Chemical Process Intensification
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Lecture 17
Cavitational Reactor Configurations and Activity

Welcome to massive open online course on Chemical Process Intensification. So in this module, module 6 we are discussing about process intensification by cavitation, so under this module, in this lecture we will discuss something about the cavitation of reactive configurations and their activities.

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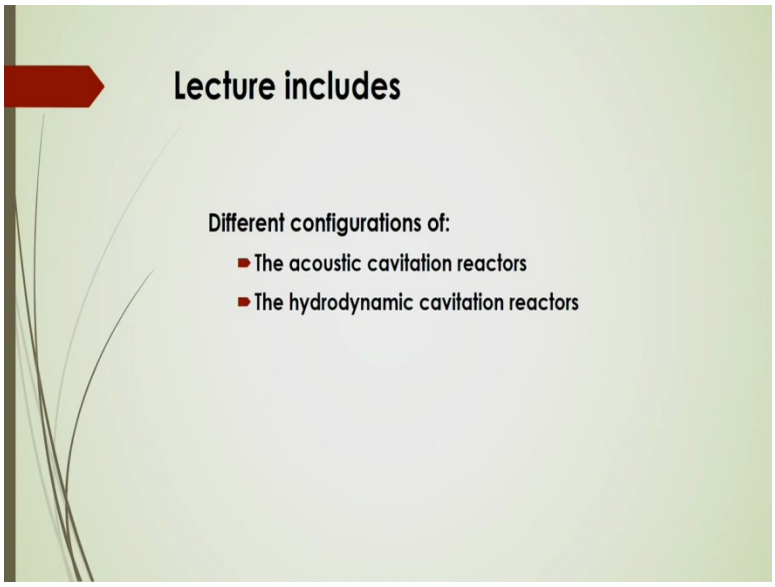

So, the lecture includes that what are the configurations of acoustic cavitation reactors and the configurations of hydrodynamic cavitation reactors. So before going to that let us have a recap of previous discussion on that cavitation that we have discussed something about that what is cavitation.

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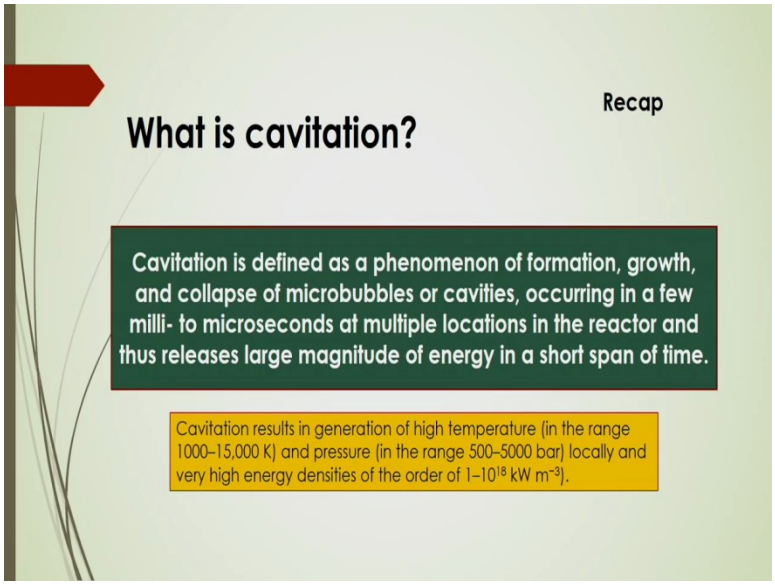

Generally it is defined as a phenomenon of formation, growth and also you can say that collapse of the cavity under some you know that external forces that maybe you know that ultrasonic forces or some other forces like you know that fluid flow forces, so based on which this you know that different types of different shapes of cavities are formed. So in that case that cavity is formed at different locations in the liquid systems or in the reactor.

And in that case during the formation of that cavity you will see there will be a release of large magnitude of energy in a short span of time. So we have discussed regarding that what will be the actually criteria to actually release that magnitude of energy and also how that cavity is formed. And in that case that cavitation results in generation of high you know temperature in the range of 1000 to 15,000 Kelvin and the pressure in the range of 500 to 5000 bar and that will be locally and very high energy densities of the order of 1 to the 10 to the power 18 kilowatt per meter cube so this is the cavitation.

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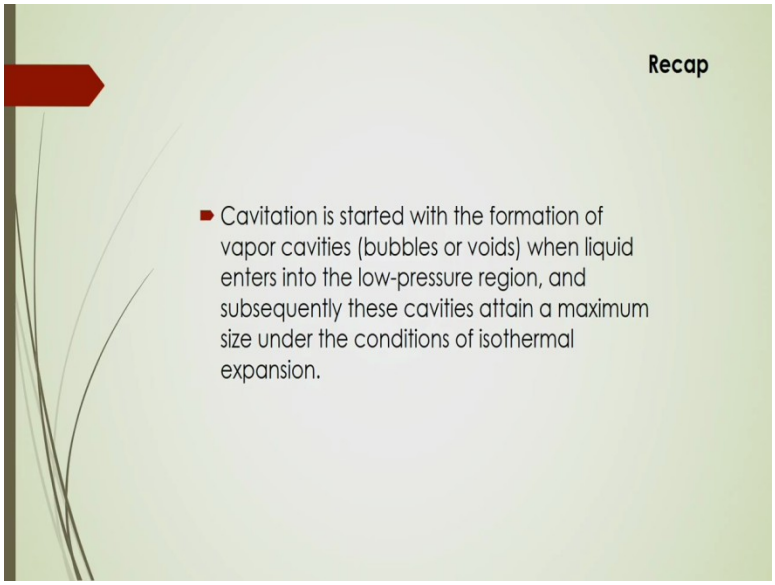

And in that case cavitation it started with the formation of vapour cavity is maybe bubbles, sometimes it is called voids and when the liquid enters into the low-pressure region from the high-pressure region and subsequently when these cavities attain a maximum size under a certain conditions, there will be you know that useful of that formatted cavity for different chemical engineering operation.

Generally this happens at the condition of isothermal expansion, so whenever this cavity will be formed that cavity sometimes it is called bubble or you can see it is sometimes called voids, so those will be actually useful generally for the chemical engineering processes like mass transfer of gas and liquid is important.

And in that case the efficiency of mass transfer depends on the interfacial phenomenon like you know that formation of interfaces by this gas and liquid. Now, that formation of interfaces basically based on this you know that cavity formation.

Now in that case there are different you know mechanism to produce this cavity and this cavity actually are formed based on that acoustic mechanism like you know that ultrasonic waves and also by you know fluid flow operations like in that case the fluid will be passing through a you know geometric constriction and based on which that cavity is formed. That already we have discussed in the previous lecture regarding the mechanism from formation of cavity based on that acoustic mechanism and also you know that hydrodynamic mechanism there.

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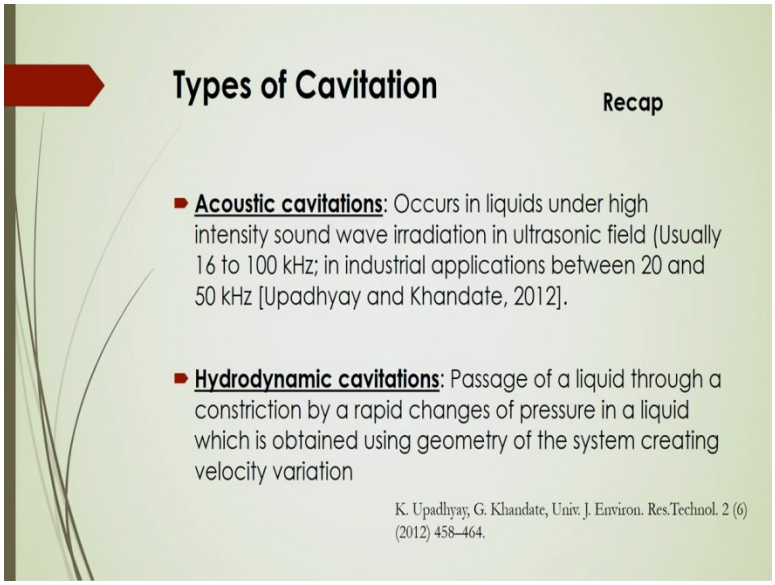

So we got that acoustic cavitation, that acoustic cavitation occurs in liquid under high intensity sound wave irradiation in ultrasonic field usually 16 to 100 kilohertz, and in industrial applications it will be generally applicable from 20 to 50 kilohertz. And also in case of hydrodynamic cavitation they are you know the passage of liquid through a you know constriction by a rapid changes of pressure in a liquid from which you can get that you know the variation of velocity and based on which you can have the formation of the cavity there.

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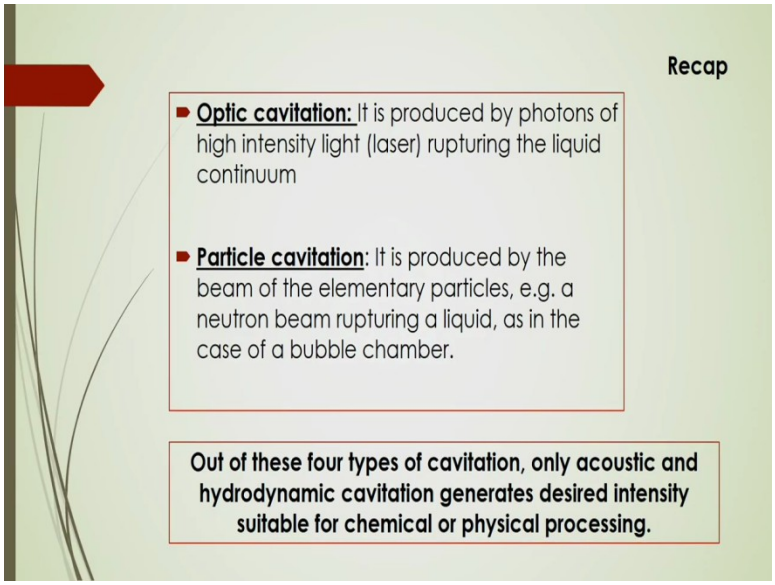

There are other different types like optic cavitation, even whistle cavitation like that and particle cavitation. And in case of optic cavitation it is produced by photons of high intensity light by rupturing the liquid continuum. And also particle cavitation in that case it is produced

by the beam of elementary particles like you know neutron beam that ruptures liquid and as in the case of bubble chamber there, so that mechanism that you can produce the cavitation by particle cavitation mechanism.

Now, out of these different types of cavitation process on the acoustic and hydrodynamic cavitations are important, where those will generate the desired intensity suitable for the chemical and you know that physical operations in Chemical Engineering Processing.

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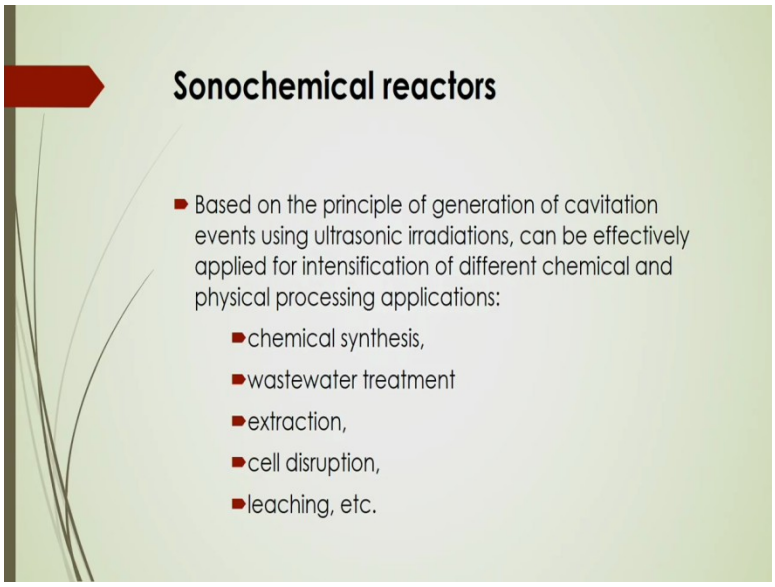

Now, we have already discussed that you know chemical cavity can be formed by that ultrasonic sound wave. Now based on which that different reactors are configured like it is called sonochemical reactors. Now based on the principle of generation of cavitation events using that you know ultrasonic irradiation can be effectively applied for intensification of different chemical and physical processes like you know that chemical synthesis, wastewater treatment and also extraction, cell disruption, even leaching there are other several different type of applications in Chemical Engineering Process.

So based on ultrasonic irradiation we are having the cavitation and the cavitation where it is formed that reactor is called as sonochemical reactors.

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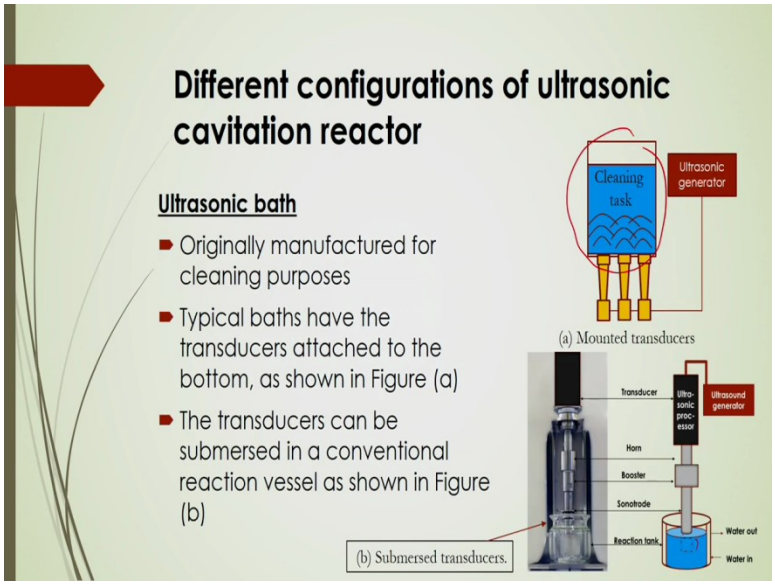

Now there are you know that several configurations of this ultrasonic cavitation reactors are there. Now, one type it is called ultrasonic bath, originally it is manufactured for cleaning purposes, you know that typical baths are shown here that in the slides in the picture. And in this case you know that in the bath that transducers are attached at the bottom, and also the transducer can be submerged in a conventional reaction vessel also.

