that bubble will then greater than the average value, and the net effect of this convection is to enhance the then rectified diffusion.

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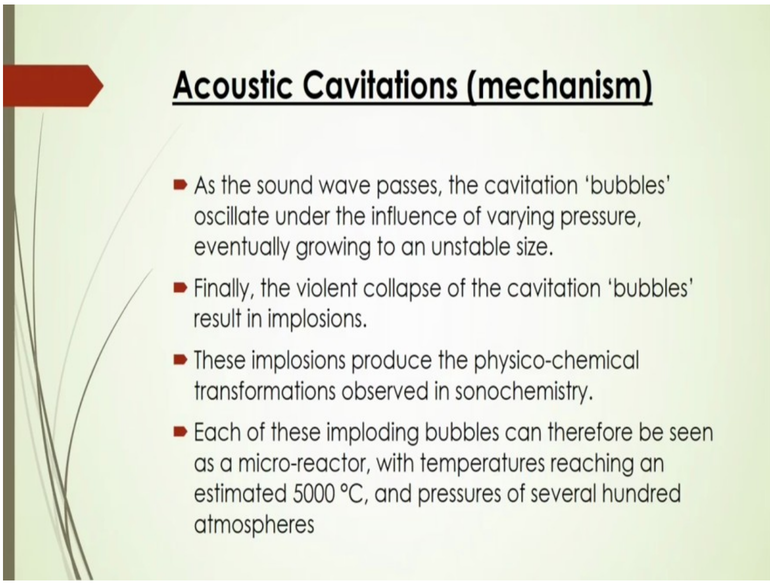

Now in the case of acoustic cavitation, as the sound wave passes, the cavitation bubbles oscillates under the influence of varying pressure, eventually growing to an unstable size. Finally, we can say that the violent collapse of the cavitation bubbles result in implosions, and also these implosions produce the physicochemical transformation that will observe in sonochemistry. And each of these you know imploding bubbles can therefore, be observed as a micro-reactor with the temperatures that will be you know that reaching and estimated value of 5000 degree celcius and pressure of several hundred atmospheres there.

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Now, what are the applications of you know acoustic cavitation? Now, based on these ultrasound enhanced you know activities or enhanced you know that effect, you can apply this cavitation process generated by ultrasound wave for the chemical engineering processes like you know ultrasound enhanced oil recovery, extraction of you know kerosene from oil shale using ultrasound cavitation, oil sand extraction using ultrasound cavitation.

Crude oil viscosity reduction by you know that cavitation that is formed by this you know ultrasound waves. And also ultrasound assisted demulsification of water crude oil emulsion is also there. Even you know that ultrasonic assisted you know oxidative desulphurisation process is very important based on this acoustic cavitation, and demetallisation can also be done by using this ultrasound cavitation. Even some times for upgradation of the heavy crude oil this ultrasound based cavitation process is actually followed for that process. So these are the several applications of that acoustic cavitation.

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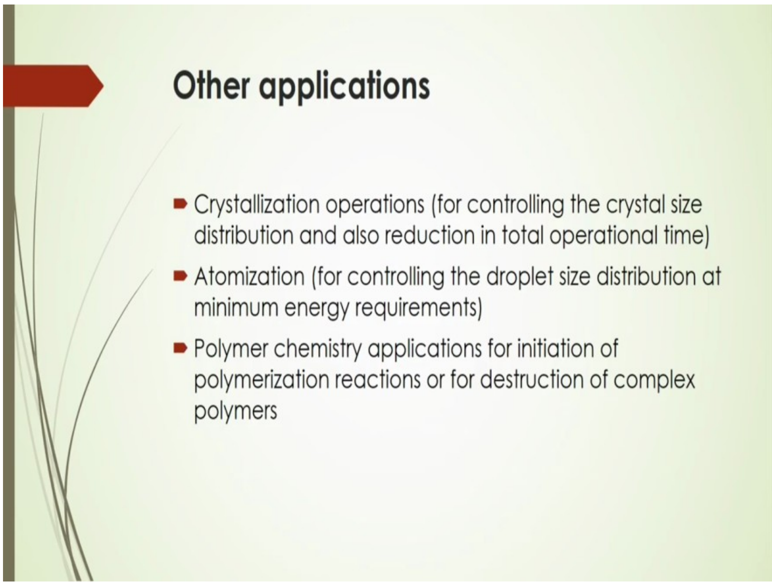

Other applications are also there like crystallization operations for controlling the crystal size distribution and also reduction in you know total operational time. Atomization for controlling the droplet size distribution at minimum energy requirements, polymer chemistry applications for initiation of polymerization reaction or for you can that destruction of complex polymers there, so these are the different applications of the ultrasound-based cavitation.

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Like other applications also you can apply this ultrasound-based cavitation like solid-liquid extraction, intensification of leaching operation, determination of composition of coal extracts, extraction of coal tars, etc. Textile industry for enhancing the efficacy of dyeing of clothes in textile industry, so these are the applications.

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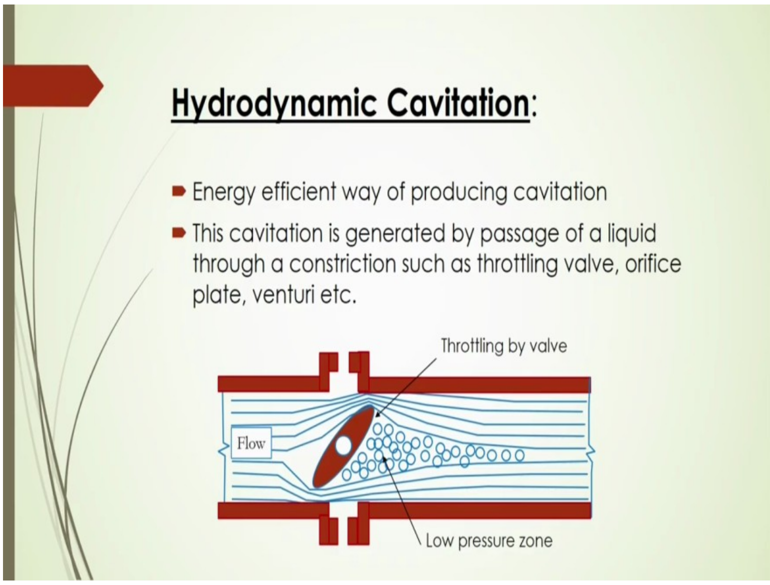

Now, what is that hydrodynamic cavitation? Now, energy efficient way of producing this cavitation, this cavitation is generated by passage of a liquid that we have already told that liquid will be processed through a constriction of you know geometry certain geometry such as throttling valve, orifice plate, venturi, etc. As shown in the figure, here one throttling valve is shown here through that the throttling valve how that liquid flow is getting obstruction during that flow and there will be a change of pressure between this upstream and downstream and there will be formation of this cavity during this pressure difference there.

