Chemical Process Intensification
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Module 8: Interfacial area based PI
Lecture 8.2: Ejector Induced downflow system for PI

Welcome to massive open online course on Chemical Process Intensification. So we were discussing something regarding process intensification by interfacial area under the module 8 and in this lecture we will try to discuss more about that interfacial area based process intensification and it will be regarding the ejector induced downflow system for process intensification.

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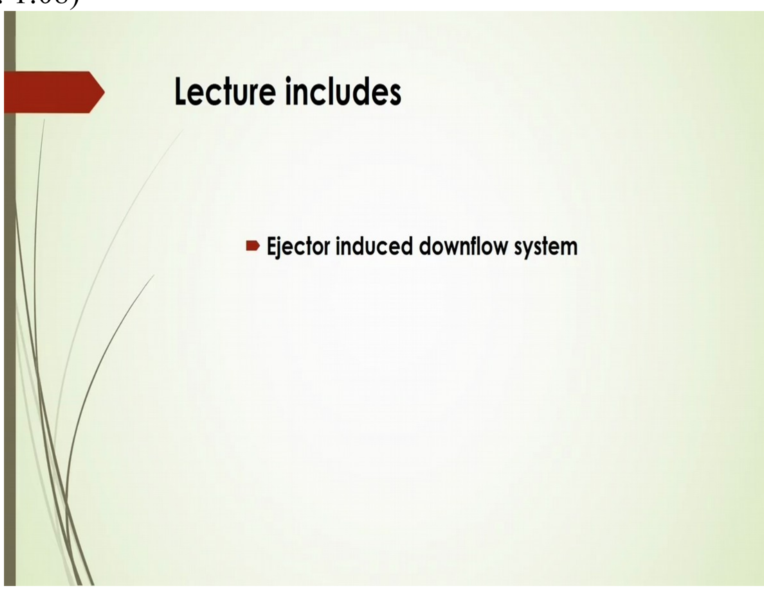

Now in this lecture, we will discuss that how to configure the downflow system for the process intensification and for that, how ejector is being used actually for creating that cavities or bubbles or droplets and also how it can actually suck the gas to disperse it through the pool of the liquid and also how create that surface area to intensify the mass transfer or any other chemical engineering processes. And in this case, a very interesting point that ejector is the one important characteristic factor by which you can use the gas to disperse in the liquid so that it will be dispersed in such a way that higher mixing will be parallely happened in the system and so that that due to that interfacial mixing, that intensification of the process can be obtained.

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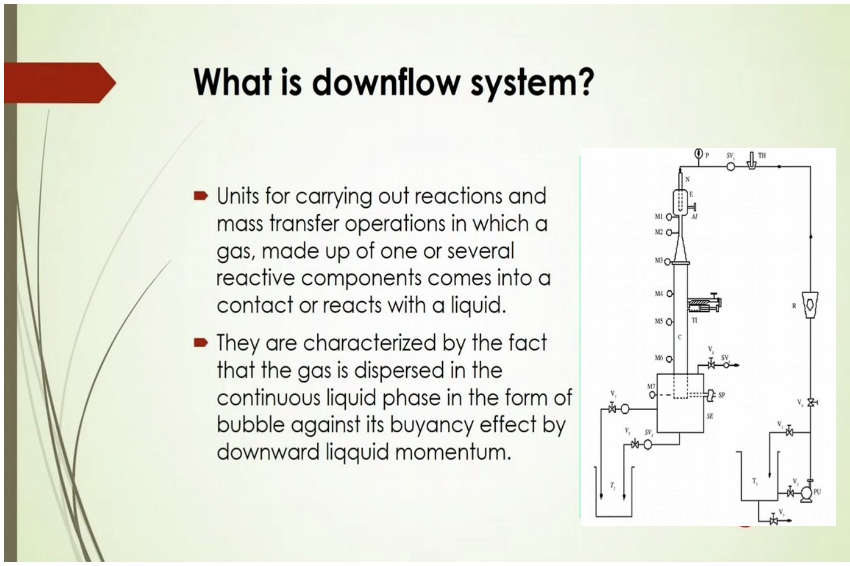

Now we will systematically discuss regarding that first of all that whenever you are using this electoral system, that can be used in up flow, downflow, even you know that horizontal flow system to perform any chemical engineering processes. So 1st of all, here we will try to discuss the process intensification by the downflow system. What is that downflow system? Now you will see that this slide we have given here, one picture of downflow system where you will see that this is the unit that carrying out reactions and mass transfer operations in which you can get the gas which will be made of one or several reactive components, that come into a contact of reactants with a liquid. In this case, you will see that it can be characterized by the fact that the gas is dispersed in the continuous liquid phase in the form of bubble against its buoyancy effect by downward liquid momentum.

What does it mean? Actually what I wanted to say here that you will see if we make a unit like this here, this part is ejector system and this part is that contactor and this part is a separator system. So if we make a downflow system in such a way that the liquid will be flowing downward system through this unit and during the downward movement that liquid will be made jet in such a way that it will be passing through a you know that suction chamber.

So when a liquid jet will be coming out from this storage tank by a pump through the rotameter at a certain velocity, whenever it will be coming through this you know that nozzle and this nozzle will give you that jet velocity and whenever this jet velocity will come through this suction chamber where one inlet will be there in the suction chamber through which gas or atmospheric air can come whenever liquid jet will be passing through this suction chamber.

And it will come through this ejector system where the pressure recovery will be done when pressure will be produced during this jet. So in this case, the jet will be automatically suck the gas which will be carrying along with that liquid jet through this ejector, that is here one throat section, here diverging section, through this ejector unit will be coming out and it will be if it is plunging in a pool of liquid in the contactor. You will see there will be a formation of bubbles, that means gas bubbles, this is actually suction by that liquid jet and then that gas bubbles will be carrying downward by the downward liquid movement.

And this movement of gas bubbles whenever it will be coming downward, it will have that more residence time. Even at this location, there will be intense mixing of that gas liquid there. So based on this concept, there is a process intensification by having more residence time where the you know that some physical operations require more you know that contact times, residence time of the gas bubbles there. So in this way, you can use this downflow system.

So whenever this liquid gas will be coming out along with that carrying that gas bubbles by this liquid movement downwardly and then it will be separating in a separator and from this separator gas will be coming out through these sections. So this way, the gas is coming in this sections and gas is coming out at this section where liquid will be coming into the unit as a liquid jet and which will be that plunging into the pool of the liquid in the contactor as a dispersed phase of bubbles will be formed and it will be coming downward through this downward liquid movement.

So this is the characteristics of the downflow system. So we can define this downflow system in such a way that the one unit which will be carrying out reactions and mass transfer operations in which a gas that will be made of one or several reactive components, that will comes into contact or react with the liquid. And they are characterized by the fact that the gas will be dispersed in the continuous liquid phase in the form of a dispersed phase of bubbles against is buoyancy effect so that it can get the more residence time there.

And in this case you can produce more finer bubbles also. Instead of gas if you use some you know that secondary fluid as the some other immiscible liquid like kerosene, paraffin or other liquids which will be immiscible with the water, then you can produce that droplet of that immiscible liquid and that may also go downward by this liquid movement. And that droplet may be useful for the extraction of the unwanted material in the liquid or water. So that also can be applied in this downflow system. So this is the concept of this downflow system.