So there are different configuration which is coming based on that you know that replacement or even the position of the transducer also whether it is the top side or in the bottom side, it is actually attached or not.

Generally in the ultrasonic bath you will see that transducers actually based on which that ultrasound radiation is produced, ultrasound wave is produced and the cavitation is produced there. So based on that transducer attached in the you know bath you can say that this type of reactor will be called ultrasonic bath reactor and the transducer can also become submerged in a conventional reaction vessel then it will be called as ultrasonic bath reactor also.

So here you will see that in this reactor in the slide that for the cleaning operations you will see that in this bath you will see other transducer by which that this you know sound wave is created by that ultrasonic generator and it is placed at the bottom and it may be series of you know that transducer mounted at the bottom of this you know bath. Whereas sometimes this you know that transducer may be mounted in a submerged way like that this will be in the reactor it will be you know submerged here, in this case also the same mechanism of that you

know the sound wave will be produced and based on which that cavitation will be formed, so these are the configurations of you know that ultrasound cavitation reactor.

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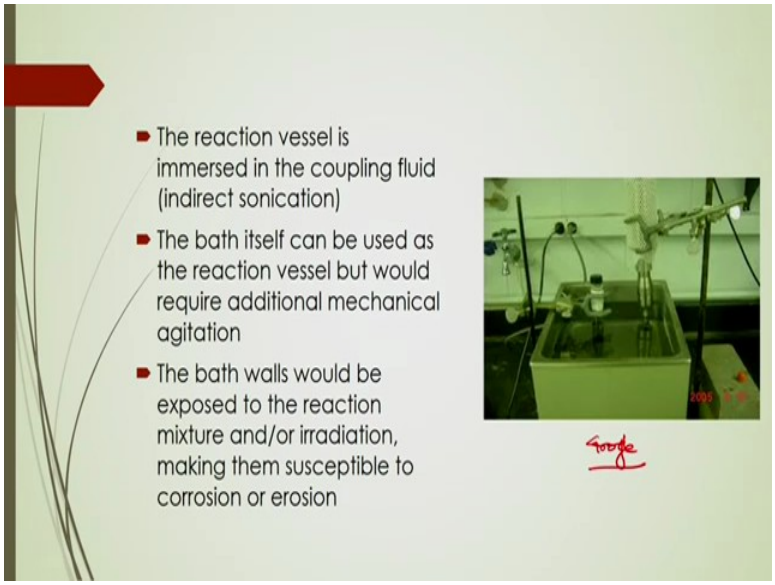

Now here one picture it is given, it is actually taken from Google image so based on this we can say that reaction vessel is here emerged in the coupling fluid, and also it is called that indirect sonication and the bath itself can be used as the reaction vessel, but would require additional mechanical agitation here to get the uniform concentration of that fluid element throughout the column.

So in that case whenever sound wave will be supplied there in generation of cavity will be there, that cavity may be you know dispersed throughout the reactor. So as per homogeneous nature of distribution of that cavity then you can get the intensified way of you know mass transfer process for chemical engineering in a particular process.

Now, the bath walls should be exposed to the reaction mixture and/or irradiation making them susceptible to the corrosion or erosion there also. So you have to you know make the bath wall in such a way that you can avoid that you know corrosion or erosion by the sound waves or irradiation that may happen during that you know the cavitation process by ultrasonic method.

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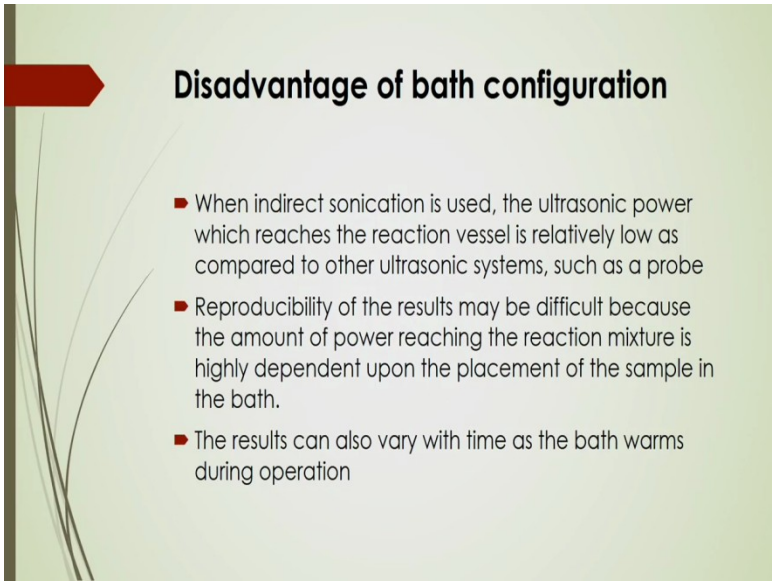

Now, there are several disadvantages of that bath configuration will be there. When indirect sonication will be used, the ultrasonic power which reaches the reaction vessel is relatively low as compared to other ultrasonic system such as probe there. And in that case you know reproduce ability of the result sometimes may be difficult because the amount of power what is reaching the reaction mixture is highly dependent on the placement of the sample in the bath, so that it should be sometimes difficult to you know that amount of power and how you are actually distributing there in the reaction itself.

And the results can also vary with time as the bath warms during the operation there, so in that case sometimes you know whenever you are supplying that ultrasound wave there may be you know that whatever you know that temperature will be produced that may be warming the total mixture solution. So in that case it may be the hindering some you know chemical engineering operations, where it may not be suitable that wave generation of the heat at that particular position.

So that should be you know that control for the specific operation of that Chemical Engineering, so that is not actually dependent on temperature. So whenever temperature will be produced then you have to control that temperature at a certain level or reduce the temperature there. So it is sometimes you know difficult to maintain that you know the reducing the temperature during the formation of cavity there.

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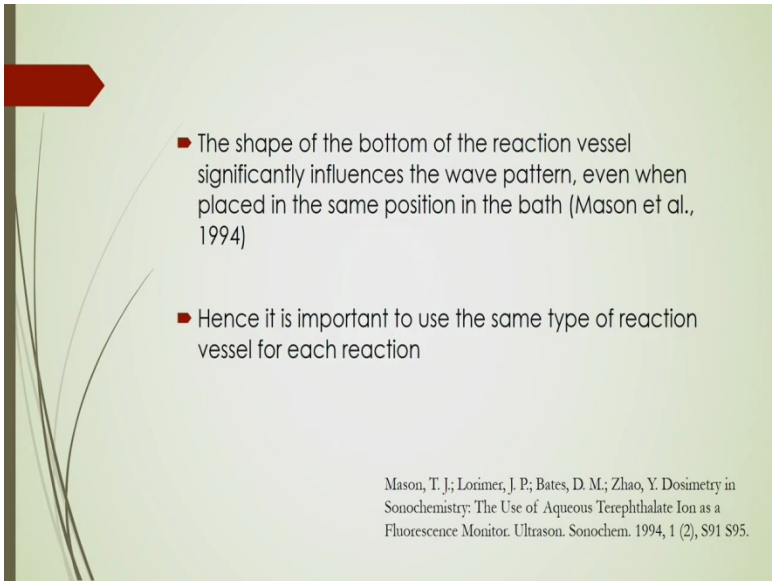

And also another important point to be remembered that the shape of the bottom of the reaction vessel sometimes it will be influences the wave pattern even when placed in the same position in the bath also. So you know that you have to design that bath in such a way that it may not be hampering any you know that probe pattern that in the bath.

So in that case the flow pattern to maintain the flow pattern for a particular you know that mass transfer operation because that mass transfer operation depends on that probe pattern, so to get that particular probe pattern like whether it is you know homogeneous or heterogeneous or slag flow or you can just slag flow phenomenon or not there.

So to maintain that you know flow pattern for that multiphase operation by you know creating that cavitation, so it is important to use the same type of reaction vessel for each reaction whenever you are maintaining or designing that bath to produce that particular flow pattern. So all those chemical engineering operations may be efficient for a particular flow pattern-based.

So to maintain that flow pattern you have to design that you know vessel or reactor bottom or you can make a shape in such a way that in all times that whenever you are going to operate that you know cavitation process there it will maintain that same flow pattern so this is important there.

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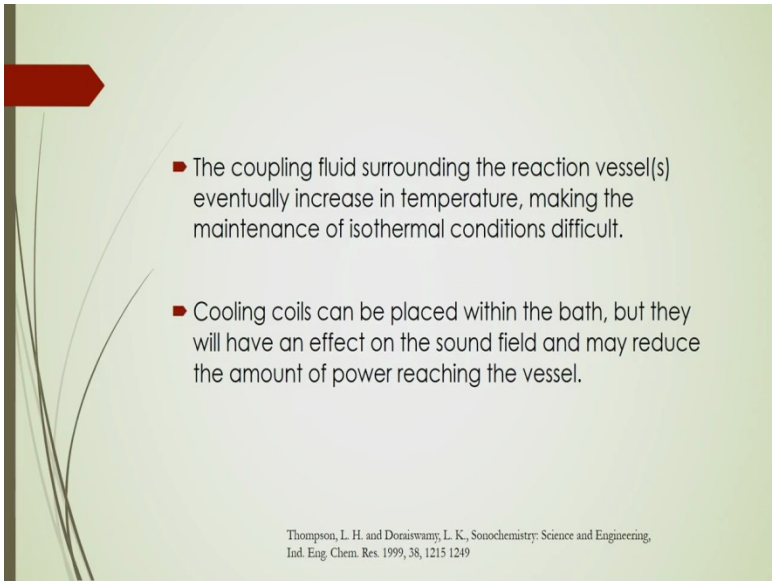

Another important that, whatever fluid will be coupled surrounding the reaction vessel, eventually increase in temperature, so making the maintenance of the isothermal condition it will be very difficult, and also if you are using some cooling coils to you know that maintain the temperature reducing the temperature there, they may have certain effect on the sound field. So in that case you have to reduce the amount of power that reaches to the vessel so that is why you have to supply the optimum energy level so that you are not actually you know disturbing the you know sound field to produce that cavitation there.

So these are the certain disadvantages these are certain points where you can actually take care of that point for the design of that particular ultrasonic bath reactor. Just to you know implement that the reduction of effect of sound field, and also that what is that the temperature maintaining of the temperature there and whether that flow pattern inside the inside the reactor will be maintained in a particular fashion or not that should be actually considered during the design.

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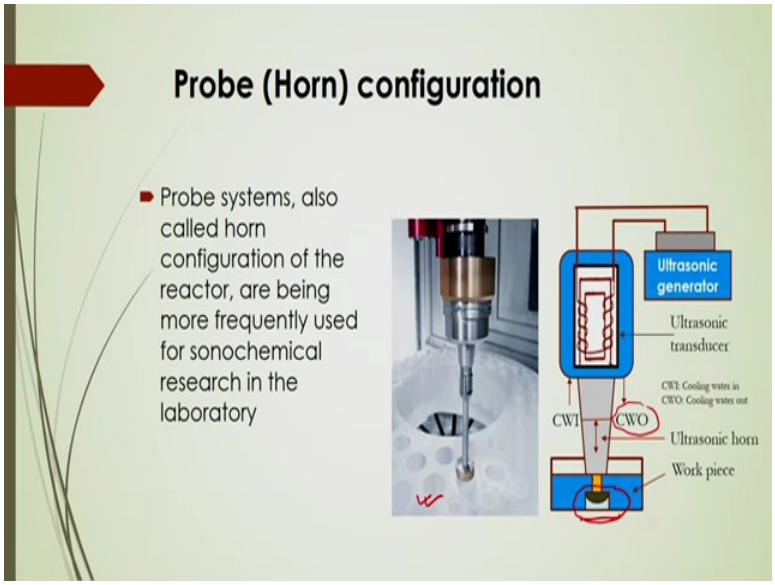

Another important consideration is called a probe configuration, in this case you will see it will be called as sometimes horn configuration of the reactor and it is more frequently used for sonochemical research in the laboratory there. Here in the figure it is shown that probe configuration of the ultrasonic reactor here, this is the picture and here the schematic diagram is shown here.

In this case this will be work piece where that you are applying that sound wave and sonochemical you know operation there, so ultrasonic horn is to be actually there and it is called this through this ultrasonic horn this you know that ultrasound is produced there and it is coming through the ultrasonic generator.

And here to maintain the temperature, some cooling water will be going and this cooling water will be out so this cooling water in and cooling water out and from that ultrasonic generator by ultrasonic transducer you are applying that ultrasonic energy to that ultrasonic horn to particular process, you know that it is generally for your mechanical operations to you know cut the peace or some other operations there in chemical engineering operations to produce that cavitation process.

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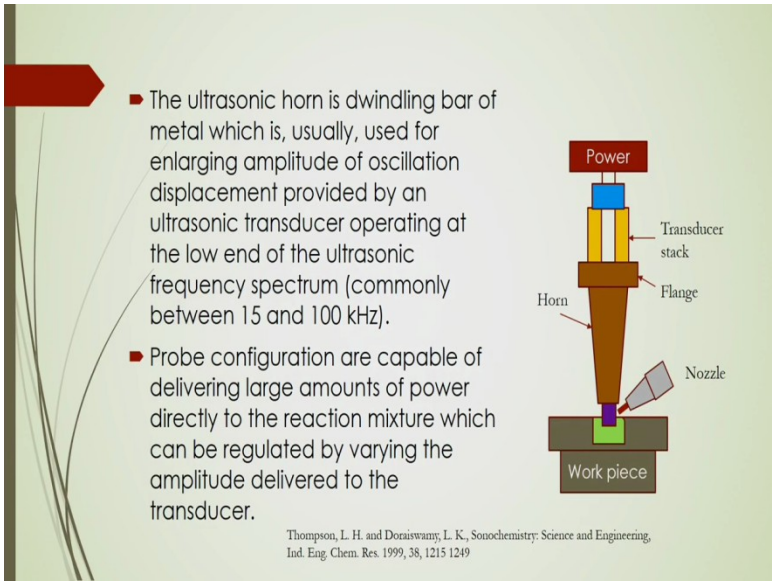

And also in this case this ultrasonic horn is actually dwindling bar of metal which is usually used for enlarging amplitude of oscillation displacement provided by an ultrasonic transducer that is operated at a low end of ultrasonic frequency spectrum commonly at you know that frequency of 15 to 100 kilohertz there and the probe configurations are this is capable of you know delivering large amount of power directly to the reaction mixture.