So in this case we can say that this cavitation is generated by passage of liquid through a constriction such as throttling valve, orifice plate and venturi, etc.

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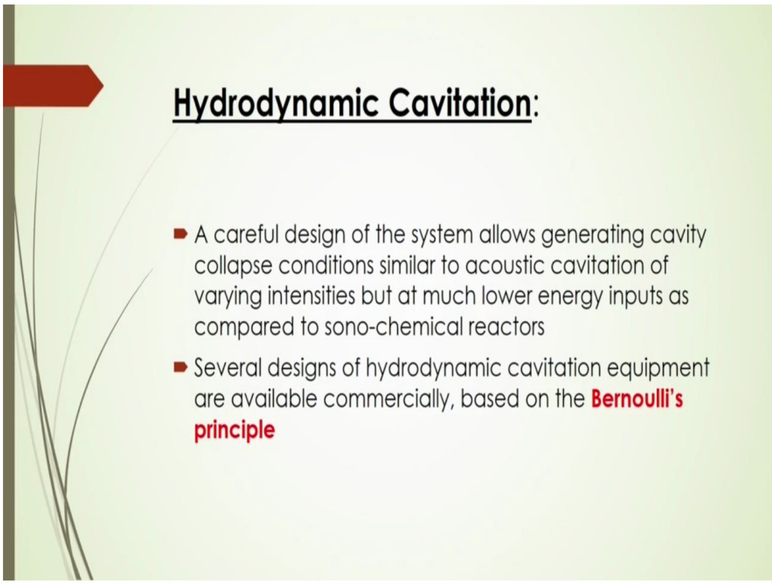

In this case you have to be very careful during you design of the system in this case you know that generating cavity you know it will be allowed based on that you know design aspects and at a certain condition of that you know that pressure difference there will be a collapse of that cavity, so the careful design of the system which will allow generating cavity collapse conditions similar to the acoustic cavitation of the varying intensities.

But you know that at a much lower energy inputs as compared to the sono-chemical reactors there. Several designs of hydrodynamic cavitation equipment are available in the literature even commercially it is now being used based on this you know certain principle it is called Bernoulli's principle.

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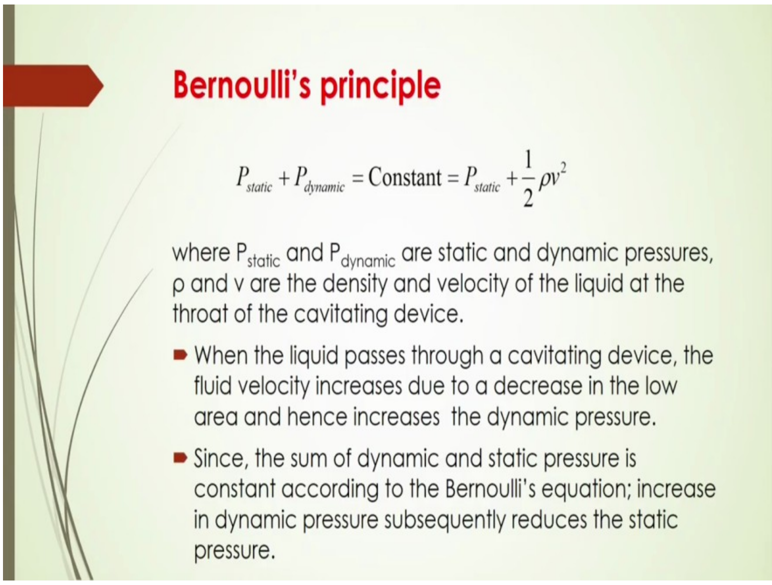

What is that Bernoulli's principal? In this case you see that energy will be constant here like you know with the submission of the static and dynamic pressure should be constant based on the Bernoulli's principle and in this case dynamic pressure will be is equal to

$$P_{static} + P_{dynamic} = \text{Constant} = P_{static} + \frac{1}{2}\rho v^2$$

$P_{dynamic}$ means dynamic pressure, Rho is the density and V as the velocity of the liquid at the throat of the cavity device.

So when the liquid passes through a cavitating device, the fluid velocity will increase due to the decrease in flow area and hence, there will be increase in dynamic pressure so that is why you have to make the geometry where that you can reduce the flow area. So due to this flow area there will be a change of you know that pressure, so whenever the velocity will increase due to this reduction of you know flow area there will be an increase of dynamic pressure.

And since the sum of this dynamic and static pressure is constant then according to the Bernoulli's equation we can say that increased in dynamic pressure subsequently reduces the static pressure.

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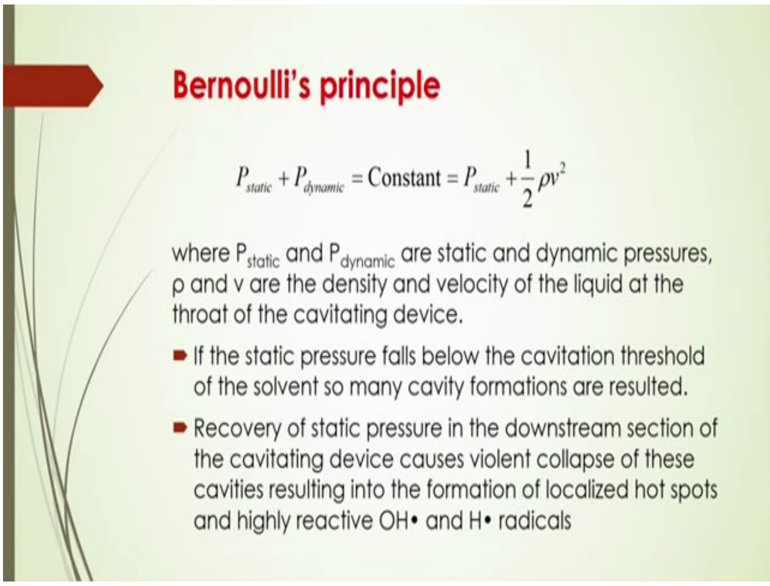

So in that case if the static pressure falls below the cavitation threshold of the solvent so many cavity formation can be you know obtained by this you know falls of static pressure.

So recovery of that static pressure also to be you know important there, so recovery of that static pressure in the downstream section of the cavitating device that will cause violent collapse of these cavities which may result into the formation of localized hotspots and highly you know that reactive you know some radicals will be formed like hydroxyl radicals and hydrogen radicals also will be formed there during this you know that violent collapse of the cavity.

So here very important that whenever hydrodynamic cavitation process will be you know carried out, there you have to see how this dynamic pressure would be changing. And then if you are changing that dynamic pressure by increasing the you know liquid velocity by reducing you know flow area, so in that case you can have that sudden falls of static pressure because summation of these both pressure will be constant so that is why if dynamic pressure increases, of course static pressure will decrease and during that decrease or fall of that static pressure there will be a you know that violent collapse of the cavities, and that violent collapse of the cavity will form some you know highly reactive hydroxyl radicals there.