Now how to dispose that gas downwardly in the liquid that we have already discussed, that there will be some entrainment of the gas whenever liquid jet will be plunging into the pool of the liquid in the column. So by entrainment, entraining the gas by the downward liquid jet, this you know downwardly liquid will disperse the gas as a dispersed phase of bubbles. And in this case, that sucking the gas by the liquid jet is happened through the ejector system and then it is plugging into the pool of the liquid.

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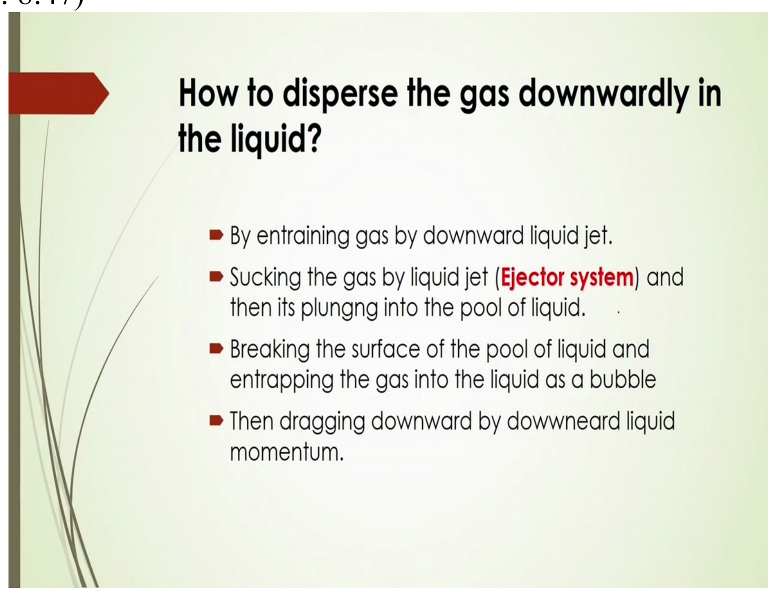

After that, you will see whenever liquid jet will be you know that plunging into the pool of the liquid, it will break the bubbles into a finer bubbles after entraining into the pool of the liquid due to the high you know that turbulence and also high mixing there. So breaking the surface of the pool of the liquid and entrapping the gas into the liquid as a bubble happened in this you know that contactor system after ejector system. And then what happened that whenever bubbles will be forming or droplet will be forming in that intense mixing zone by entraining of that gas or entrapping of the gas by entrainment mechanism, then it will be dragging downward by the downward liquid movement there.

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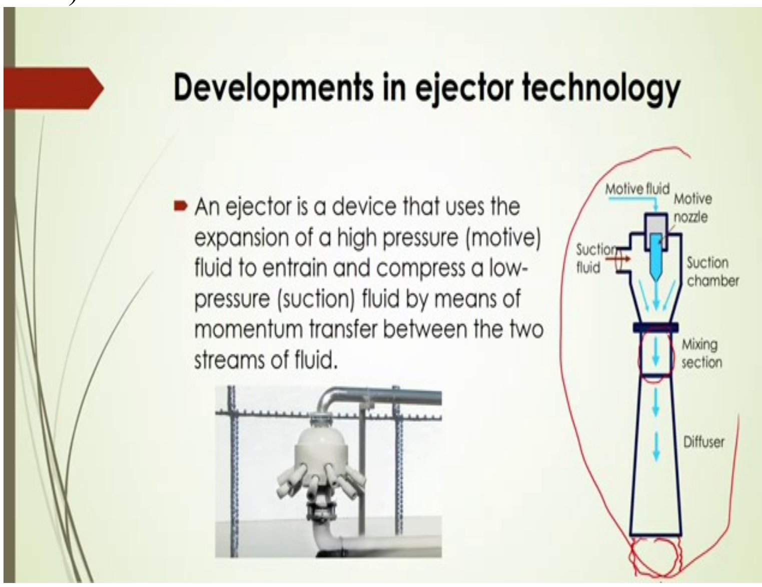

So in this case the ejector technology is the most important driving force for getting the process intensification in this downward system or the technology based on that ejector system. So what is that ejector? We can define that ejector is an device that uses the expansion of a high-pressure that is created by the fluid to entrain and also compress a low-pressure that is suction there. Fluid by means of momentum transfer between the two streams of the fluid.

So here in this figure it is shown that you will see there will be a two fluid, one fluid would be motive fluid and that fluid will be you know act as a fluid jet and it will be passing through a nozzle here shown in the figure and whenever it will be coming out through the nozzle, a jet, liquid jet will be produced and that liquid jet will be coming downward through a section that is called suction chamber. Now this suction chamber whenever this liquid jet will pass through this suction chamber, there will be a dragging of the liquid or sucking of the fluid, sucking of the gas that is maybe different types of gas or maybe you know that directly atmospheric gas, that will be sucked by this liquid jet and it will be coming through this you know that mixing section here at this location.

And after that, it will go through the diverging section. You will see there in this case there will be high pressure creation and this diverse section, there will be a low-pressure creation. So in this case here whenever the liquid will be sucking gas, it will come out through the liquid and it will be entraining in the contactor later on there. In this case, in this contactor, there will be a pool of liquid where this liquid jet will be plunging and this sucking gas will be entrapped in the liquid. So this can be used you know that several chemical engineering operations there.

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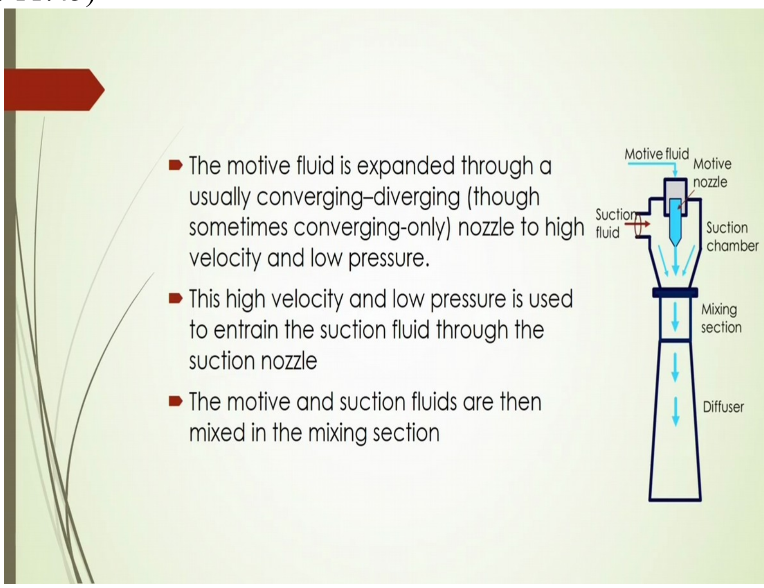

So and this motive fluid is expanded through a usually converging diverging that is through sometimes converging only also, nozzle to high velocity and low-pressure. And high you know that velocity and the low-pressure is used to entrain that suction fluid through the suction nozzle. And the motive and the suction fluids are then mixed in the mixing section. And also you will see that high-speed mixed flow is then decelerated in the diffuser and static pressure is recovered that is resulting in a pressure increase provided to the suction stream across the ejector.