And in that case it can be regulated by varying amplitude that is delivered to the transducer also, so that is why you have to supply the you know that power directly to the reaction mixture by this you know that probe configuration there.

So instead of the transducer you can directly you know transfer energy to the probe, so this probe maybe it is called horn type probe, why it is called horn, maybe sometimes it is rod shape, sometimes it is you know that block shape also, so there are several different types of you know probe configurations also there so based on this you know ultrasonic reactors are being configured.

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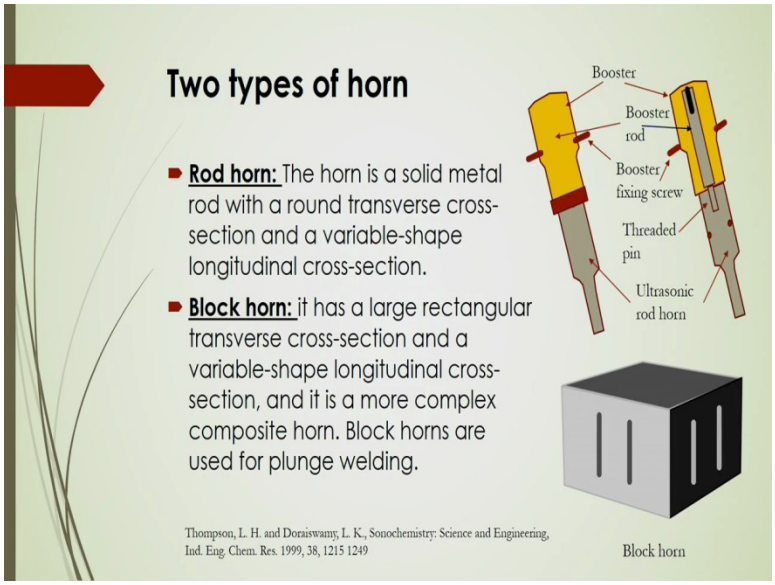

Now 2 types of horns or you can say that probes, it is called rod horn and block horn. So the rod horn actually is a solid metal it is shown in the figure, it is a solid metal rod with a round transverse cross-sectional area and variable shape the longitudinal cross-sectional area. And whereas, this block horn has a rectangular you know transverse cross-section and a variable shape longitudinal cross-section and it is more complex composite you know horn relative to that rod horn.

And block horns are used for you know that plunging of welding that is plunged welding, so this is this horn is basically used in mechanical engineering whereas rod horn is generally used in Chemical Engineering Processes for cavitation generation and based on that cavity interfaces that mass transfer like absorption, like you know that extraction, like you know gas-liquid reactions are being carried out.

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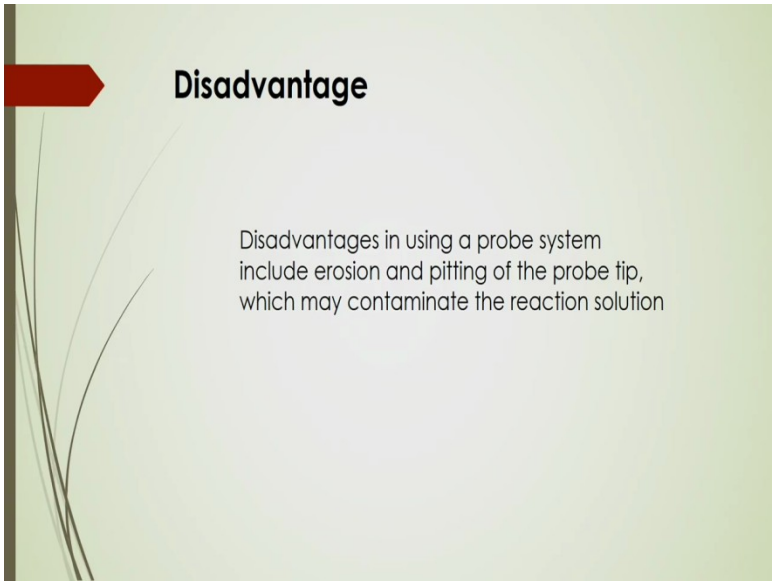

Now in this case also there have some disadvantages like you know that if you are using this probe system this may get the erosion during that operation because you know during that you know mechanical operations it may you know that breakdown of the that horn systems will be there, possibility of the breakdown of that horn and also if you are using in the chemical substances or in chemical reactions there may be you know that the erosion or corrosion will be there based on that chemical type.

If you are using suppose ozonated reactor there or ozone cavity will be produced there you can say that ozone may be you know reacting with that horn material there, so that is why sometimes the probe type you know configuration of the ultrasonic reactor may be sometimes difficult for the Chemical Engineering Processes.

But that maybe you know sometimes optimized just by selecting some synthesized material where the corrosion or erosion will be less there, and in that case the pitting of the probe tip is also corroded or eroded by that mechanical operations or chemical engineering operations there which may sometimes contaminate the reaction solution also.

So if suppose probe particles is you know that reacting with that you know solution then you will see there will be several other products will be coming out in the solutions so that solution may hinder the reaction performance there, so that is why this is one disadvantage of this probe system there.

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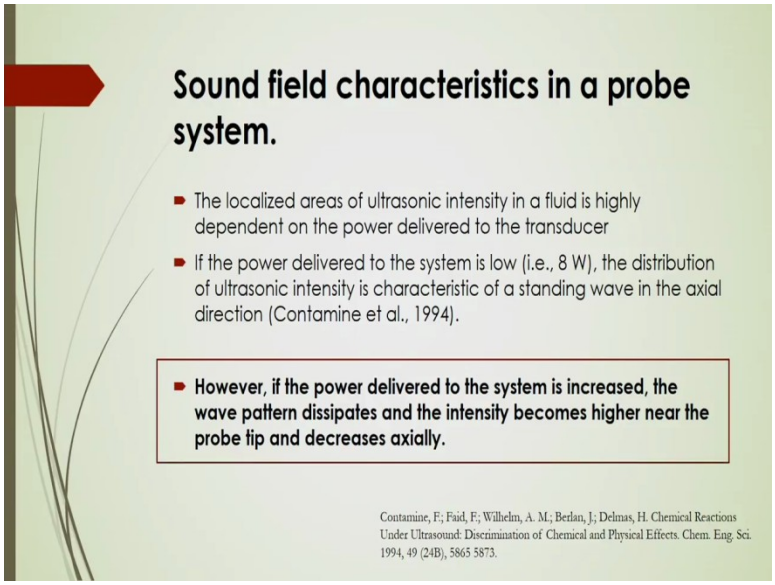

Now, what are the characteristics of that sound field in a probe system that you have to consider there? In the case of you know localized areas of ultra sound intensity in a field you will see that it will be very highly dependent on the power delivered to the transducer there. If the power delivered to the system is low like around 8 watts, the distribution of the ultrasonic intensity it will be the characteristic factor of the standing wave in the actual direction.

So actually this has been observed in you know that experimental study by Contamine et al., 1994. So they have reported that this when power delivered will be you know low, in that case distribution of the ultra sound intensity is the characteristics of the standing wave in the axial direction there.

And however, if the power delivered to the system is increased, they have also you know point out at that the wave pattern dissipated and the intensity becomes higher in that case near the probe tip and it will decrease axially.

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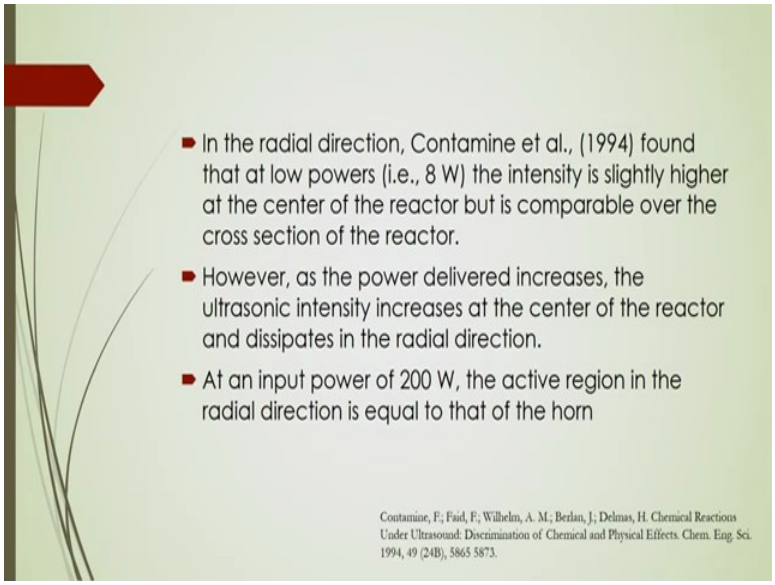

So in that case the radial direction that Contamine et al. found that at low powers that is at around 8 watt as per their experimental observation, the intensity is slightly higher at the Centre of the reactor. But they have observed that it is actually comparable over the cross-section of the reactor. Also in the case of power delivered where it will be increased, the ultrasonic intensity it will be increased at the Centre of the reactor and dissipates in the radial directions there they have actually observed and as per their observation the input power of 200 watt they have observed that there will be active region in the radial direction which will be equal to that of the horn. So this is very important and it will be noted down that power delegation is important for that particular operation of you know that ultrasonic reactor.

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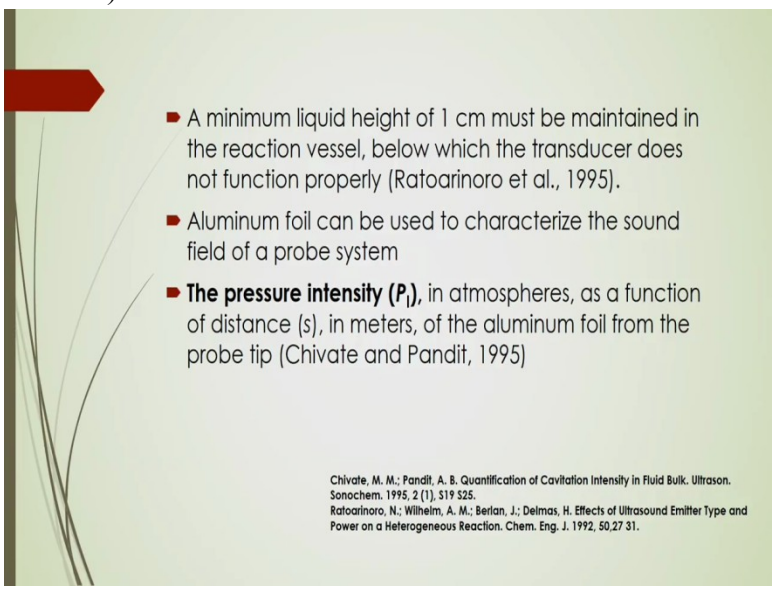

Now a minimum liquid height of 1 centimeter must be maintained in the reaction vessel as per you know the conclusion of Ratoarinoro et al. in 1995, they have observed that these things. In that case if you are you know maintaining the liquid height of less than 1 centimeter, the transducer may not you know that giving the proper you know functioning in the reaction vessel and for the formation of the cavitation.

And in that case aluminum foil can be used to characterize the sound field of a probe systems to you know that minimize the malfunction of the transducer and the reactor. And in this case during the supply of energy through the transducer by the sound field of a probe system, you may actually you know that have some pressure intensity in the reactor so that pressure intensity will be a function of distance in meters of aluminum foil from the probe tip.

And Chivate and Pandit in 1995, they have suggested one you know that co-relation to calculate this pressure intensity in atmosphere as a function of distance in meter of the aluminum foil from the probe tip.

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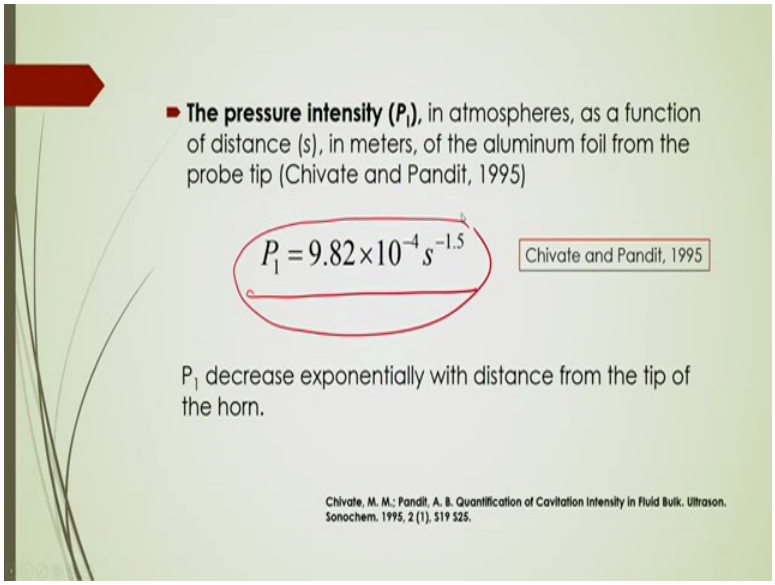

So according to them, the pressure intensity can be calculated by this equation here, this P1 would be is equal to

$$P_1 = 9.82 \times 10^{-4} s^{-1.5}$$

Here you know that P1 decreases exponentially with distance from the tip of the horn, where s is actually the distance in meters of the aluminum foil from the probe tip, this is as per

Chivate and Pandit 1995. They have suggested this you know correlation to estimate the pressure intensity that during the cavitation process.