And these hydroxyl radicals will be you know that useful in chemical reactions like in ozonation process if you are producing ozone you know that micro bubbles or micro cavities there you do hydroxyl radicals will be formed there and O_3 ozone you will see that there will be reacting like an example application like you know arsenic removal to convert that arsenic 3 to arsenic 5 that how ozone cavity will be you know that helpful for enhancing that reaction of that arsenic 3 to arsenic 5 like this.

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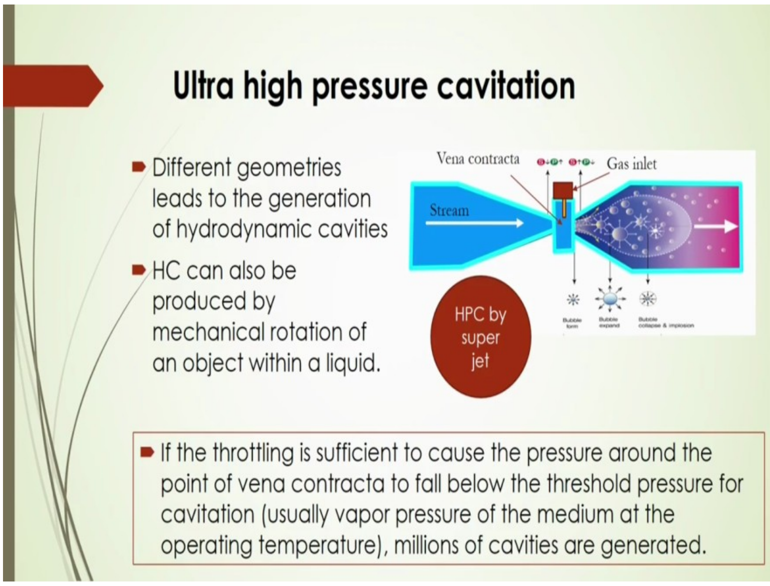

And then another is ultra-high-pressure cavitation here also you will see different geometries leads to the generation of hydrodynamic cavities like hydrodynamic cavity can also be produced by mechanical rotation of the objects within a liquid also. So they are also like you know mixer grinder, if you start this liquids at high speed there will be a formation of you know cavity or bubbles there.

So in that way you know that you can produce that cavity by rotating that mechanical devices. So high-pressure cavitation by super jet also can be produced there so that super Jet can be formed through that you know that nozzle or you know some other geometry like this is called Vena contracta.

So if the throttling is sufficient to cause that pressure around the point of vena contracta at this figure show here then it has to fall below the threshold pressure of cavitation usually vapour pressure of the medium at the operating temperature it is called threshold pressure and in that case many of the cavities will be generated.

So that is why you know that you have to process throttling into sufficient manner so that there will be pressure change around the point of vena contracta and it will fall below the threshold pressure to formation of cavity there, so it is called vapour pressure that is if it is less than vapour pressure then you can have that cavity that in the downstream location or that fluid, so this is called high-pressure cavitation.

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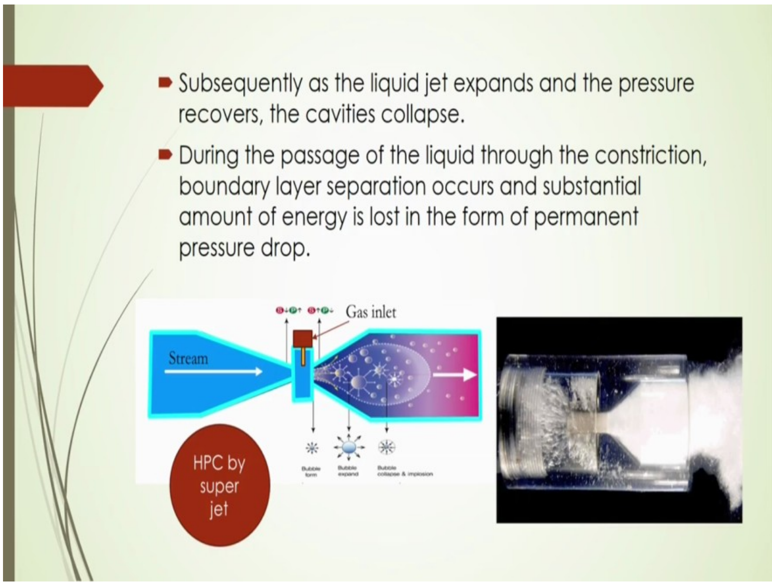

In this case as the liquid jet expands and the pressure recovers, in that case the cavities will collapse. And during the passage of the liquid through the constriction, boundary layer separation will occur and substantial amount of energy will be lost in the form of it is called permanent pressure drop, so that is why there will be a multi-number, or it is called that millions of cavities will be formed based on this loss of energy in terms of pressure drop. So this is the mechanism you can say for hydrodynamic cavitation for the formation of you know that shorn of bubbles by this you know geometrical constriction.

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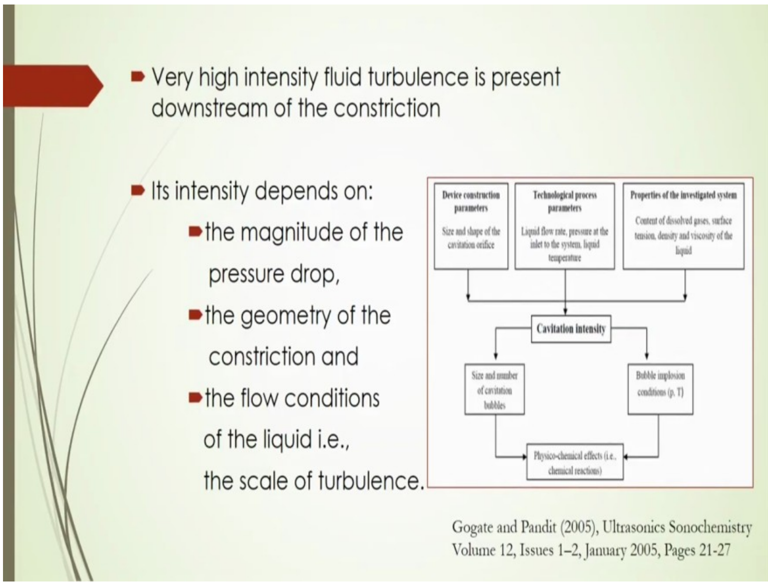

Now, if there is very high intensity of fluid turbulence if it is present in the downstream of the constriction then you can say that there will be a you know that swarm of bubbles or cavities will be formed. And its intensity actually depends on the magnitude of the pressure drop, the geometry of the constriction and also the flow conditions of the liquid that is the scale of turbulence in the you know fluid. So, you can say that if you are having high intensity of turbulence, you may get that you know formation of more cavities there.