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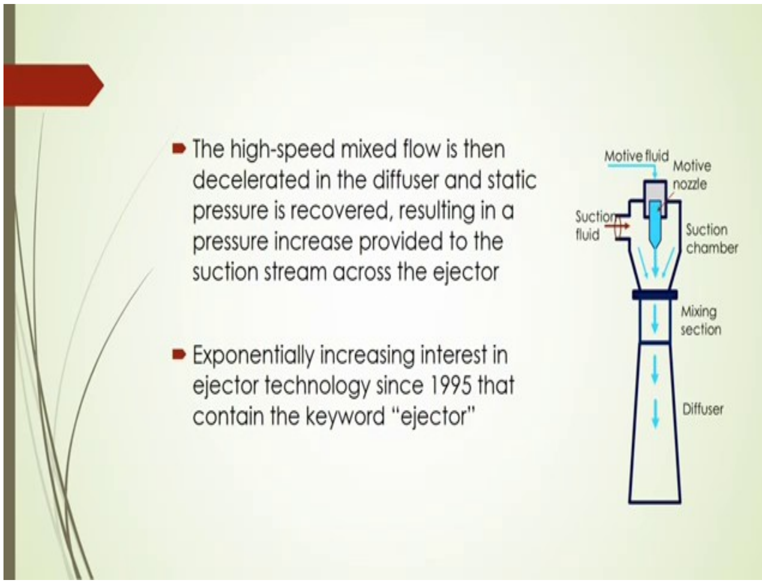

And in this case, you will see exponential increase in the interest in the ejector technology because of this mechanism for the formation of the fine bubbles or gas that is entrained and dragging downward through the liquid medium by that downward liquid momentum and also getting the advantage of more surface area as well as more residence time. So that is why, exponential increase in this interest in the ejector technology since 1995 that contains the keyword 'ejector'.

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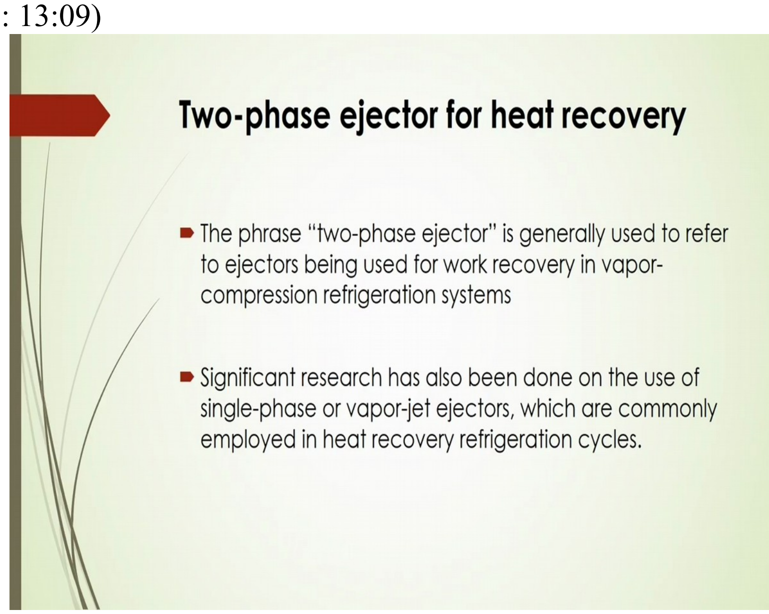

Now there are several different types of ejector systems, mainly two-phase ejector for heat recovery is used in you know that compression refrigeration system there, vapor compression refrigeration system there. So in that case the two-phase ejector is generally used to refer to ejectors being used for work recovery in the the regeneration system. In that case, significant research has been done on the use of single phase or vapor jet ejector system which are commonly employed in heat recovery refrigeration cycle.

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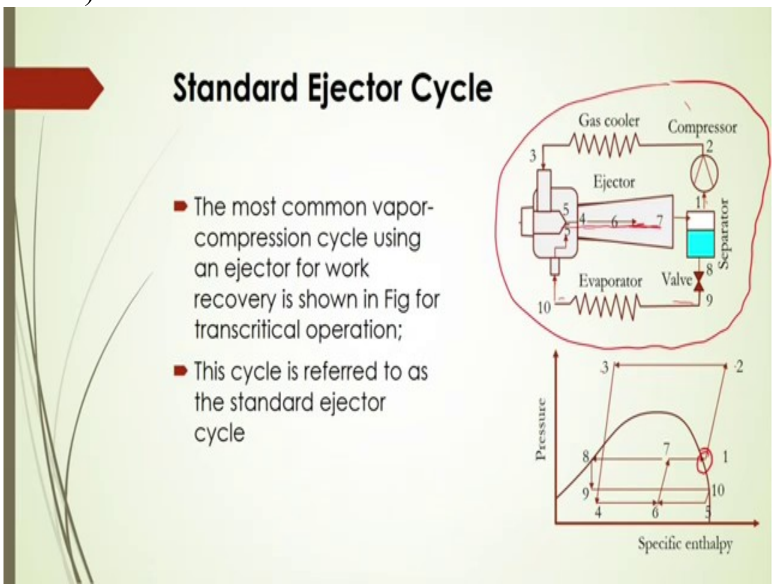

And you know that what is that standard ejector cycle? In this case the most common vapor compression cycle that used this ejector for the work recovery is shown in the figure for the trans-critical operation there. And this critical why you know that cycle is referred to as that standard ejector cycle there. So here in the figure it is shown that here see this is the ejector system and this, through this ejector system that gas is coming through this ejector and that through ejector and as a jet and then it will be that separated in the separator and then that by compressor this that compressor this gas will be supplied here to this and here again that from the separator liquid will be passing through that evaporator section for controlling the temperature and it passes through this you know that ejector system.

And in this way, that these continuous cycles will be applied there where this pressure how it will be changing at different locations, that is given in this with respect to specific enthalpy. At this location 1 here you will see this pressure will be there and then 1, 2, 3, here 4, 5 and then you know that 6, 7, 8, 9 and then 10. According to this cycle, that ejector compressor system, even evaporator system, then how this pressure is changing with respect to different unit whenever ejector system is being used for this you know that vapor compression for refrigerating system there. So this is one important application of the ejector system there.

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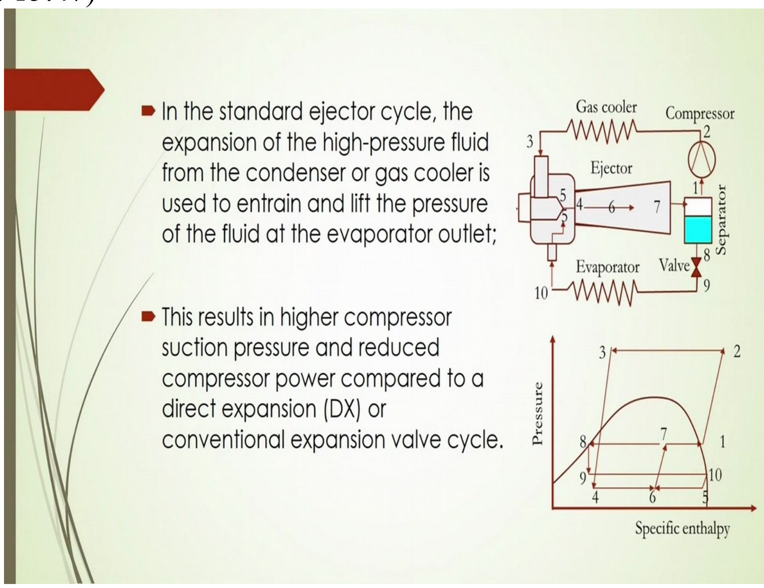

And in this case, the standard ejector cycle, the expansion of the high-pressure fluid from the condenser or gas cooler is used to entrain and lift the pressure of the fluid at the evaporator outlet. And then this result will give you the higher compressor suction pressure and reduced compressor power that compared to a direct expansion or conventional expansion valve cycle there.