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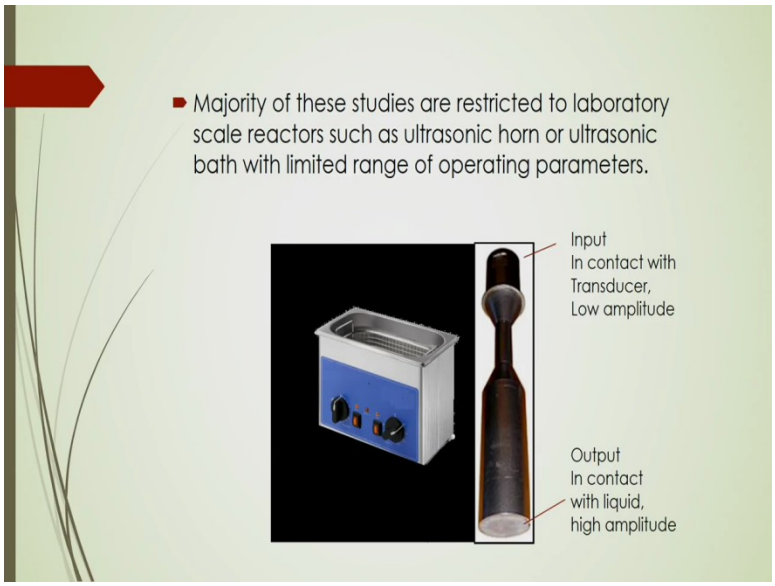

Now, majority of these studies are restricted to laboratories scale reactors such as ultrasonic horn or ultrasonic bath with limited rate of operating parameters there, so in that case for pilot scale operations you have to design in different way, maybe you can install the multiple probe there for a big reaction vessel and also series of operation of that cavitation process can be done for the pilot scale operation there.

So these are the systems for simple you know that for this is ultrasonic bath and this is you know that it is one type of you know horn type or rod type that probe or transducer you can say that can be used or installed along with this ultrasonic bath there. So you can install this in series like you know may be n numbers may be as per that reaction criteria, even what type of you know that what is the amount of output you need daily basis.

So based on which that you have to design the operation, you have to design that ultrasonic bath whether it should be series in operation or it may be the single reactor or not that can be designed based on this. So based on the laboratory scale study then you have to scale it up to the pilot scale.

Now to scale up of those grocery have to study all those things in laboratory scale to get the generation of the data experimental data and based on which you can analyze and you can you do make a certain model and based on which you can predict the output of the

performance of the reactor output of the product or output efficiency of the product or output efficiency of that reactor, performance of the reactor. You can actually predict by that you know model.

Now, if there are more than one variables will be there then it is very difficult to you know that to make a model based on that one variable. May be you know during that operation any chemical operation more than you know 1 variables will be there. So if there are supposed multi variables are there, so there will be interactions of one variables to the other variables to get the intensity of the you know that mixing intensity of the you know that reactions, intensity of the hydrodynamic parameters there, it will be changed based on that operating conditions.

So, if there are more than 1 variables maybe multi variables, with that case it is sometimes very difficult to predict the output or yield of the reactions or yield of the process based on that operating variable, so sometimes it is suggested to make a you know correlation model or multiple you know regression analysis will be there to make a you know that multivariable correlations that.

Now, that correlation maybe you know used to you know scale up those particular process based on that operating variables and you can design based on that scale up of the study based on that you know experimental or laboratory studies there within you know certain range of operating parameters.

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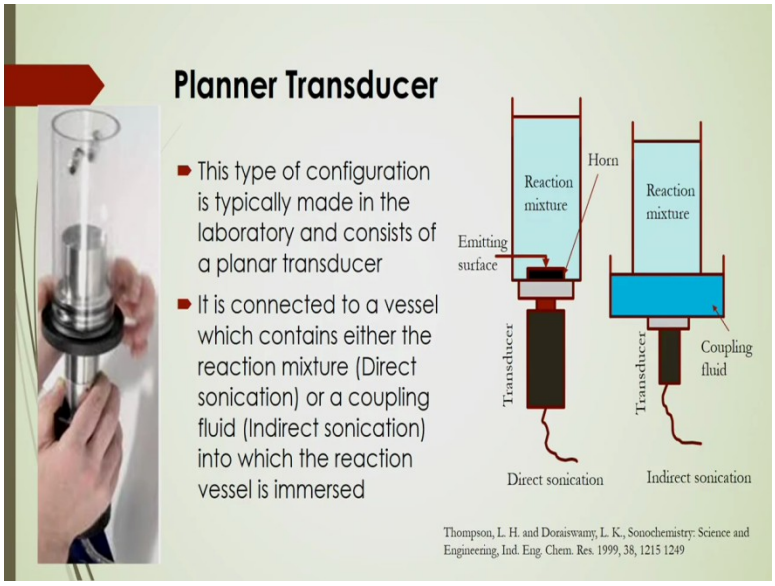

There are another type of transducer, it is called Planner transducer, this is also important configuration of you know that ultrasonic reactor there. This type of configuration generally made in the laboratory and consists of planner transducer there and in this case it is connected to a vessel which contains either the reaction mixtures, direct sonication or a coupling of the fluid that is called indirect sonication into which the reaction vessel is immersed there.

So here shown in the figure is called the direct sonication, this is indirect sonication, and in direct sonication how this transducer is placed in the reaction mixture from the bottom, and in this case from this plate there will be you know that emitting energy or you know the sound wave is emitting and based on which there will be formation of cavity. And here also there coupling fluid will be used to you know that to generate that cavity and which will be used for that reaction mixture just by you know that optimizing the temperature whatever produced during that cavitation there.

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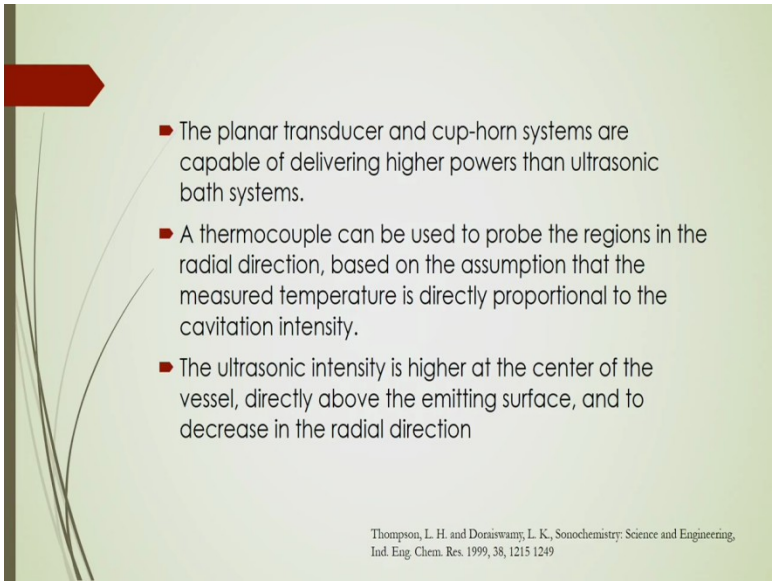

And also the planner transducer and cup-horn systems are also important there which are very capable of delivering very high-power than ultrasonic bath systems, so in that case a thermocouple is suggested to you know used to probe the region in the radial direction there based on the assumption that the measured temperature is directly proportional to the cavitation intensity there.

So based on which that you have too you know design the probe to just to get the undisturbed by the higher supply of energy there in the ultrasonic bath system. So the ultrasonic intensity

is higher at the center of the vessel and it will be directly emitting the energy from the surface and to decrease in the radial direction the reaction vessel there.

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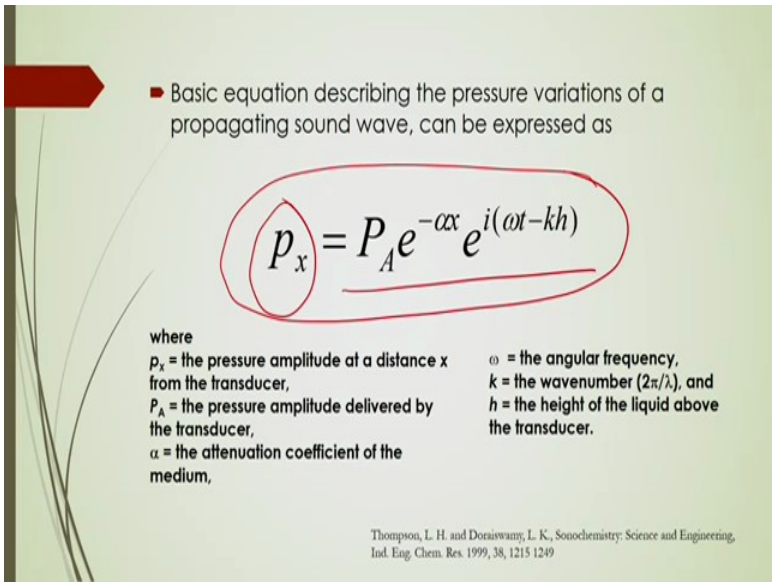

Now, what are the pressure variation of propagating sound wave during the cavitation process? So in that case a basic equation that is given by Thomson et al in 1999 to calculate the pressure variations of that propagating sound waves there and it is denoted by you know that pressure amplitude and which is referred by this symbol that is p_x. And this p_x that is you know pressure amplitude at distance x from the transducer which will be equal to

$$p_x = P_A e^{-\alpha x} e^{i(\omega t - kh)}$$

as per this equation here, see the slide where this equation is given.

So, in this case this p_x is called the pressure amplitude at distance x from the transducer and here P_A is called the pressure amplitude delivered by the transducer whereas this you know constant, Alpha (α) it is called the attenuation coefficient of the medium and Omega (ω) is the angular frequency, k is another parameter it is called wave number which will be calculated by $2\pi/\lambda$. And here the height of the liquid about the transducer is denoted by small h here, so based on this equation you will be able to calculate how the pressure is varying during that propagating of the sound wave in the reaction vessel.

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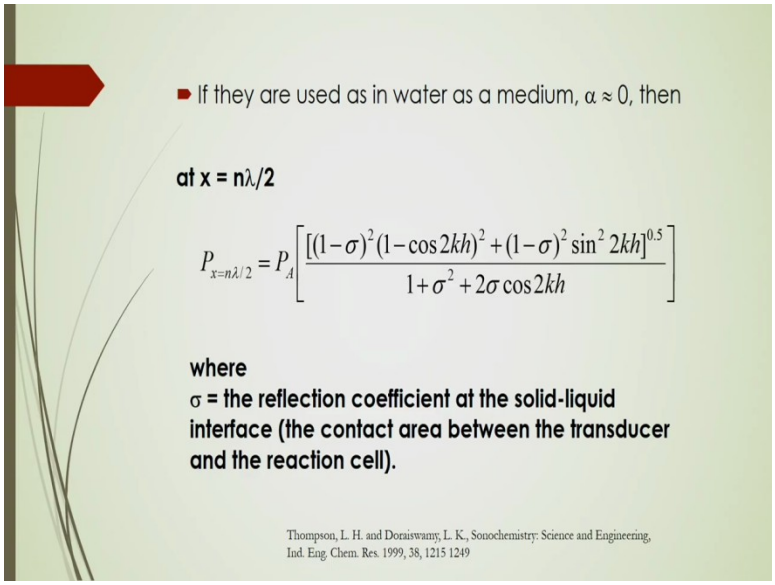

If they are used as in water as a medium then Alpha (α) that is attenuation coefficient should be 0, then at x is equal to nλ/2 then you can calculate that pressure amplitude that will be equal to

$$P_{x=n\lambda/2} = P_A\left[\frac{[(1-\sigma)^2(1-\cos 2kh)^2+(1-\sigma)^2\sin^2 2kh]^{0.5}}{1+\sigma^2+2\sigma\cos 2kh}\right]$$

So in this case Sigma is one parameter, it is called the reflection coefficient at the solid-liquid if there is a process of that solid-liquid operation. So this Sigma is reflected or referred to as reflection coefficient at the solid-liquid interface and the contact area between the transducer and the reaction cell also it will be referred to as Sigma here.

So if you know that Sigma (σ) value and k and other parameters then you will be able to calculate easily what should be the pressure variation or pressure amplitude delivered by the transducer by this equation.

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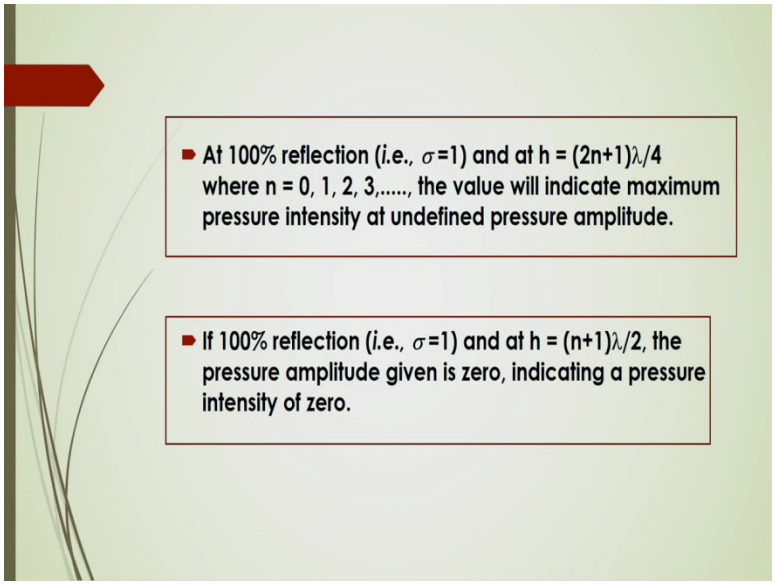

Now it is to be noted that if there is 100 percent reflection that if Sigma (σ) is equal to 1 and at a distance h you get $h = (2n+1)\lambda/4$ where n is equal to 0, 1, 2, 3. The value will include the maximum pressure at you know under pressure intensity at that pressure vessel at undefined pressure amplitude there. If 100 percent reflection Sigma (σ) is equal to 1 and $h = (n+1)\lambda/2$, the pressure amplitude will be 0 there. And then in that case it will be actually it will be giving you know that pressure intensity equals to 0. So these are the two cases whether the Sigma (σ) value is 1 or not that is one case and if h is changing then you can have that pressure amplitude at a different value.

So, if $h = (2n+1)\lambda/4$, it will give you that pressure intensity of you know that maximum value, whereas if $h = (n+1)\lambda/2$ then in that case pressure intensity will be 0 there at that particular 100 percent reflection. So these are the very important point where that probe design and also transducer design that you have to consider these equations to calculate that how the pressure variance, what will be the pressure intensity inside the reactor to be calculated there.