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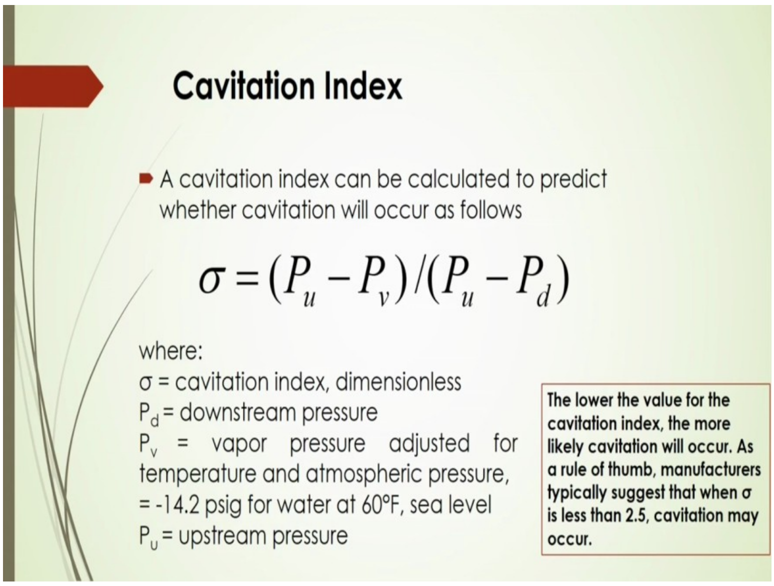

Now, you will see one parameter, it is called the cavitation index. This cavitation index can be calculated to predict whether the cavitation will occur or not. So that cavitation index can be defined as or it is denoted by Sigma and which will be calculated based on that pressure here in this equation given,

$$\sigma = (P_u - P_v)/(P_u - P_d)$$

where this Sigma is called the cavitation index, it is dimensionless and P_d is called downstream pressure, P_v is called the vapour pressure or it is called that threshold pressure adjusted for temperature and atmospheric pressure and it will be you know that 14.2 psi that is gauge pressure for water at 60 degree Fahrenheit even at sea level it will be you know that this pressure and then P_u, P_u is called upstream pressure.

So that is why the lower the value for cavitation index, you can say the more likely the cavitation will occur. As a rule of thumb that manufacturers typically suggests that when Sigma is less than 2.5 then cavitation may occur, so that you have to remember when this actually that cavitation occurs there. If you know that value of you know that upstream pressure, downstream pressure and the vapour pressure then you can easily say what should be the cavitation index there.

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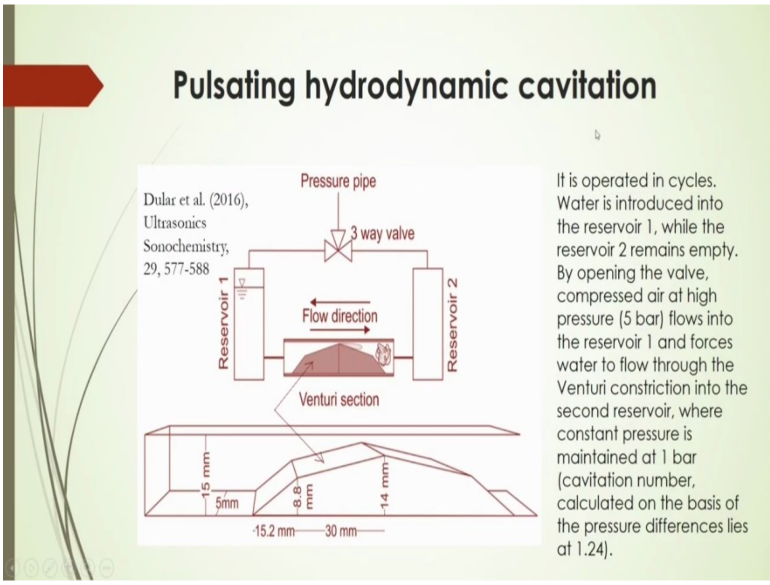

Now, pulsating hydrodynamic cavitation is also another one type of cavitation, so it is generally operated in cycles. Water is actually introduced into the reservoir, here as shown in figure, we have reservoir 1 and while the reservoir 2 remains here empty during that cycle. By opening the valve here you will see that the compressed air at high-pressure that is at around 5 bar flows into the reservoir 1 here and then forces the water to flow through the venturi constriction here, this is venturi constriction here into the second reservoir and then we will see whenever it will be passing through this constriction there will be a constant pressure to be maintained at 1 bar.

In that case the cavitation number calculated on the basis of pressure difference will be lying this at 1.24 then you can have this you will see that formation of cavity at this region. So this is one which is called pulsating hydrodynamic cavitation here.

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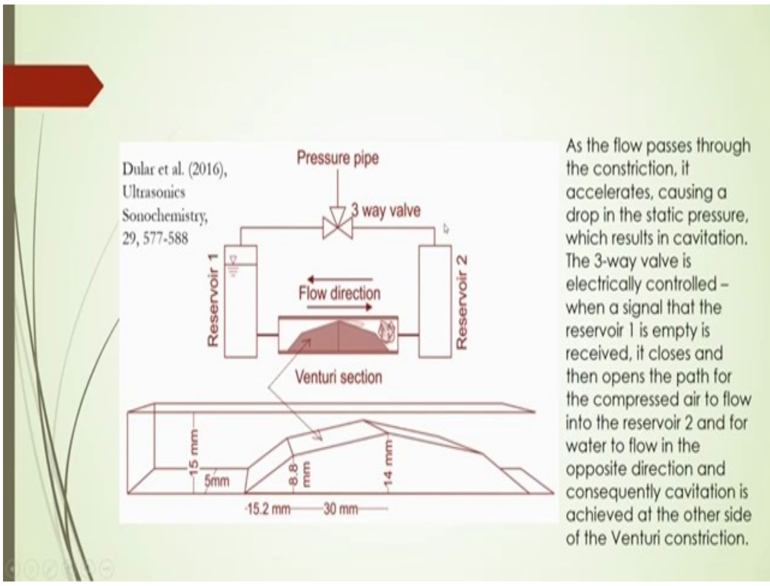

And here as the flow passes through the constriction, it accelerates and causing a drop in the static pressure which results in cavitation and the three-way valve is electrically controlled when a signal that the reservoir 1 is empty is received and it closes and then opens the path for the compressed air to flow into the reservoir 2. And for water to flow in the opposite direction and consequently cavitation is achieved at the other side of the venturi constriction.

So this is actually explained by Dural et al 2016 and he has published this in ultrasonic sonochemistry journal in volume 29, so you can follow how this you know that venturi section is designed here, what will be the size of that venturi sections and also you know that what is the length for that which is given here in the slides geometry. So based on this design you can produce that you know that cavity even you know that millions of cavities based on this mechanism, so this is called one type of pulsating hydrodynamic cavitation.