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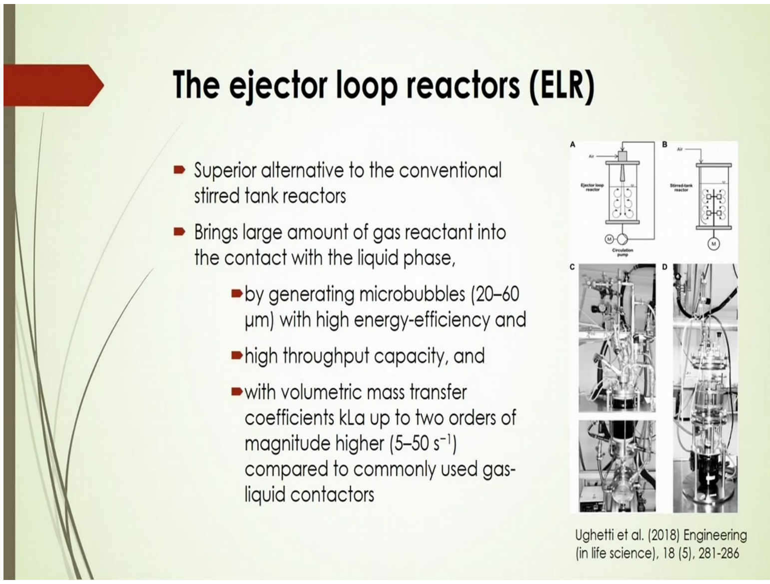

Now another important application of the ejector system in the chemical engineering or even biochemical industry, it is called that ejector loop reactor, ELR. In this case it is a superior alternative to the conventional stirred tank reactors. We will see that stirred tank reactors here you are using that mechanical device to start their fluid in the reactor. Whereas in the ejector system, that advantage is that that you can have the advantage of producing high shear inside the reactor and mixing high mixing inside the reactor as well as you the formation of cavity and that formation of more finer bubbles and more interfacial area there.

So that is why, it will be that advantageous relative to the conventional stirred tank reactors and in this case, this type of reactors being large amount of gas reactant into the contact with the liquid phase and in this case, you can produce the more finer bubbles that is called microbubbles of around 20 to 60 micrometer which give you the high efficiency, high energy efficiency, production of that interfacial area.

And in this case, high throughput capacity also can be done for the chemical engineering operation or even bio-chemical industry and also in this case this application of this ejector loop reactors will be advantageous because of getting the volumetric mass transfer coefficient relatively higher, in this case k_La up to two orders of the magnitude higher of 5 to 50 second inverse compared to the commonly used gas liquid contactors are there. And it is reported by that Ughetti et al. in 2018 in Engineering Journal in life science sections there. So I think it is very interesting that ejector loop reactors, how ejectors is being used to produce that finer bubbles, more interfacial area, more mass transfer, more that volumetric mass transfer coefficient so that you can get higher order of you know that process efficiency in this ejector loop reactors.

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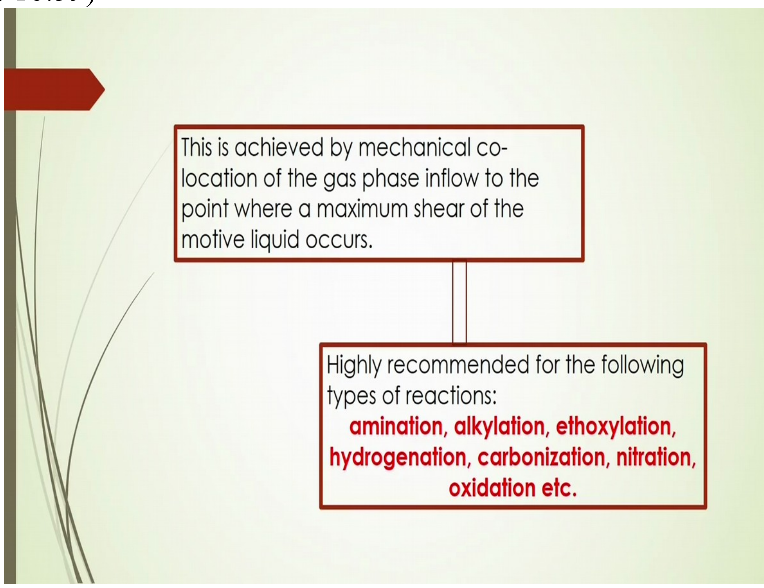

And this is achieved by mechanical you know that co-location of the gas phase inflow to the point where a maximum shear of the motive fluid occurs there and it is highly recommended for the following types of few reactors as shown in the slides like amination, alkylation, even ethoxylation, and hydrogenation, even carbonization, nitration, oxidation, et cetera, several you know chemical processes are being carried out in this ejector that loop reactor system.

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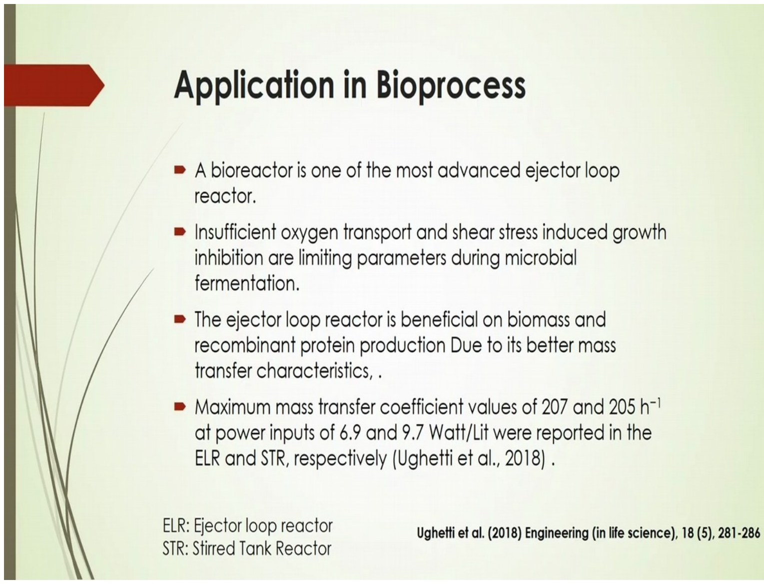

And the case of bioprocess in this case, the bioreactor can be treated as one of the most advanced ejector loop reactor. In that case, insufficient oxygen transport and shear stress induced growth inhibition are limiting parameters during the microbial fermentation process in the bioreactor. And the ejector loop reactor is beneficial on biomass and you can consider that it will be a recombinant protein production due to its better mass transfer characteristics. And also you can get the maximum mass transfer coefficient values of 207 and 205 hour inverse at power inputs of 6.9 to 9.7 Watt per liter where it is reported in ELR and STR respectively by Ughetti et al., 2018.