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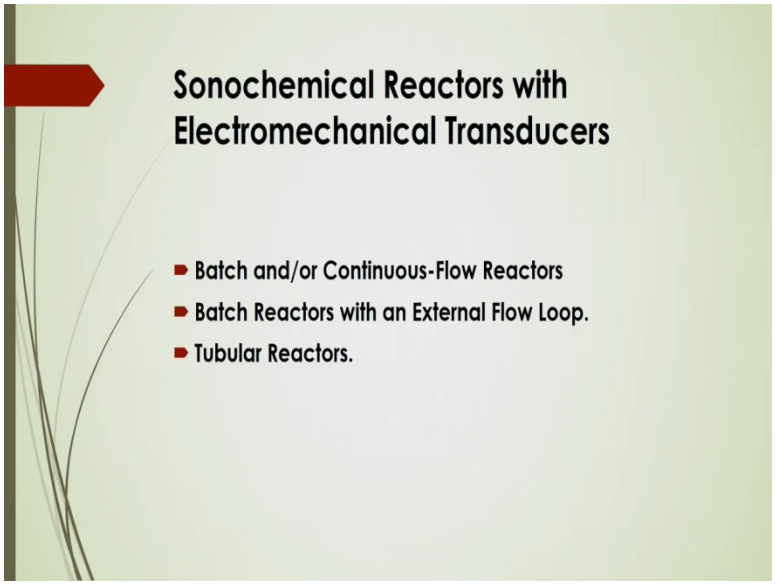

Now, another consideration is that sonochemical reactors with electrochemical transducer there. In that case this type of reactors are generally operated in batch or continuous mode without external loop or with external loop also, sometimes these types of reactors are configured as a tubular reactors there.

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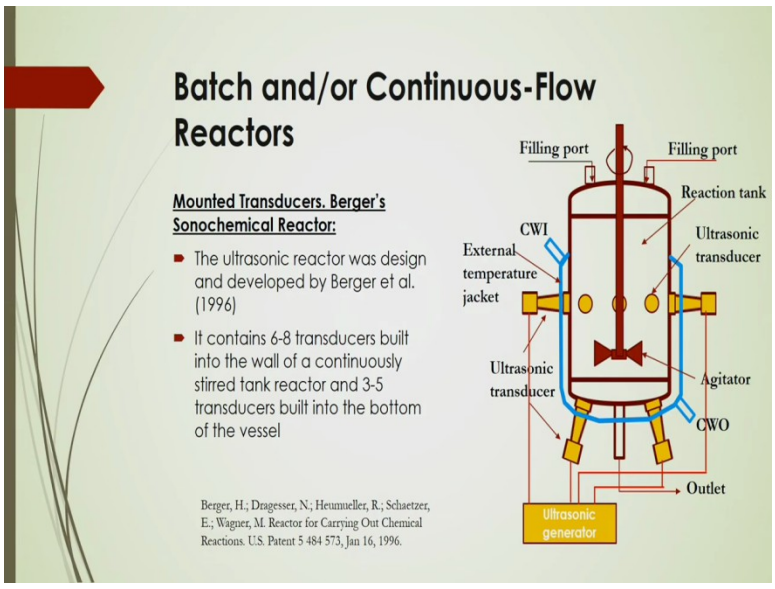

So there are different types of you know that batch or continuous flow reactors will be based on that mounting of you know transducer there. In that case, Berger's sonochemical reactor based on the mounted transducer they have actually designed that ultrasonic reactor in 1996 and based on their design actually it contains 6 to 8 transducer which is built into the wall of

a continuously stirred tank reactor and 3 to 5 transducer built into the bottom of the vessel as shown in the figure in the slides here.

So this is very important that this type of reactors actually configured based on the transducers how you are mounting, whether it is at the bottom and how many transducers will be there that is there should be some optimal you know location where you can install this transducer to generate that you know ultrasound waves to create that cavitation there.

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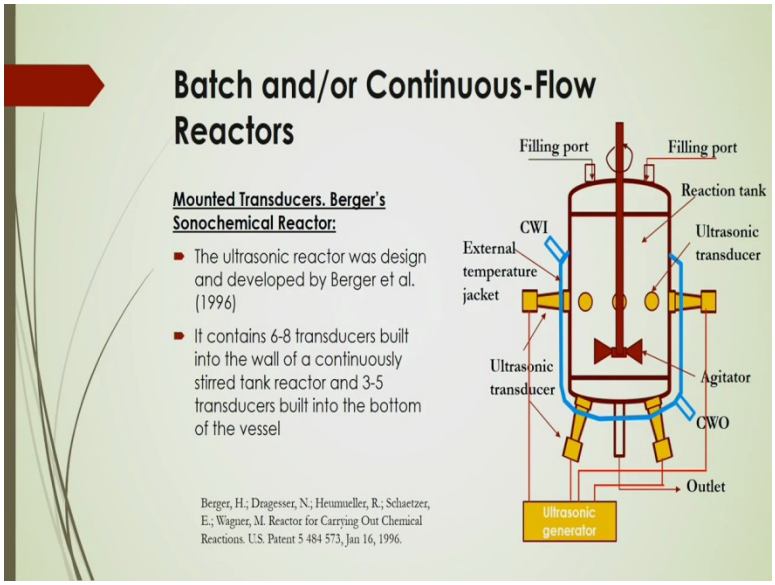

So in this case the reactor is actually assembled with an impeller for mechanical agitation of that mixing solution, and external jacket for isothermal controlling and also reaction ports which allow for operation in the batch, semi-batch or continuous mode there, here it is there, this is the filling port there from the outlet position also how that liquid is coming out that this

port should be there and this is the you know this one is you know impeller device or you can say that other mechanical also device you can use. You can use magnetic stirrer also to mix the fluid there inside the reactor. And outside that reactor there will be you know controlling of that isothermal system there by jacketing that reactor where that cooling water input and cooling water output will be there continuously so that you can maintain that particular temperature of this reaction.

So in this case the transducer may be operated independently of one another and are designed with you know caps that will be protecting them from the you know atmospheric if there is any disturbance or not.

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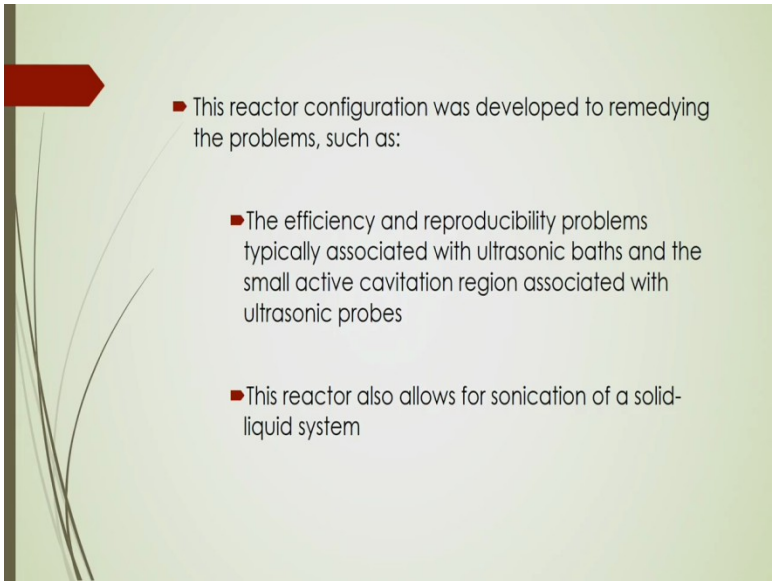

And in this case you know the reactor configuration was developed to you know remedying the problems such as, the efficiency and the reproducibility problems typically actually associated with ultrasonic baths and the small activation regions which are actually associated with the ultrasonic probes. And also this type of reactor you can use for the chemical engineering operation where solid-liquid systems are very important.

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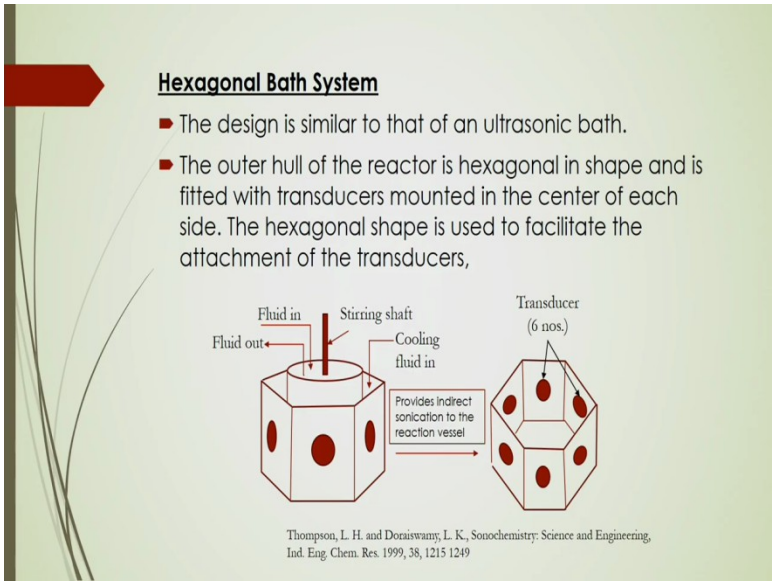

Another configuration it is called Hexagonal bath systems, in this case the design is similar to that of an ultrasonic bath, only thing is that the outer hull of the reactor is to be configured as an hexagonal in shape and is fitted with transducer which will be mounted in the centre of each side as shown in figure in the slide. This is likely design based on that the concept of Thomson that is given in 1999, and they have actually published this type of design in industrial engineering and chemistry research.

And based on their design they have actually given the shape of that particular reactor as hexagonal shape. Why that hexagonal shape is actually designed? Because they have concluded that this type of shape may be given the facilitation or you can say that this type of shape can be used to facilitate the attachment of the transducer in the reactor more easily so that you can optimize the homogeneousness actually you know that supply of irradiation or sound wave there and formation of cavitation in you know well distributed inside the reactor, so that is why this type of reactor are you know useful for that better attachment of the transducer to keep the better reaction performance.

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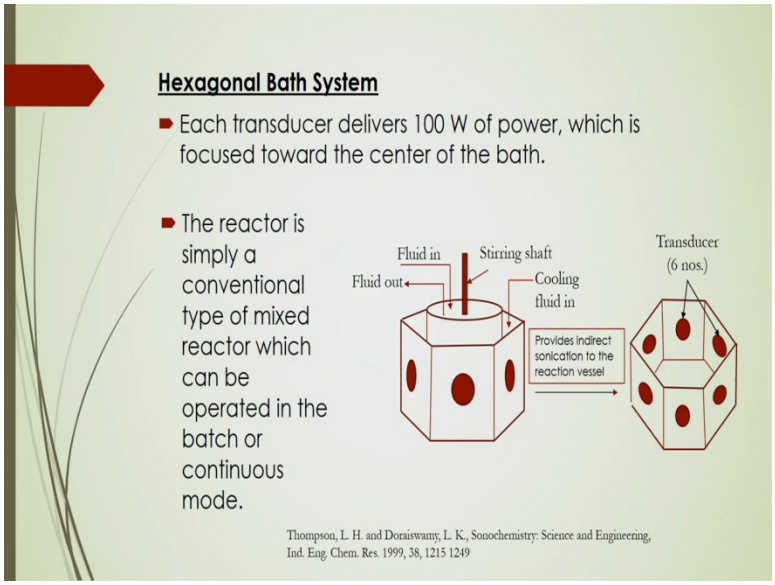

And each transducer in this case as per they are actually experimental observations delivers 100 watt of power, which is focused towards the centre of the bath, and the reactor is simply a conventional type of mixed reactor which can be operated in the batch or continuous mode also there.

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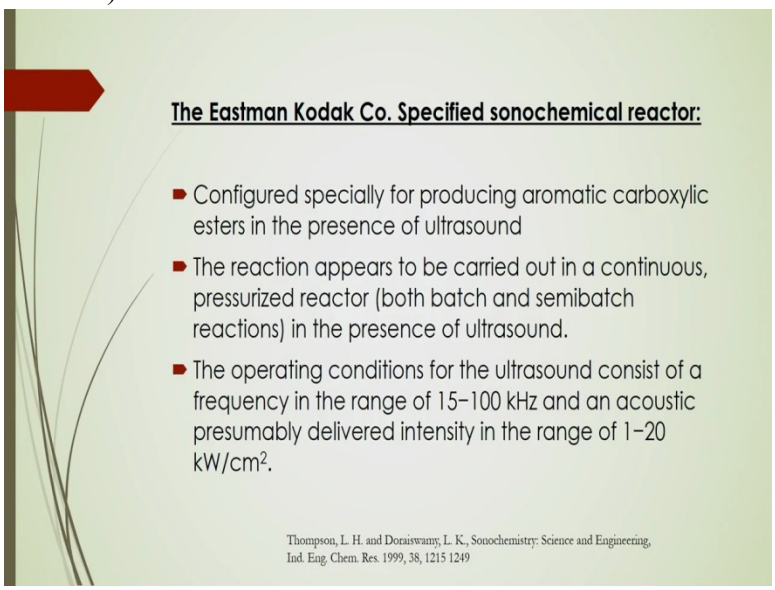

And another important you know that design of sonochemical reactor, or they have actually designed like here as per Thomson that is they have published, that they have reported that the Eastman or Kodak Company, they have developed one sonochemical reactor, it is very specified, it is configured specially for producing aromatic carboxylic esters in the presence of ultrasound.

So in that case the reaction appears to be carried out in a continuous or batch wise also, sometimes batch wise also can be there so that the reaction actually to be carried out in the continuous in a pressurized reactor in the presence of ultrasound there. So in this case the ultrasound consists of a frequency in the range of 15 to 100 kilohertz and an acoustic reasonably deliver intensity in the range of 1 to 20 kilo watt per centimeter there.