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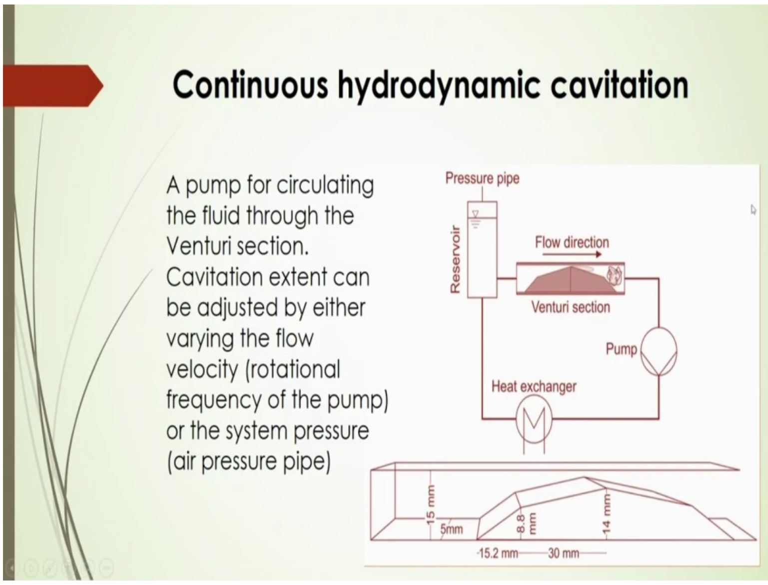

Another important continuous hydrodynamic cavitation is very important based on that same mechanism, in this case a pump for circulating the fluid is used which will pump the fluid through the Venturi section and cavitation extent can be adjusted by either varying the flow, velocity that is the rotational frequency of the pump or the system pressure at certain condition that is called air pressure and in that case that the pump will you know supply that liquid to the Venturi section to form that cavitation there.

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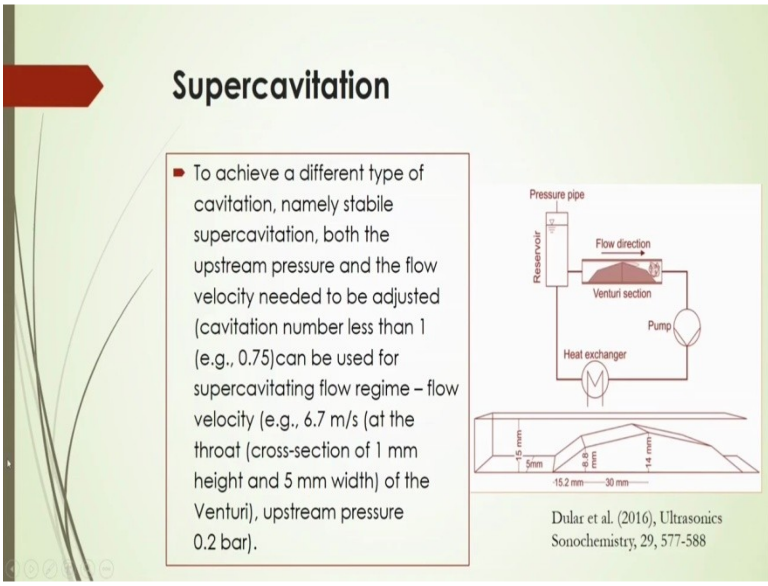

And another important mechanism which is called super cavitation, in this case to achieve a different types of cavitation like you know that stable super cavitation both the upstream pressure and the flow velocity needed to be adjusted in that case the cavitation number should be in that case less than 1 like 0.75 that is Dural et al. 2016 they have given this mechanism or the design to know that process super cavitation at the cavitation number at 0.75.

And in this case this super cavitation can be used for you know super cavitating flow regimes, flow velocity at around 6.7 meter per second at the throat, cross-section of 1 millimetre height and 5 millimetres width of the venturi can be used and in that case upstream pressure should be around 0.2 bar. So based on this cavitation number of 0.75, you can then produce that super cavitating flow regimes based on this geometry as well as that flow velocity.

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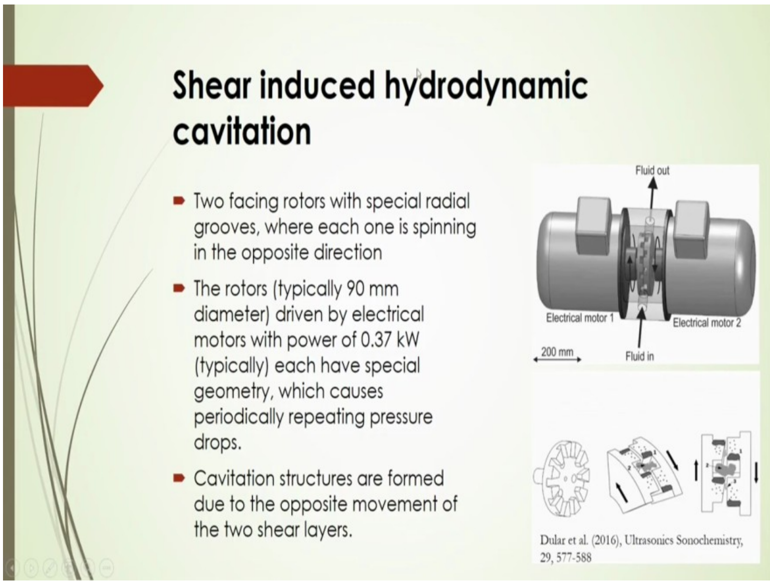

Another important is called shear induced hydrodynamic cavitation, in this case two facing rotators will be used to create this cavity. In that case special radial grooves are generally procured in these rotors where each one will be speeding in the opposite direction and in that case the rotors typically size will be 90 millimetre diameter it will be driven by electrical motors with power of around 0.37 kilowatt typically as per Dural et al. 2016.

And it will have this rotors is have special geometry in that case which causes that periodically repeating pressure drops and based on which there will be a formation of cavity. And that cavitation structures are formed due to the opposite movement of the 2 shear layers, so this is the mechanism based on which you can get that shear induced hydrodynamic cavitation process.