So we can say that this ELR system for biotechnological application, you will see for the fermentation process, you can get the maximum mass transfer coefficient relative to that you know that stirred tank reactor.

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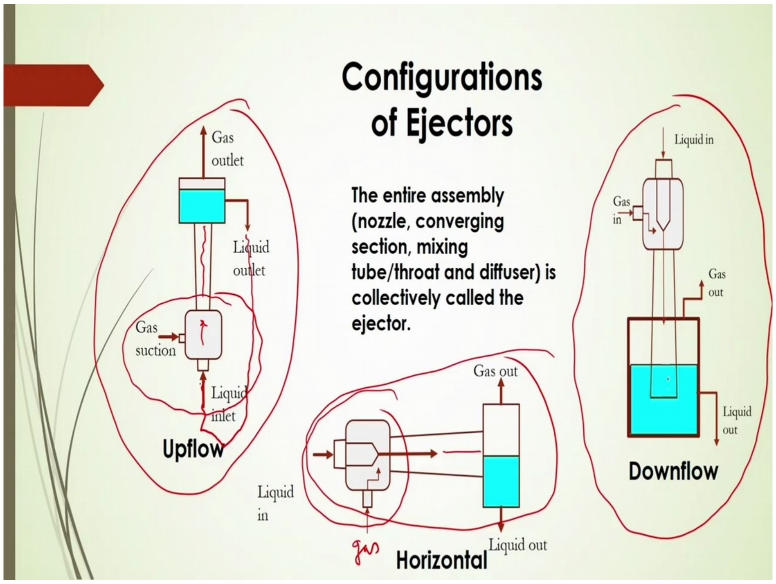

And since we are talking about the ejectors, of course there are several configurations of that ejector system. In this case you know that we are having generally upflow, downflow and horizontal systems. In the figure, it is shown that this is your that upflow systems. From the bottom of the column ejector is attached so that the gas should be sucking by that liquid jet from this you know that inlet and whenever liquid jet will be coming up and then gas will be automatically sucked by this liquid jet and then it will be dispersed in the column and then it will be separated in a separator and also you can say that the liquid will be coming out from that separator can be used again as you know that liquid inlet through this nozzle as a liquid jet.

So that continuous operation of this upflow can be possible. Even here also this horizontal system also can be done here, this the configuration of this horizontal here, in this case also this ejector systems are being used to get that liquid jet and sucking that gas from this portion here. And then it will go through that diffuser sections and then producing that finer bubbles and then it will be coming in a separator which will be separating that gas and liquid in these 2 outlet streams. And then liquid again you can use as a you know that continuous manner through this nozzle again to get it that continuous operations of that processes.

So in this case, very interesting that upflow and horizontal but in this upflow and horizontal system, you will not get that maximum you know that residence time distribution whereas in the downflow systems, you can get that maximum residence time distribution because in this case, whenever this liquid jet will be sucking gas and producing the finer bubbles, it will be going downward through this downward liquid movement and during that movement of that gas bubbles, whenever you will see that just balancing that buoyancy effects of that bubbles, it will go downward.

So at a certain operation, you will see some bubbles those who are not going upward against that its momentum, liquid momentum and or, some bubbles are not going downward because of this higher buoyancy effect. So there will be a balance of that buoyancy effects and downward liquid movement by which you can get the residence time of the bubbles in that particular location for long time. Even if you are producing more finer bubbles, it may go downward through this downward liquid momentum but if your bubbles or bubble size in such a way that the balance of this buoyancy force and its downward momentum are there, so those bubbles will be that residing on that column for a longer time.

So in this way, you can get more residence time of the gas inside the column where that slow reactions sometimes it is recommended for getting more residence time or longer time to get the more mass transfer there. So this is so, so in this way downward system here, a liquid jet will be sucking liquid and in this separator the liquid will be coming out from this portion and gas will be separated and it will be coming upward in this location. So this is the downward movement or downward configuration of the ejector system.

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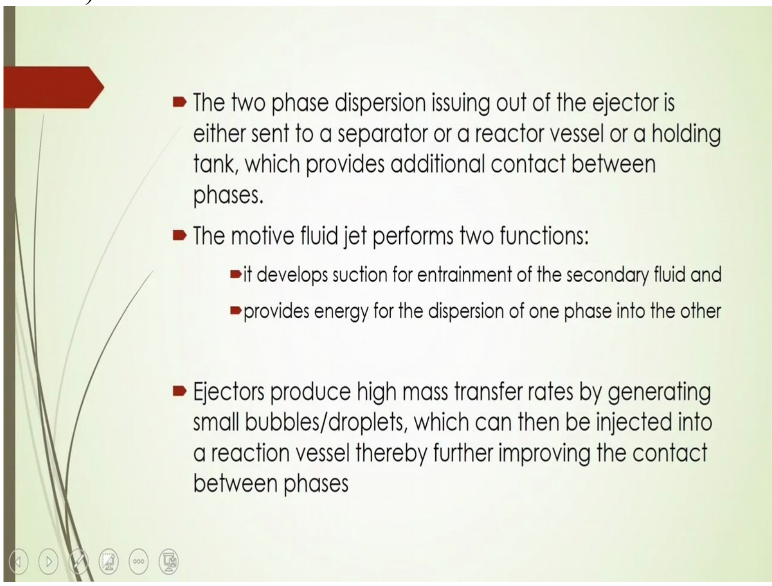

And then also you will see that the two-phase dispersion issuing out of the ejector is either sent to the separator or a reactor vessel or a holding tank which provides additional contact between the phases. So that is why, it is more important or more advantageous processes based on this you know that ejector system. And in this case, the motive fluid jet that will perform into 2 functions like you know that it develops suction for entertainment of the secondary fluid and also provides energy for the dispersion of one phase into the other. And in this case, the ejector produces high mass transfer rates by generating smaller bubbles or droplets if you are flying liquid-liquid system which can then be injected into a reaction vessel.

Thereby, further improving the contact between the phases. So in this way, that you can intensify the chemical process by ejector system.

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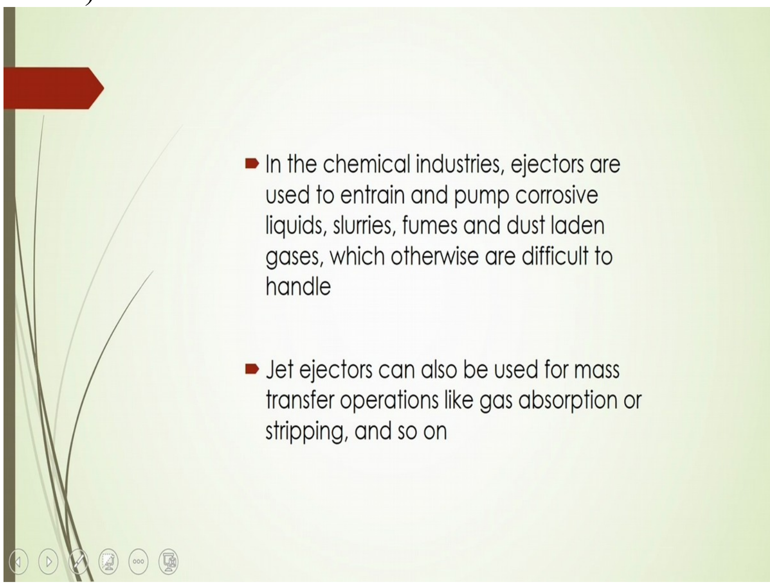

And in the chemical industries, you will see that ejectors are used to entrain and pump corrosive liquids, slurries, fumes and dust laden gases which otherwise very difficult to handle. And jet ejectors can also be used for mass transfer operations like gas absorption or stripping and also others.