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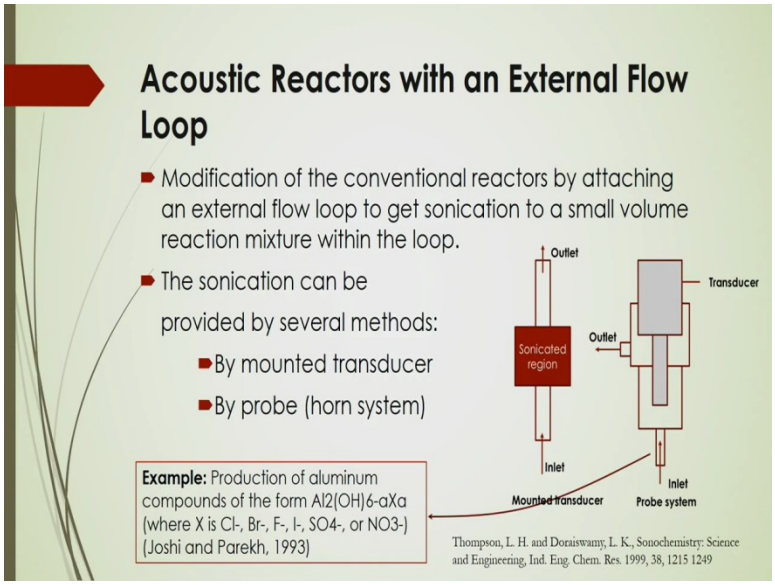

Another important you know that reactor for this sonochemical operations there these reactors actually designed are with external flow loop, in that case this modification by this external flow loop is considered because there is an intensification of the you know that operation compared to the conventional reactors by attaching an external flow loop to get the sonication to a small volume of reaction mixture within the loop there. So this is the advantage that within a small you know volume of reaction mixture within a certain loop you can get the intensification of the chemical process there.

So the sonication can be provided in this case by several methods, by mounted transducer or by probe system as earlier whatever we have shown that different types of transducers and probes. So that type of transducer and prove you can mount there, so this type of design actually is suitable for you know that sonication to a small volume of reaction mixture within the loop.

Example, like you know like production of aluminum compounds of the form here it is given in the slides, where X here in this complex form it is chloride, bromide, fluoride, iodide, sulphate or nitrate is there, so these types of the compounds you can form.

So this is why for special consideration of the chemical processes, the modification of the conventional reactors by just providing that external flow condition flow you know mechanism to get the intensification of the process.

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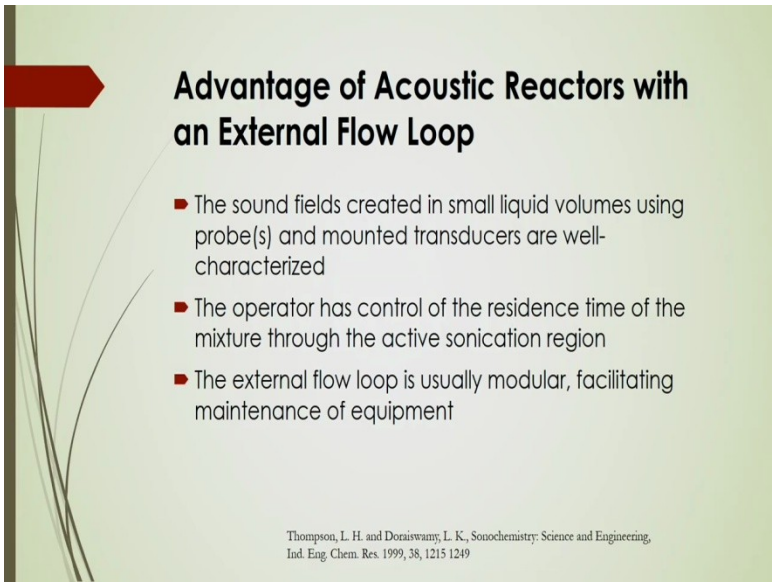

Now, advantage of acoustic reactor with the external loop reactor, here in this case some advantages like you know that the sound fields which are created in the small liquid volumes using probes and mounted transducers are well characterized there and operator has control of the residents time of the mixture through the active sonication region and also the external flow loop is usually it will be modular facilitating the maintenance of the equipment there.

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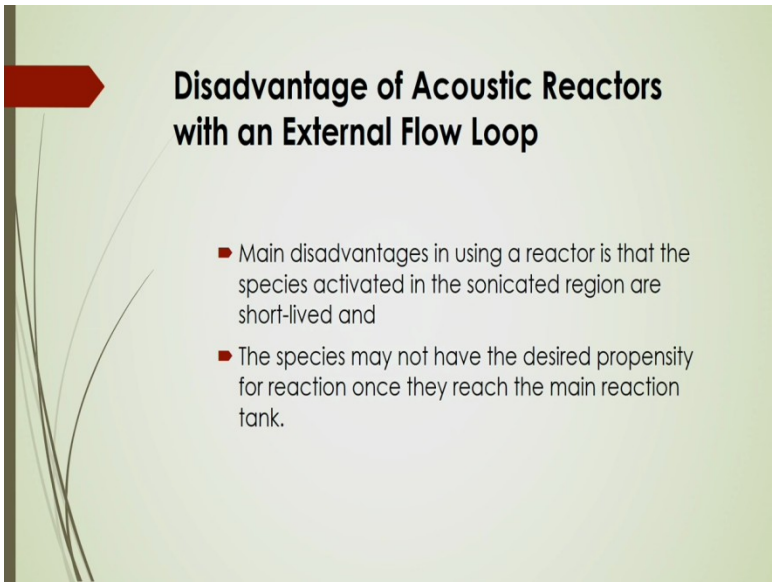

Also you will see that the certain you know that disadvantage of course will be there with the design of this external loop flow. So in that case the main disadvantage in using the reactor is that the species which are activated in the sonicated regions are sometimes you know that short-lived and in that case the species may not have the desired propensity for the reaction once they reach the main reaction tank there. So that is why there is some disadvantage of this type of thing, so main disadvantage that it is short-lived that is retention time or you can say that expiry will be very within a short period there of that species for particular biochemical operation.

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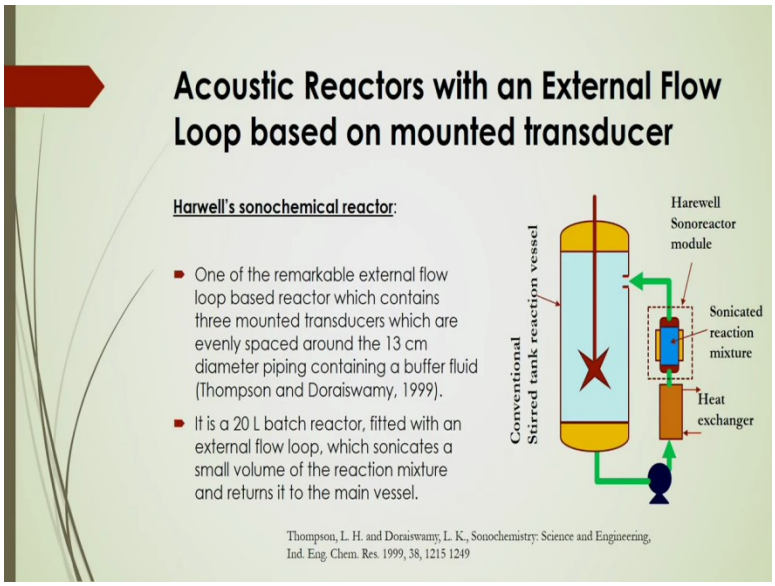

Now in that case if you are considering that acoustic reactor with an external flow loop based on the mounted transducer, in this case the remarkable you know that the reactor is that based on which you can say that the three mounted transducers sometimes or multiple transducer may be you know installed in the reactor based on a certain you know the space around you know 13 centimeter as per given by Thompson and Doraiswamy in 1999.

So in that case there will be a gap of that piping diameter of 13 centimeter containing a buffer fluid there. And in that case the reactor may be of 20 liter batch reactor which will be fitted with an external loop which sonicates a small volume of the reaction mixture and returns it to the main vessel there, so this is the schematic diagram of the that acoustic reactors with external flow loop based on mounted transducer is shown here in the slides.

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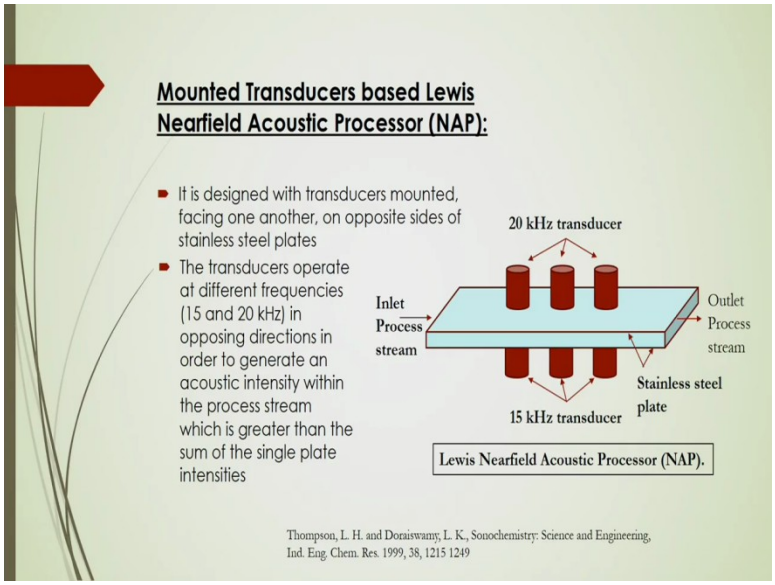

Now, another important reactor based on this mounted transducer that is developed by in the researcher that is called Lewis Nearfield Acoustic Processor. And in that case it is designed with the transducer that is mounted facing one another opposite sides of this stainless steel plate as shown figure here in the slide. In this case the transducer operate at different frequencies in the top 1 it is you know that around 20 kilohertz, where as in the bottom one it is 15 kilohertz and these are mounted in a stainless steel plate through which that some process stream will be going from one side to the another side.

And in that case you will see that whenever you are you know that generating that frequencies of 15 or 20 opposite to each other in the order to generate an acoustic intensity within the process stream. And in this case you will see that it will give you the greater intensity then the sum of the single plate intensity. Whereas you will see in any conventional reactor with that you know that mounted transducer that is general mounted transducer which will give you the intensity you know that only by the single you know stream where you can apply that either 15 or 20, but if you are you know mounting that transducer opposite to each other than you can have more intensity than some of the single plate intensity if you separately just mount it on the stream.

So this is the advantage that it is called sometimes conjugated or you can say that it is integrated system of the transducer mounting where you can get that higher acoustic intensity during that cavitation process.

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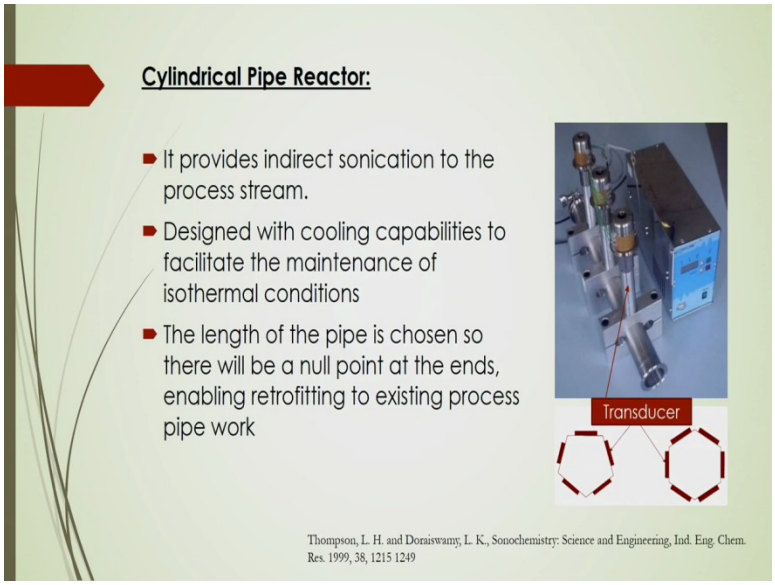

Another important reactor it is called cylindrical pipe reactor, it generally provides the indirect sonication to the process stream, typical snapshot is shown here in the slides as per Thomson and Doraiswamy as reported in journal industrial engineering chemistry in 1999. And it is generally designed with a cooling capabilities to facilitate the maintenance of isothermal condition and also in this case the optimal pipe lengths should be chosen so that there will be no you know there will be you know that null point at the ends there enabling retrofitting to existing process pipe work there.

So that is why it is getting important because there you can do the reactions in the pipe systems in the continuous mode just by you know that maintaining the cooling capacities or you know the maintaining the temperature at the reactor easily. And also in this case the mounting of the transducer will be more you know easier compared to the other system there.

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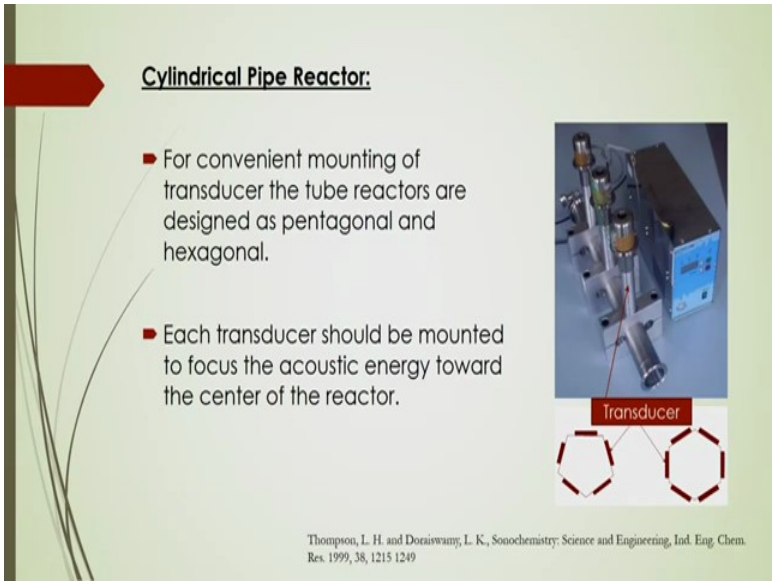

And in this case so convenient mounting of the transducer, the tube reactors are designed as Pentagonal and hexagonal shape and each transducer should be mounted to focus the acoustic energy towards the centre of the reactor there. Even for the transport processes, even for the prediction, even simulation of this type of reaction it will be more easier as compared to the other complex you know mixture there.

And in this case maybe you will sometimes see that you can maintain the flow pattern of the you know fluid or liquid or reaction mixture or reactant at a certain flow pattern so that is why this type of cylindrical pipe reactor that is sonochemical cylindrical pipe reactors will be more beneficial compared to the other there.