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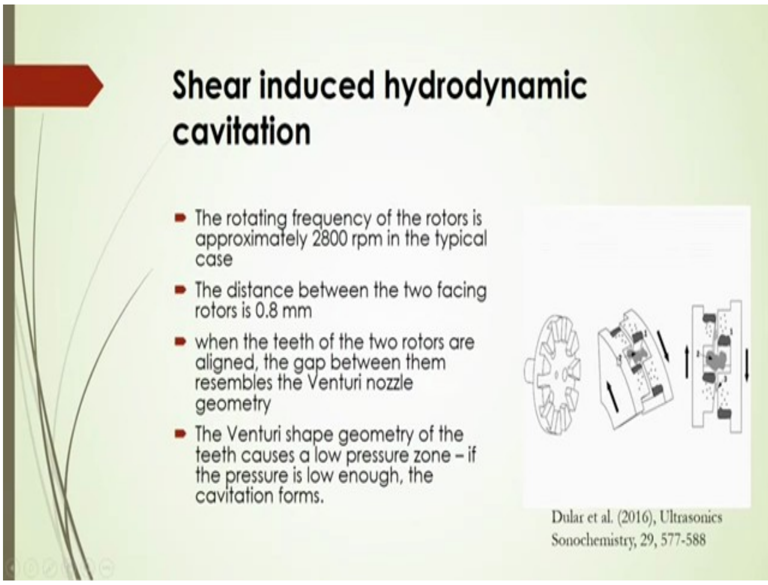

And in this case this rotating frequency of the rotors is approximately you know that 2800 rpm in the typical case as you know given by Dural et al. in 2016. And they actually designed it based on the distance between the 2 facing rotors of around 0.8 millimetre, and in this case they reported that when the teeth of the 2 rotors are aligned, the gap between them resembles the venturi nozzle geometry, in that case this special venturi shape geometry of the teeth will cause a low pressure zone and in that case if the pressure is low enough, then cavitation will form.

So this is the mechanism based on which you can form also that you know cavity in the reactor and you can apply this cavitation process in chemical engineering process.

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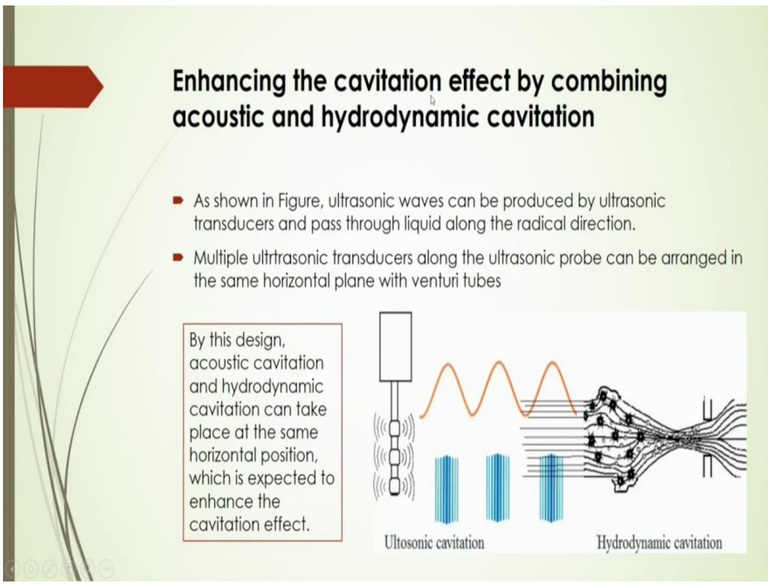

Now, enhancing the cavitation effect by combining acoustic and hydrodynamic cavitation, so both the mechanism you can combine together and then you can get that enhancement of the cavitation effect for that particular chemical engineering process. As shown in the figure here that in this case ultrasonic waves can be produced by ultrasonic transducer and pass through the liquid along the radial direction, whereas the ultrasonic transducer along the ultrasonic probe can be arranged in the same horizontal plane with the venturi tubes.

So based on these venturi tubes as well as the ultrasonic transducers based you know that cavitation process you can apply this mechanism this is called integrated system to produce that cavitation even finer and more finer cavity also can be produced and also you can get more interfacial area to apply for chemical engineering process where mass transfer will be the governing factor there.

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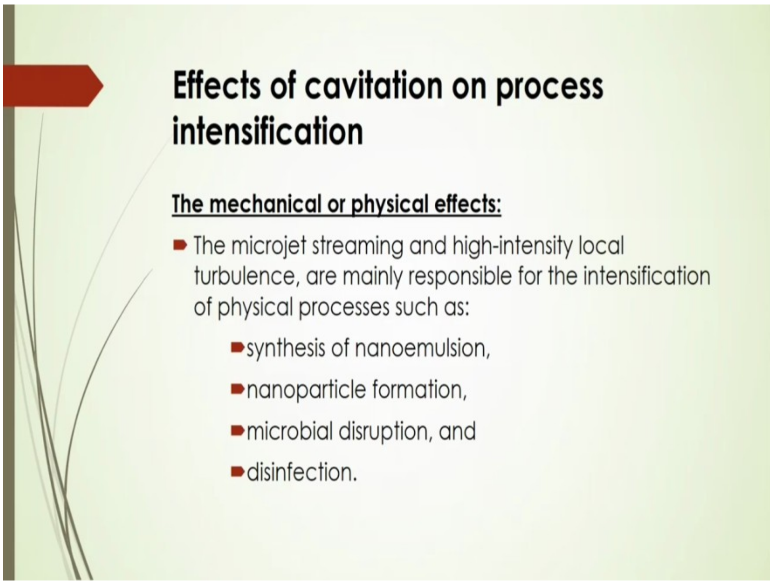

And in this case the effect of cavitation on process intensification is very important like you know that mechanical or physical effects, the microjet streaming or high-intensity local turbulence are mainly responsible for the intensification of physical process such as synthesis of nano emulsion, nano particle formation, microbial disruption and also disinfection there.

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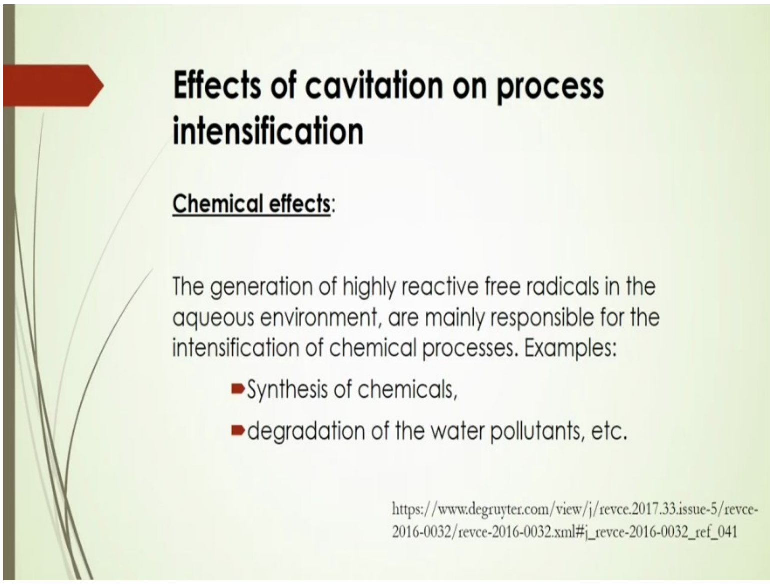

Chemical effects like generation of highly reactive free radicals in the aqueous environment and these are mainly responsible for the intensification of process like synthesis of chemicals, you do degradation of the water pollutants, even removal of the hazardous compounds of the water. So in that case you can use these you know that hydroxyl radicals to enhance that reaction to convert it into you know certain compound to get it more you know easily separated in a particular operation or processes where that removal of that you know hazardous materials are important there.