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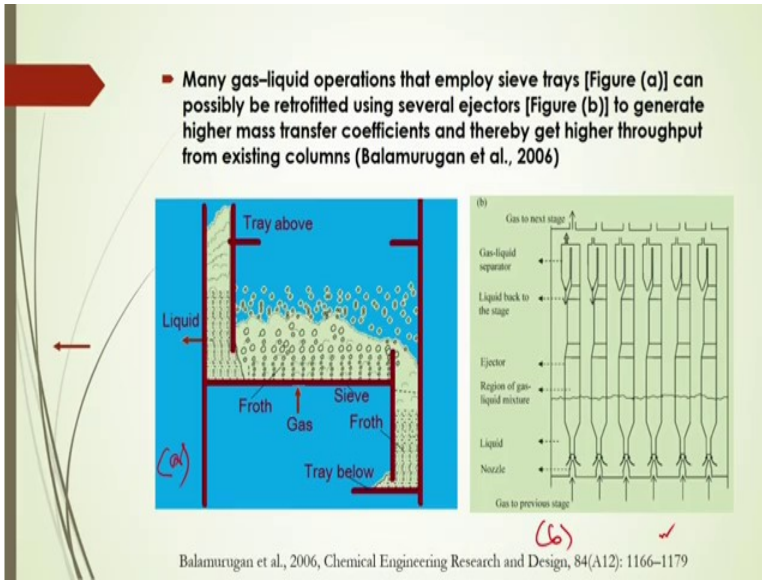

Now here you will see as per Balamurugan et al. reported in 2006 that many gas liquid operations that employ sieve trays can possibly be retrofitted using several ejector systems as shown in figure here a and you will see you can use also several ejector systems in b as shown here to generate that higher mass transfer coefficients and thereby get higher throughput from existing columns there. So this is the recommendation to get the more you know that process intensification by this ejector systems in the replacement or the retrofitting by these gas liquid operations in the distillation column or other gas liquid contact system.

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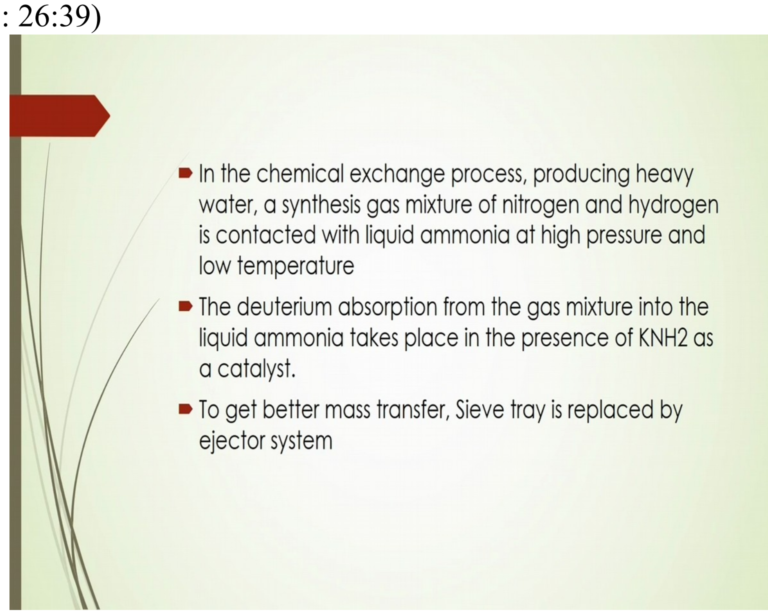

And in the chemical exchange process producing heavy water, in that case a synthesis gas mixture of nitrogen and hydrogen is actually generally come in contact with the liquid ammonia at high pressure and low temperature. And in that case the deuterium absorption from the gas mixture into the liquid ammonia that takes place in the presence of KNH2 as a catalyst there, to get better mass transfer, then this sieve tray is replaced by the ejector system. So this is one of the important application part where you can get the process intensification by this ejector systems by replacing that sieve tray gas distributor by this ejector system.

And in that case of course you have to you know that use the catalyst particles where it will not be you know that treated by this high liquid jet by ejector system. So that should be taken care for these processes. And now what are the advantages of this ejector induced co-current downflow system over the other conventional devices? In this case you will see, for this downflow system, ejector system need new compressor for the gas entertainment and higher gas resistance time you can obtain, higher contact efficiency between the phases you can get, collisions of bubbles will be very negligible. Even bubbles are finer and more uniform in size you can say, higher mixing efficiency, even you can get the large interfacial area available for the heat, mass and momentum transfer there.

So these are the some important advantages of this ejector induced co-current downflow system over other conventional devices.

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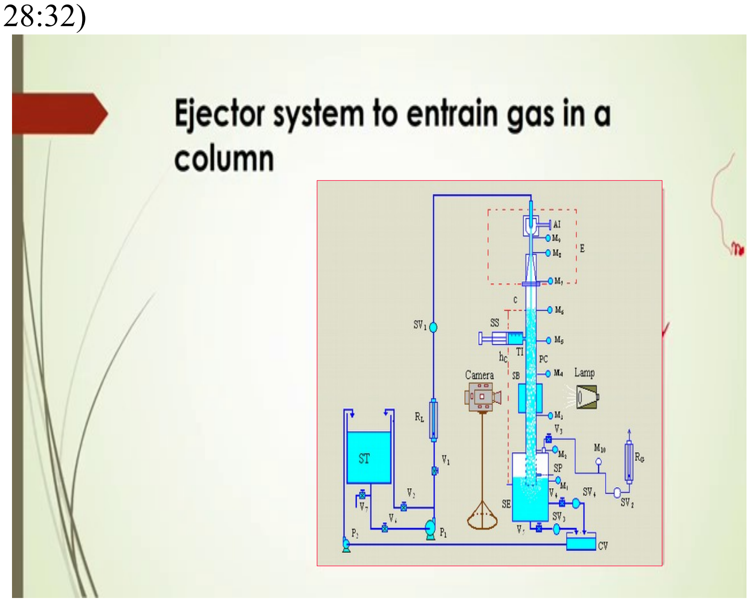

Now you see the ejector system to entrain gas in a column here as shown in figure it is shown that how the liquid jet is producing finer bubbles there. So this is the storage tank. From this storage tank, this liquid will be allowed to pass through this rotameter and this rotameter will give you the measurement of the you know that liquid flow rate and also after that, this liquid will be coming through this nozzle and this nozzle will produce that liquid jet and will come through this suction chamber. In the suction chamber air will be automatically sucked by that liquid jet and then it will pass through this ejector system and where in this ejector system that the whenever liquid jet will be coming in contact with the pool of the liquid in this section, then it will produce that finer bubbles and those bubbles at this location, there will be intermixing and then due to the downward movement, it will go downward, it will go downward and it will come downward up to that separator.

And in this case the contactor will be extended in the separator up to a certain length because here to get it that liquid pool here, above this contactor so that the pressure will be generated inside the separator and due to that pressure generation, this liquid will be, go up into the column by that high pressure there.