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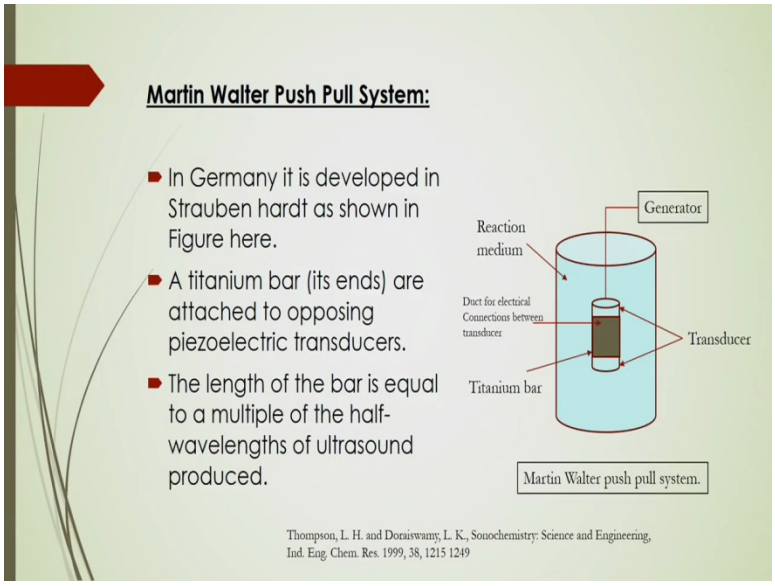

Another important reactor of this type that is developed by Martin Walter based on their push pull system there. It is reported there in Thomson-Doraiswamy channel in their journal, in Germany it is developed in Strauben hardt as shown in figure here. A titanium bar is actually attached to opposite piezoelectric transducers as shown in the figure, the length of the bar is equal to a multiple of half wavelengths of ultrasound produced there.

So in this case the produced cavitation in the reaction medium more uniformly compared to the other mounting system. In this case you know that the generation of the wave which is actually directly in the centre of the reactors there, so in this case the opposing piezoelectric transducers are acting in the generation of that you know cavitation there.

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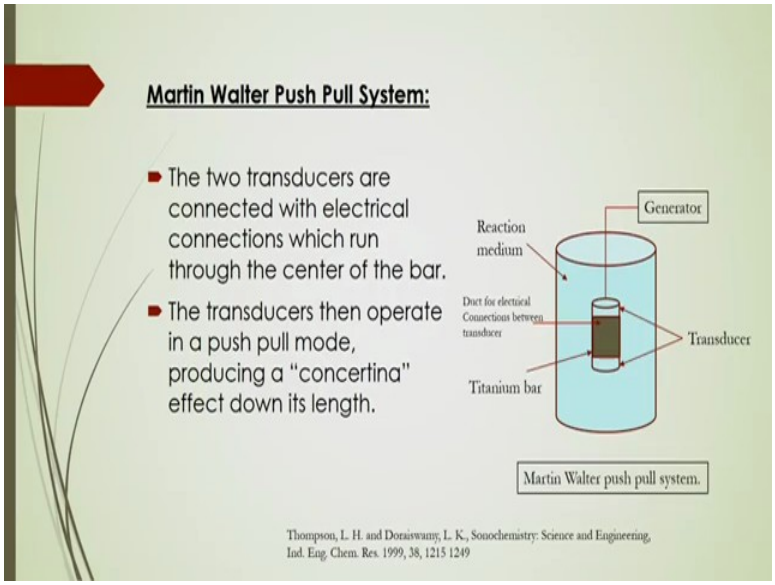

The two transducers are connected with electrical connections which run through the Centre of the bar and the transducers then operate in a push-pull mode which will produce you know concertina effect, it is called "concertina" effect down its length there. That means here you will see during that you know that production of sound wave there, generation of sound wave it will be uniformly distributed throughout the reaction mixture there.

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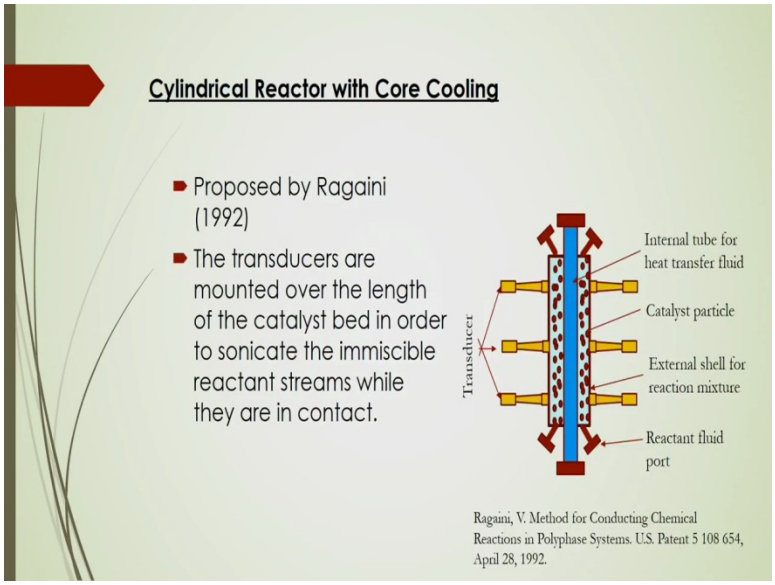

Another important reactor is called cylindrical reactor with core cooling there, it is proposed by Ragaini in 1992. The transducer are mounted over the length of the catalyst bed as shown in figure here, in order to sonicate the immiscible reactant streams while they are in the contact. So as per you know Ragaini they have you know actually patented this type of reactor for the you know operation in the system when immiscible fluid systems are to be contacted to each other for giving the better mass transfer operation.

In this case you will see the internal tube for the heat transfer fluid will be used and catalyst particles will be you know surrounded of that internal tube for the heat transfer fluid, external shell for reactant mixture to be used there and reactant fluid port you know that separately used to you know supply and also taking out of that fluid mix are there.

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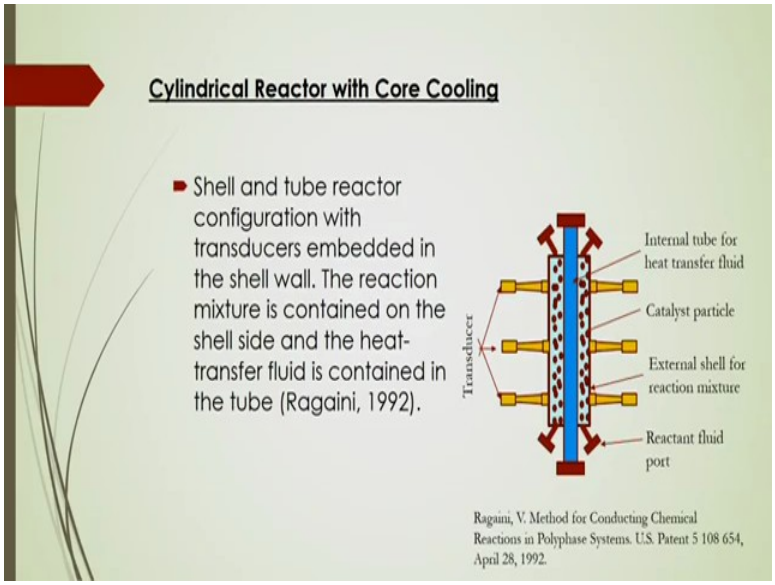

And shell and tube reactor configuration with this transducers that embedded in the shell wall there, the reaction mixer is contained on the shell side and heat transfer fluid is contained in the tube as per Ragaini that is report in their patent.

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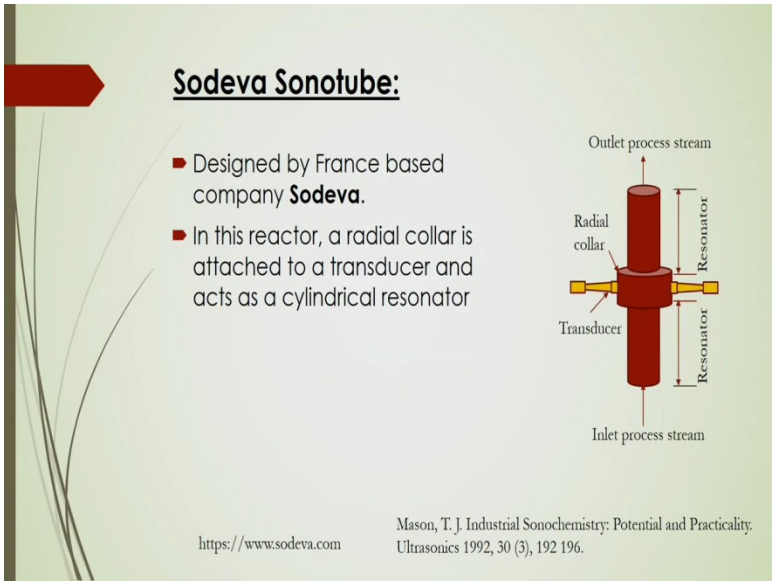

Nowadays in industry you know that in commercial sector one important sonotube are there for chemical reactions being used based on that sonochemical mechanism and it is designed by France based company it is called Sodeva. In this reactor a Radial collar is attached to a transducer and act as a cylindrical resonator there. So this is also important, you can see this type of reactor on the company's website it is given here.

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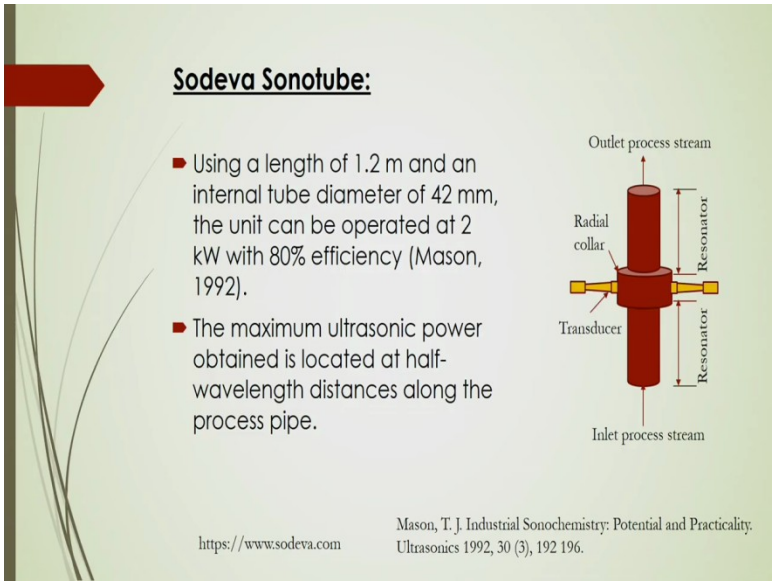

And using a length of 1.2 meter and an internal tube diameter of 42 millimetre typically the unit can be operated at 2 kilowatt with 80 percent efficiency as per reported by Mason 1992. And the maximum ultrasonic power obtained in this case is located at half wavelength distances along the probe pipe shown in the figure here.

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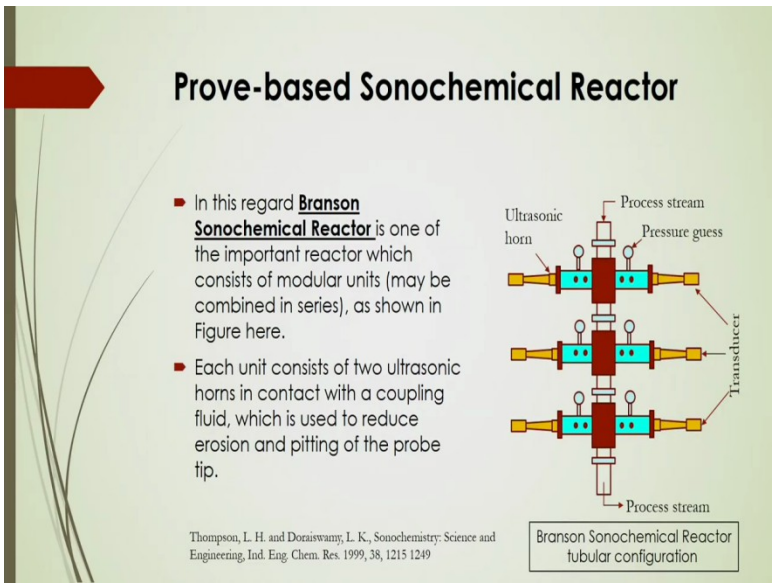

Then prove based sonochemical reactors, in this case the Branson sonochemical reactor is very important which consist of modular units may be combined in series there as shown in figure. In this case, each unit consist of 2 ultrasonic horns in contact with a coupling fluid, which is used to reduce the erosion and pitting of the probe tip, so that is why these types of

reactors are actually used nowadays for the chemical engineering operation for a specific thing.

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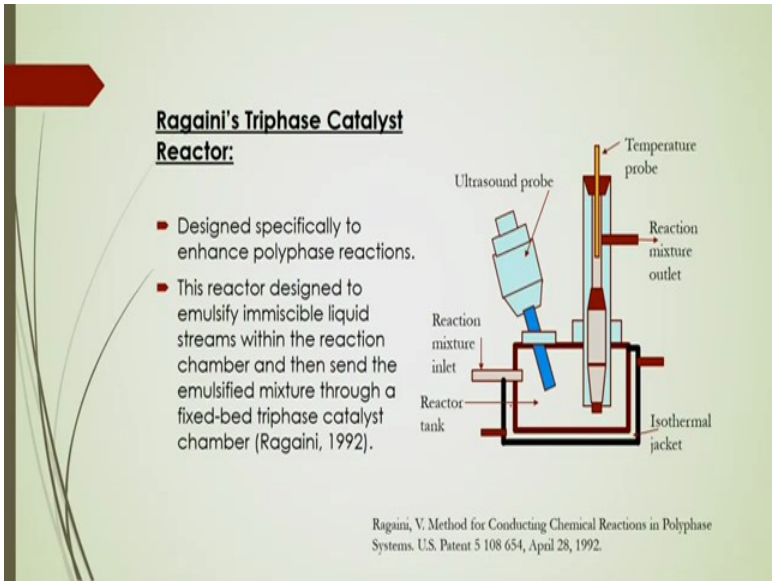

And another important it is called a Ragaini's tri-phase catalyst reactor, in this case it is designed specially to enhance poly-phase reactions. And these are actually designed to emulsify immiscible liquid streams within the reaction chamber and then it is sent to the emulsified mixture through a you know fixed bed tri-phase catalyst chamber there, so this is the mechanism based on which you can have this type of reactor configuration for that particular operation of immiscible fluid streams.