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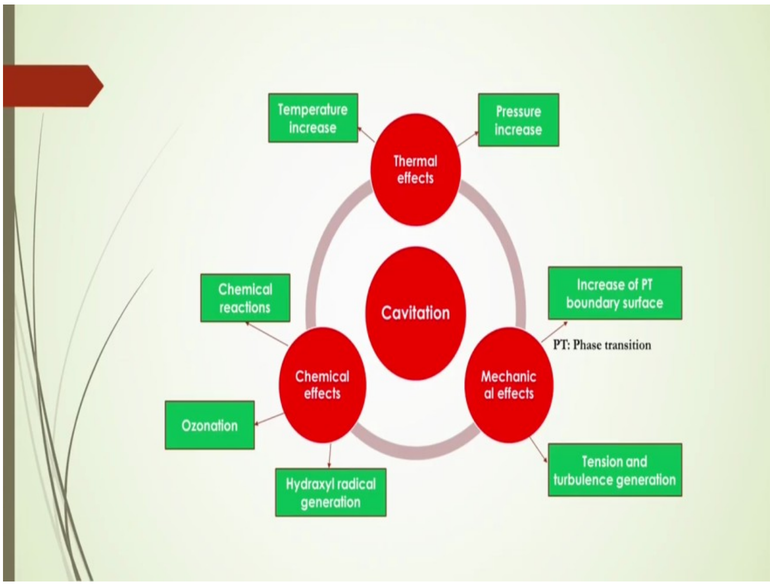

Now, we are having that different effects they are for cavitation like thermodynamic effects, it is called thermal effects, even you know that chemical effects, mechanical effects like this.

Thermal effects like temperature increase, pressure increase how it will be affecting, even you know that in chemical effects like chemical reactions how it will be intensified, ozonation process, hydroxyl radical generation, mechanical effects like you know that tension and turbulence generation will also keep that intensity of that formation of cavity.

Increase of you know that phase transition boundaries surface there so that is why you know that you can increase that cavitation efficiency they are based on this you know phase transition boundary surface modulations. So these are the different effects of that cavitation process which can be used for that specific Chemical Engineering Process Intensification.

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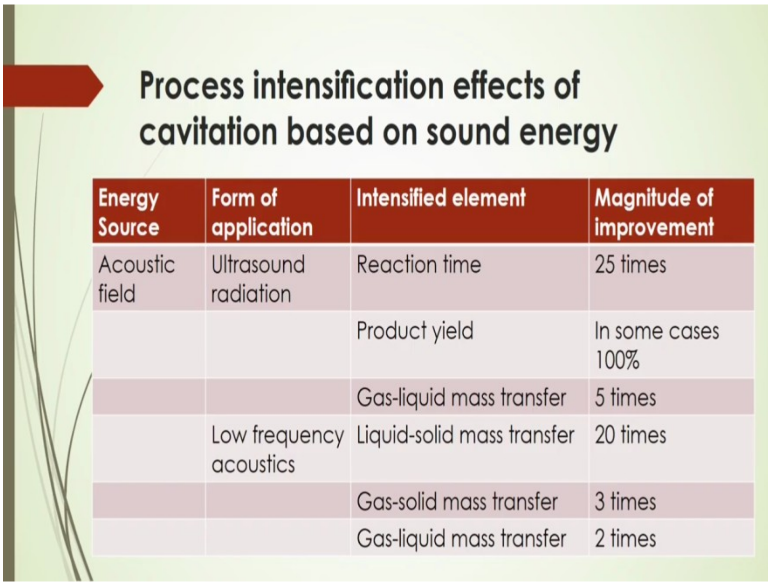
Process intensification effects of cavitation based on sound energy

Energy Source	Form of application	Intensified element	Magnitude of improvement
Acoustic field	Ultrasound radiation	Reaction time	25 times
		Product yield	In some cases 100%
		Gas-liquid mass transfer	5 times
	Low frequency acoustics	Liquid-solid mass transfer	20 times
		Gas-solid mass transfer	3 times
		Gas-liquid mass transfer	2 times

Now, process intensification effects of cavitation based on sound energy like you know that if you are using energy source as acoustic field, in that case applications will be as ultrasound radiation and low frequency acoustic. In that case if you are using ultrasound radiation then reaction time, product yield and gas liquid mass transfer will be intensified, in that case reaction time can be intensified up to 25 times, whereas, product yield can be intensified up to 100 percent, even intensification of the mass transfer when there will be mass transfer between gas and liquid it will be more than 5 times.

And if you are applying low frequency acoustic therefore, the formation of cavity and application for the liquid-solid mass transfer, that you can increase the efficiency of the process up to 20 times, even for you know that gas-solid mass transfer there you can increase the intensification up to 3 times, and also you can increase the gas-liquid mass transfer by 2 times also based on this low frequency acoustic there.

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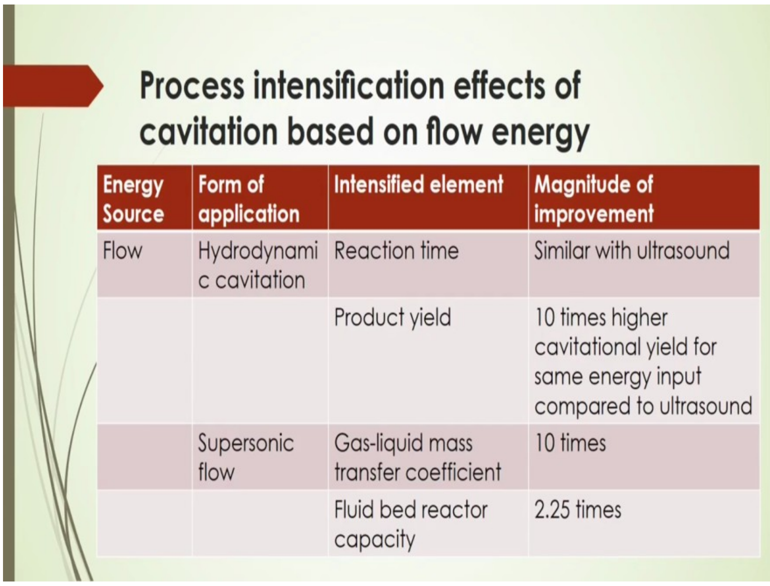

Energy Source	Form of application	Intensified element	Magnitude of improvement
Flow	Hydrodynamic cavitation	Reaction time	Similar with ultrasound
		Product yield	10 times higher cavitational yield for same energy input compared to ultrasound
	Supersonic flow	Gas-liquid mass transfer coefficient	10 times
		Fluid bed reactor capacity	2.25 times

And based on that energy source by flow of the fluid in that case application like hydrodynamic cavitation and in that case you can increase that process of reaction time you know similar to that ultrasound process, even you can increase that intensification efficiency up to you know that 10 times higher cavitation yield for same energy input compared with the ultrasound for the products yield.