And through this outlet that gas whatever it will be separated in this separator from this liquid it will be coming out there. So this is the process by which you can produce that finer bubbles and get the gas liquid contact by intense mixing and the more interfacial area by this ejector system. Now there will be a certain operational flow regime map so that you can get this stable operation for this.

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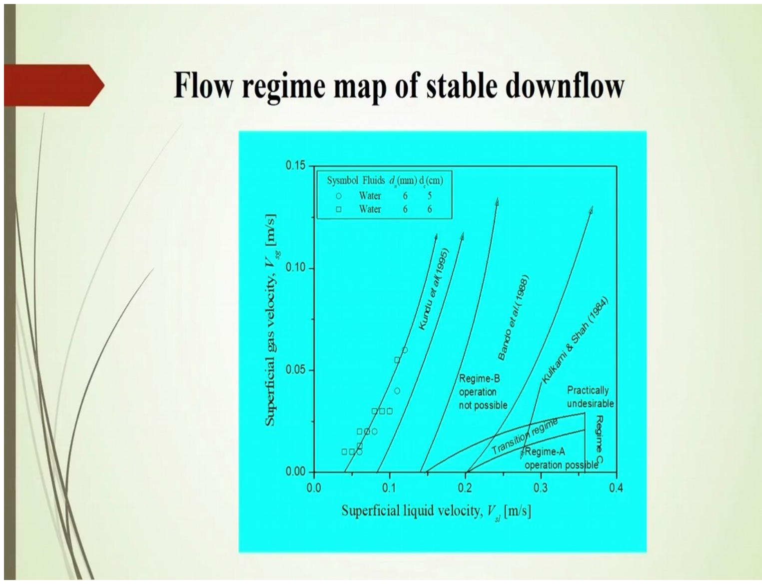

So for this downflow system to get this stable operation, you have to maintain this you know that certain superficial liquid velocity and superficial gas velocity, you can get from this flow regime map at which superficial liquid velocity and superficial gas velocity you can obtain that the stable operation of the downflow system to get more finer bubbles and more residence time for this air water system. And what are the mechanism of that gas entertainment by you know that liquid jet whenever that it will be plunging into the pool of the liquid?

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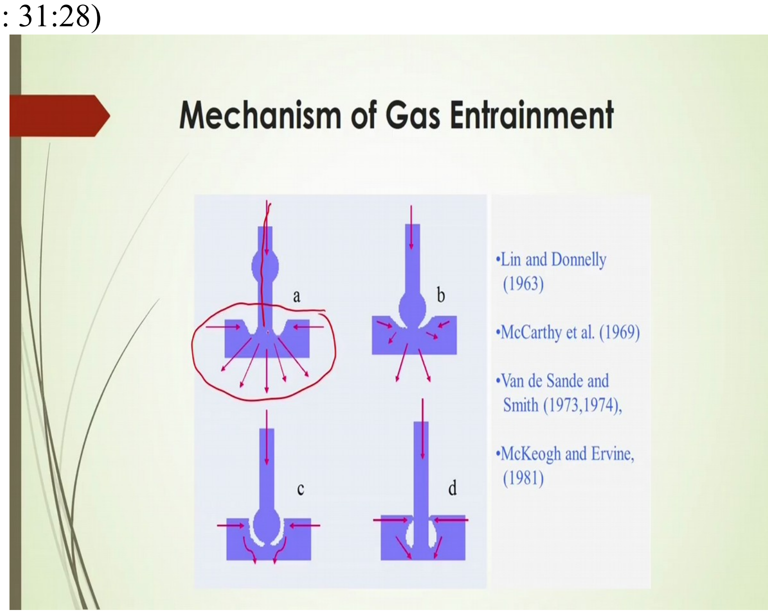

So whenever liquid jet is coming into the pool of the liquid, you will see there will be thrust of the liquid surface and because of that downward movement of that thrust, force applied by this liquid jet on the pool of the liquid and then you will see that force will break that surface of the liquid and after you know that breaking of this pool, this liquid jet, thus entraining that gas in this location and finally it will be entrapped into the pool of the liquid and in this way you will see that there will be a entrainment of the gas is happened in the liquid.

And then this mechanism of course whenever you are applying that liquid jet, you have to maintain a certain liquid velocity so that you can get this minimum condition for getting this entrainment of the gas. What is that minimum condition?

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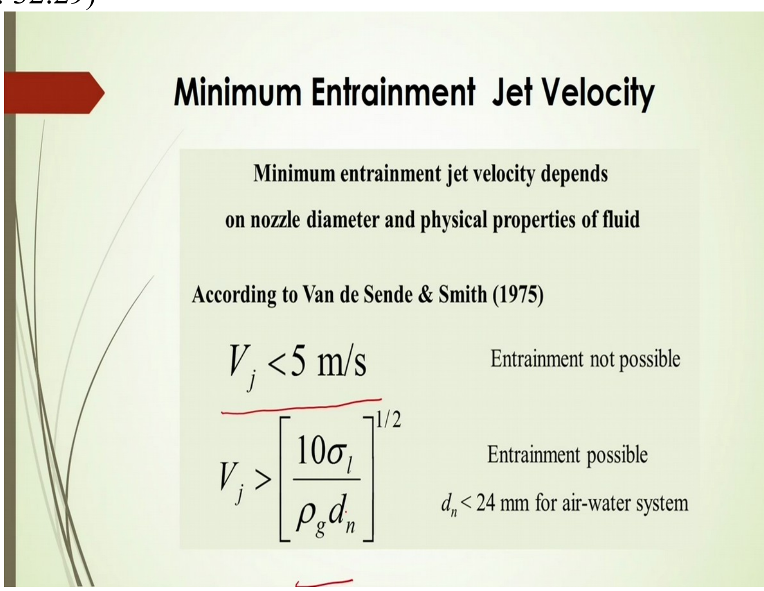

So minimum entrainment jet velocity, that depends on the nozzle diameter and physical properties of the fluid. And according to Van de Sende and Smith, you can say that this jet velocity should be less than 5 meter per second. If it is less than 5 meter per second, then entrainment will not happen. So jet velocity should be greater than 5 meter per second and also for this you know if you are applying this you know that jet velocity for you know that surfactant solution, in that case this $V_j > \left[\frac{10\sigma_l}{\rho_g d_n}\right]^{1/2}$. So for the system where surface tension if you know and the gas density knows, and then you can calculate what should be the minimum jet velocity for the entrainment of the gas.