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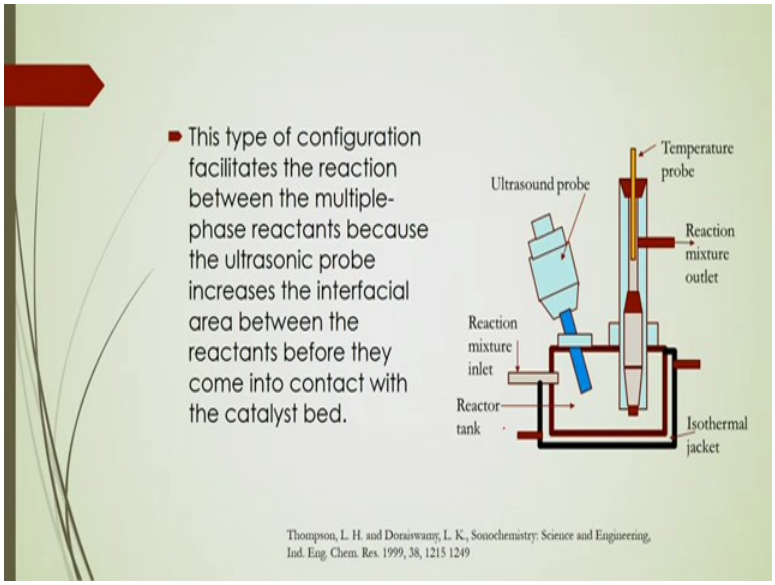

This type of configuration facilitates the reaction between the multiple phase reactants because the ultrasonic probe in that case increases the interfacial area between the reactants before you know they come into contact with the catalyst beds, so that is why for multiphase reaction gas-solid, gas-liquid, liquid-liquid, where the you know that density difference there so you can use the immiscible liquids also, liquid-liquid operation so these types of reactions are very important for those multiphase reactants.

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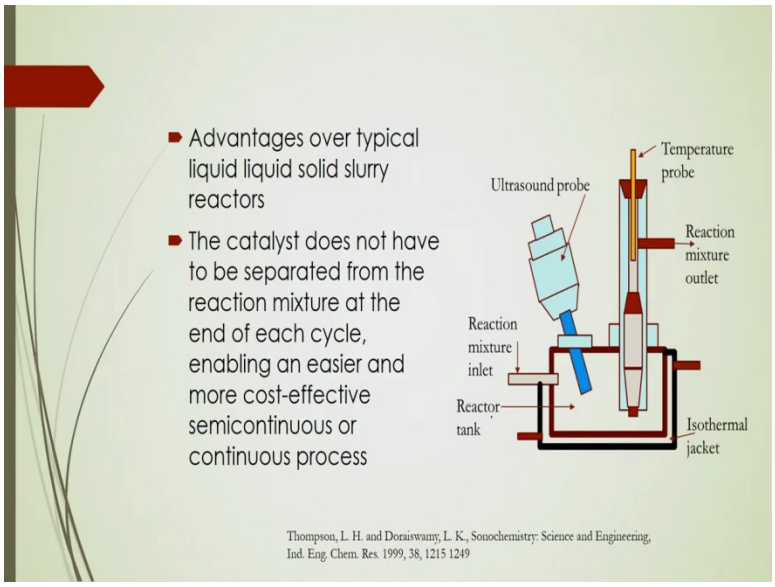

Now in this case it is advantageous over the typical liquid-liquid solid slurry reactors because in this case the catalyst does not have to be separated from the reaction mixture at the end of each cycle because in this case if you are not actually separating the catalyst, it will enable an easier and more cost-effective; semi-continuous or continuous process of chemical synthesis.

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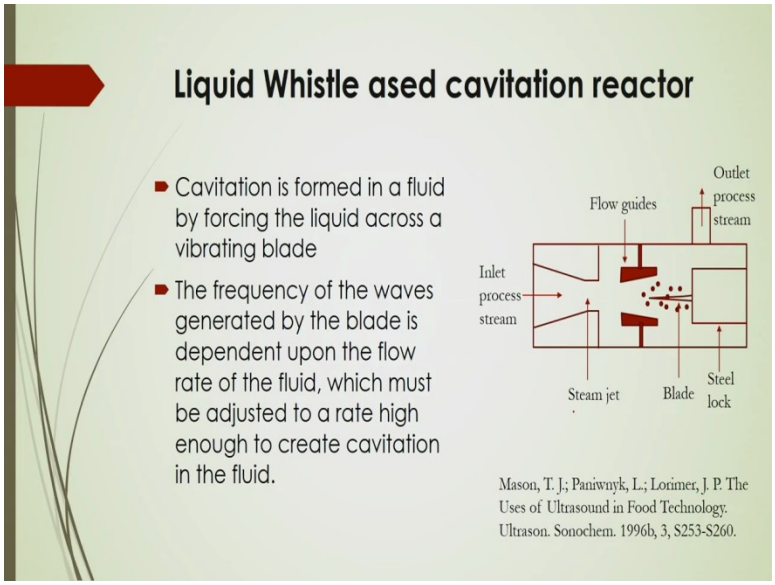

Liquid whistle-based cavitation reactor is also important reactor based on which you can produce the cavitation. In this case the cavities formed in the fluid by forcing the liquid across a vibrating blade here. This is one blade as shown in the figure so this vibrating blade will you know that produce that cavity. In this case the frequency of the waves of the blade that is generated dependent upon the flow rate of the fluid here as shown in figure in the schematic diagram which must be adjusted to a rate that is high enough to create the cavitation in the fluid there.

So this is also reported by Mason et al. in 1996 therein you know that ultrasound in food technology this is being used for this particular you know cavitation operation where the cavity is formed based on this liquid whistle just by vibrating the blade.

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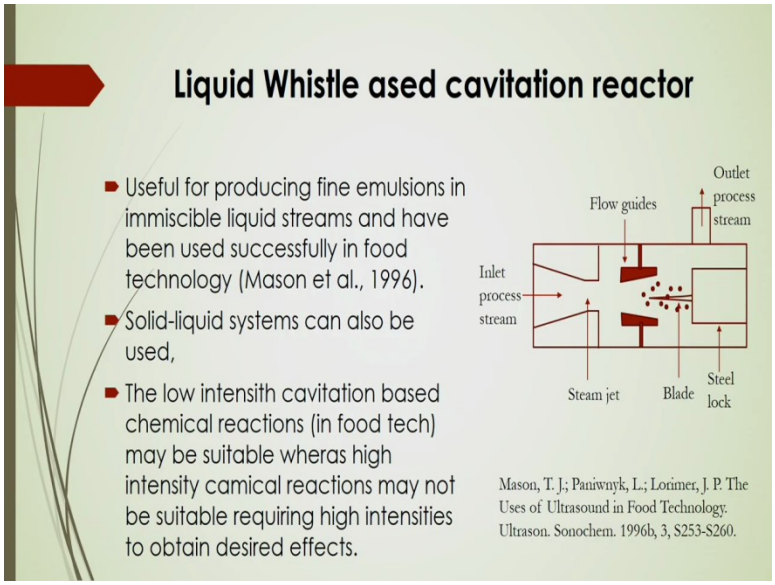

Now, in this case producing fine emulsions is very important in case of immiscible liquid streams and have been used successfully in food technology. Solid-liquid systems can also be used, the low intensity cavitation-based chemical reactions it is important in food Tech, maybe suitable, whereas high-intensity chemical reactions may not be suitable requiring high intensities to obtain desired effect there.

So this is to be noted down that whenever you are using high-intensity you know chemical, perform high-intensity chemical reactions there, this may not be useful this type of liquid whistle cavitation reactor.

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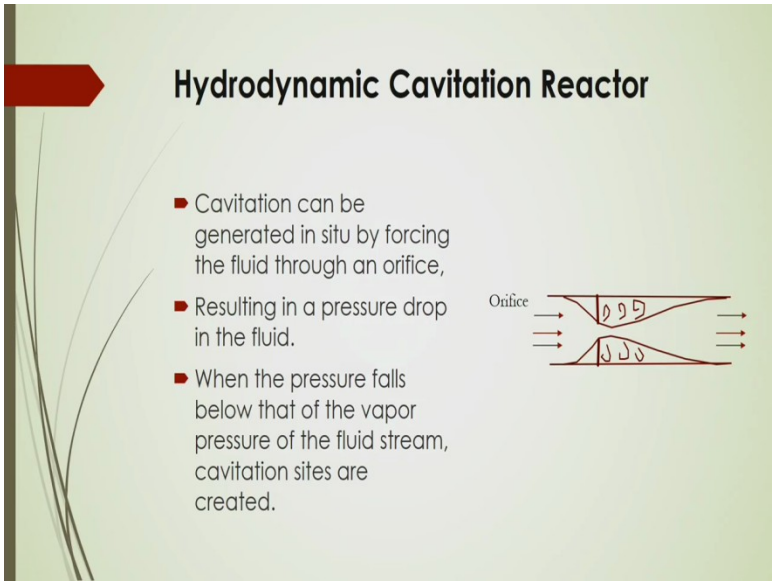

Now, another important configuration that is called the reactor which is actually developed based on hydrodynamic mechanism. In this case, cavitation can be generated in situ by forcing the liquid through the orifice or some other mechanism, some other geometry also, which will result in a pressure drop in the fluid. When the pressure will falls below that of the vapour pressure of the fluid stream then cavity will be forming that already discussed in the previous lecture the mechanism of formation of cavity based on this orifice or by the geometry of obstruction in the liquid medium.

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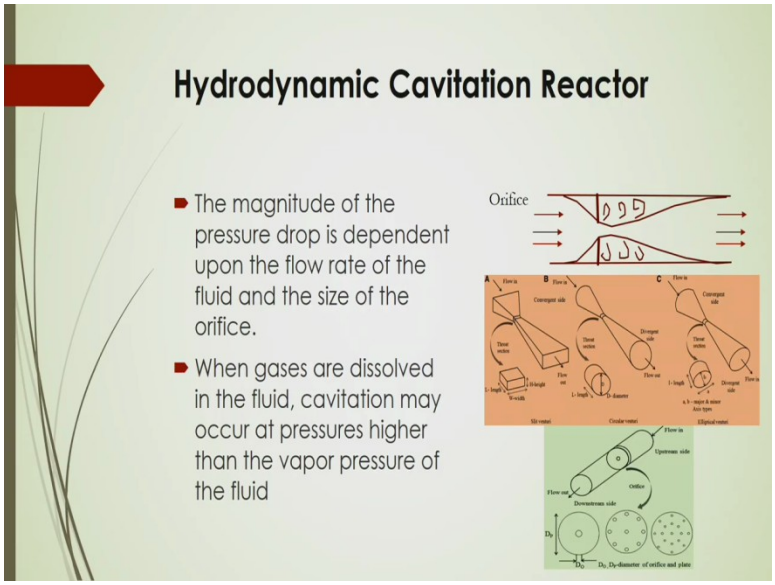

Now, there are several you know that configuration of this orifice based or hydrodynamic-based cavitation reactors as shown here in the figure. So in this case the magnitude of the pressure drop that will actually depend on the flow rate of the fluid and size of the orifice. So when if you are considering that gases are dissolved with the fluid then cavitation may occur at pressures higher than the vapour pressure of the fluid.

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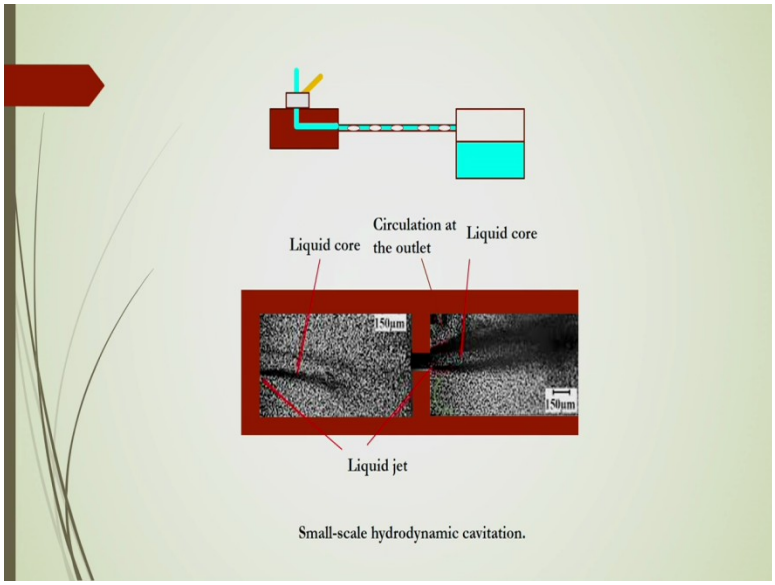

Other you know configuration is called that small-scale hydrodynamic cavitation, in that case in micro channel micron size you know that cavity may be formed just by you know high-pressure or high energy supplied through the micro channel there. In that case the cavity will be more you know that finer even micron size cavity you can produce. Even you know that sometimes high shear stress also can be used for generation of cavity there.

Other type of cavity may be formed like you know that plunging a liquid jet systems also, there where liquid jet will be plunging in a pool of liquid there and in that case the breaking of the surface of the liquid and entering the gaseous medium into the pool of the liquid and formation of the bubbles. It is called plunging jet you know that cavitation reactor there.

So we are having that different type of you know reactor based on the mechanism of sonication, based on the mechanism of you know fluid force, so even other type of you know small-scale, even the plunging liquid jet. So we have discussed here in this lecture there are different configurations of this ultrasonic reactor, even fluid flow based even you know that geometric obstruction based you know that cavitation reactor are there.

So I think it will be very helpful for understanding of the reactor based on that mechanism of you know formation of the cavitation and you can design the reactor based on this mechanism either by fluid flow or by sonication. And you can apply this type of cavitation process, then cavitation reactor for the particular you know chemical engineering operation for your process intensification.

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I will suggest you to go further for better understanding even more information for these type of books you can follow is given in the slides. So thank you for giving the attention for this lecture, okay next lecture we will discuss again more about you know cavitation process there, thank you.