And also if you are using that supersonic flow for the formation of you know that cavitation and if you are applying this supersonic flow for that gas-liquid mass transfer and in that case you can increase the gas-liquid mass transfer coefficient of by 10 times even you can increase that fluid bed reactor capacity up to 2.25 point times based on this mechanism of formation of cavitation based on that flow energy.

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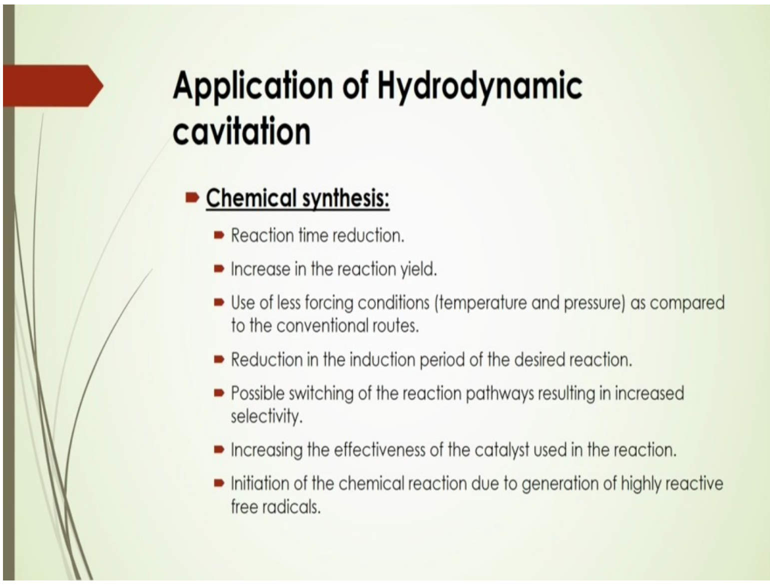

And what are the different applications of hydrodynamic cavitation? In that case you can increase that reaction time, for the chemical synthesis to reduce that reaction time instead of increase that reaction time so that cavitation process will be helpful for the reduction of reaction time because it is very faster to create that formation of hydroxyl radicals and the first reactions will be there.

Increase in the reaction yield, use of less forcing conditions like temperature and pressures as compared to the conventional routes to form this cavitation. And also reduction in the induction period of the desired reaction. Possible switching of the reaction pathways that will result in the increased selectivity. Increasing the effectiveness of the catalyst that will be used in the reaction. And also initiation of the chemical reaction that will be due to the generation of highly reactive free radicals there.

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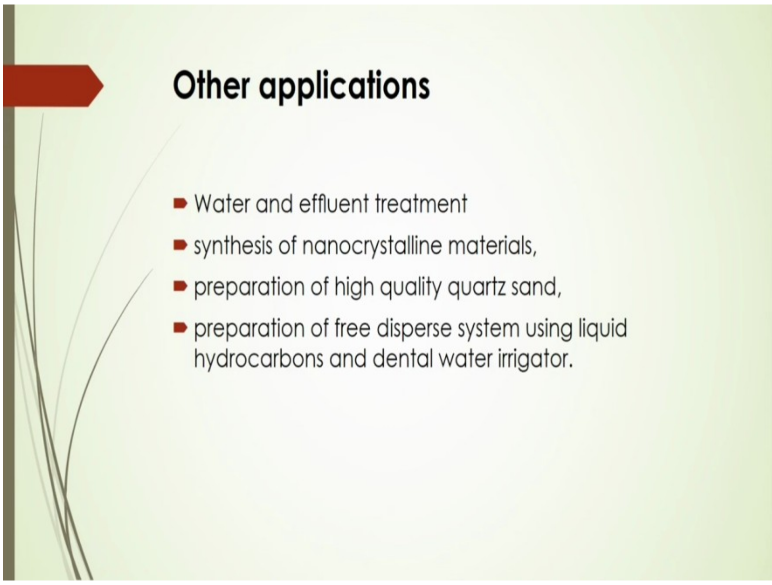

Other applications like water and effluent treatment, I told that if you are producing ozone micro bubbles or ozone gas cavities then you can use for you know that removal of arsenic from the wastewater. Synthesis of nanocrystalline you know that material and also the condition of high quality quartz sand, preparation of free disperse systems using liquid hydrocarbons and dental water irrigator there. So in that case these are the other several applications based on which you can apply that cavitation process accordingly.

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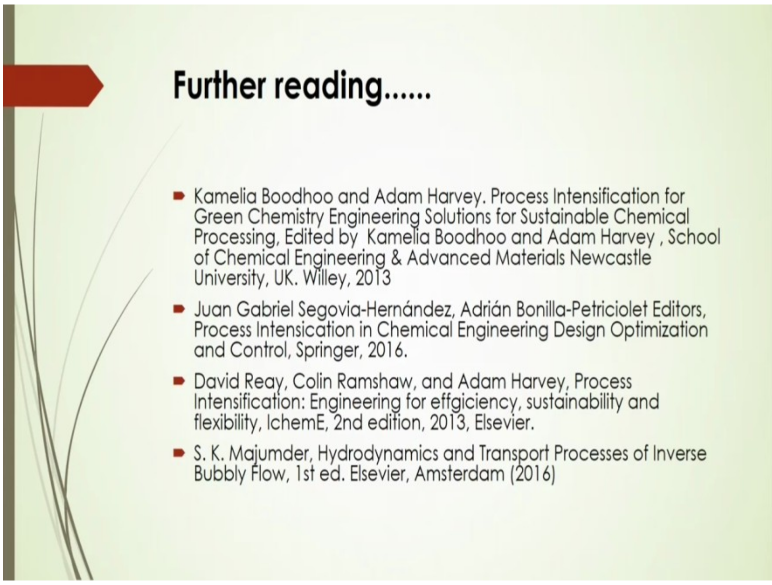

So, I would suggest you to go further about this you know that cavitation process from these suggested books that given in the slide. And so I think it will be helpful for you to better understand, even further understanding of that cavitation process and also different applications how it can be applied in different you know that Chemical Engineering Processes.

So in this lecture we have learned different aspects of cavitation, how it can be formed, what are the pressure, what are the upstream pressures, what are the downstream pressure, how ultrasound you know that irradiation will be helpful to form that you know that cavitation and what are the different other types of cavitation, hydrodynamic cavitation, acoustic cavitation that we have already discussed.

So I think you have lots of preliminary idea about the cavitation process which will be helpful for you know that processing of Chemical Engineering and Processes in the Intensification category, so thank you for this lecture.