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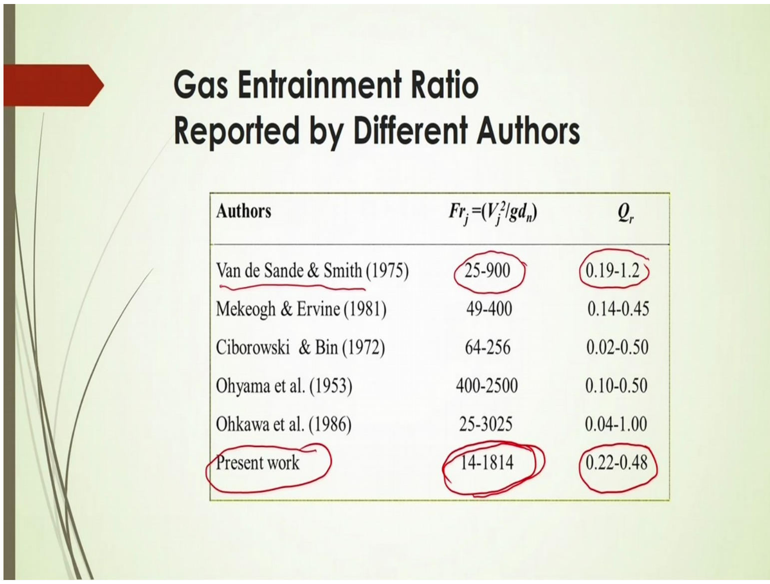

And based on that entrainment ratio, you know that different authors, they have done several investigations for that gas liquid contact based on the energy you know how entrainment is happened based on that energy supplied there. So you know that several investigator like this Van de Sende and Smith, they got that entrainment, gas entrainment ratio that is Q_r that is Q_g by Q_l will be 0.19 to 1.2 if its jet sprout number is you know that 25 to 900.

You know that in our system the present work in this ejector system downflow system, we can get this Q_r ratio as 0.2 to 0.48 based on this sprout number of 14 to 1814 there within this range. So relatively better you know downflow system giving the better operational mode to get the process intensification for the chemical engineering process to more gas entrant into the liquid and gas, get more you know that gas liquid contact and more interfacial area.

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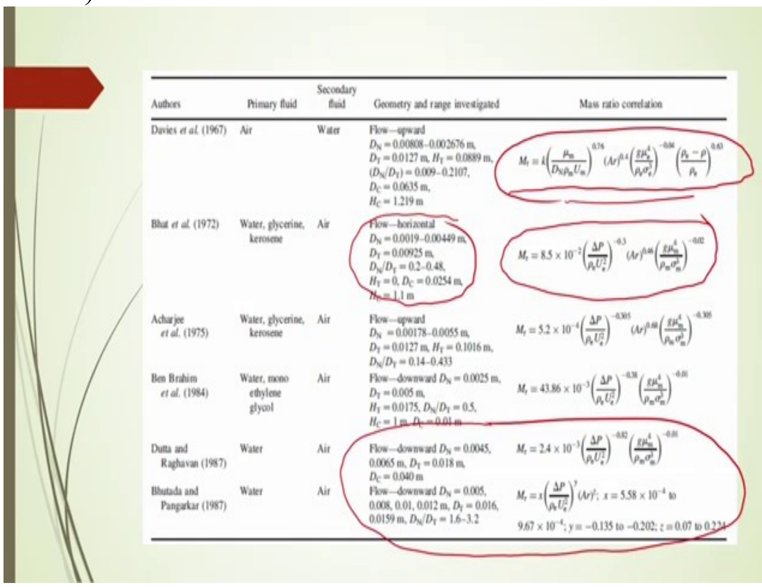

Authors	Primary fluid	Secondary fluid	Geometry and range investigated	Mass ratio correlation
Davies *et al.* (1967)	Air	Water	Flow—upward $D_N = 0.00808–0.002676$ m, $D_T = 0.0127$ m, $H_T = 0.0889$ m, $(D_N/D_T) = 0.009–0.2107$, $D_C = 0.0635$ m, $H_C = 1.219$ m	$M_r = k\left(\frac{\mu_m}{D_N \rho_m U_m}\right)^{0.76} (Ar)^{0.4} \left(\frac{g\mu_e^4}{\rho_e \sigma_e^3}\right)^{-0.04} \left(\frac{\rho_e - \rho}{\rho_e}\right)^{0.63}$
Bhat *et al.* (1972)	Water, glycerine, kerosene	Air	Flow—horizontal $D_N = 0.0019–0.00449$ m, $D_T = 0.00925$ m, $D_N/D_T = 0.2–0.48$, $H_T = 0$, $D_C = 0.0254$ m, $H_C = 1.1$ m	$M_r = 8.5 \times 10^{-2}\left(\frac{\Delta P}{\rho_e U_e^2}\right)^{-0.3} (Ar)^{0.46} \left(\frac{g\mu_m^4}{\rho_m \sigma_m^3}\right)^{-0.02}$
Acharjee *et al.* (1975)	Water, glycerine, kerosene	Air	Flow—upward $D_N = 0.00178–0.0055$ m, $D_T = 0.0127$ m, $H_T = 0.1016$ m, $D_N/D_T = 0.14–0.433$	$M_r = 5.2 \times 10^{-4}\left(\frac{\Delta P}{\rho_e U_e^2}\right)^{-0.305} (Ar)^{0.68} \left(\frac{g\mu_m^4}{\rho_m \sigma_m^3}\right)^{-0.305}$
Ben Brahim *et al.* (1984)	Water, mono ethylene glycol	Air	Flow—downward $D_N = 0.0025$ m, $D_T = 0.005$ m, $H_T = 0.0175$, $D_N/D_T = 0.5$, $H_C = 1$ m, $D_C = 0.01$ m	$M_r = 43.86 \times 10^{-3}\left(\frac{\Delta P}{\rho_e U_e^2}\right)^{-0.38} \left(\frac{g\mu_m^4}{\rho_m \sigma_m^3}\right)^{-0.01}$
Dutta and Raghavan (1987)	Water	Air	Flow—downward $D_N = 0.0045$, 0.0065 m, $D_T = 0.018$ m, $D_C = 0.040$ m	$M_r = 2.4 \times 10^{-3}\left(\frac{\Delta P}{\rho_e U_e^2}\right)^{-0.82} \left(\frac{g\mu_m^4}{\rho_m \sigma_m^3}\right)^{-0.01}$
Bhutada and Pangarkar (1987)	Water	Air	Flow—downward $D_N = 0.005$, 0.008, 0.01, 0.012 m, $D_T = 0.016$, 0.0159 m, $D_N/D_T = 1.6–3.2$	$M_r = x\left(\frac{\Delta P}{\rho_e U_e^2}\right)^{y} (Ar)^{z}$; $x = 5.58 \times 10^{-4}$ to 9.67×10^{-4}; $y = -0.135$ to -0.202; $z = 0.07$ to 0.224

There are several you know that correlations are proposed by different investigators based on that upward, downward, even horizontal movement system of this ejector system and in this case, some you know that whenever flow is upward, then how this mass flow rate of this gas entrained in the system, that can be calculated from these correlations? Whereas for horizontal system how gas is entrained and what will be the amount of gases entrained in the horizontal movement? You can calculate from this correlation and also for the downward system, that you can calculate that gas entrainment amount by this correlation.

So remember this whenever you are applying this downflow system, what are the different parameters that affect that entrainment characteristics there? One is geometric configurations like ejector diffuser section flow section, even you can say that nozzle, that is nozzle diameter, that is one of the important because smaller nozzle will give you the higher jet velocity, that means more kinetic energy production and based on which you can get the more mixing and more production of more entrainment of the gas and more finer bubbles production.

And you can also say that there will be that operating parameters like physical properties of the system there. If you know use the higher viscous fluid, in that case you may get the lower entrainment of the gas. Even lower entrainment of the fluid also. Suppose if you are willing to get the entrainment of immiscible liquid like kerosene in a you know that high viscous CMC solution, carboxymethyl cellulose, so in that case you will see that kerosene entrainment will be very difficult because the viscosity of that CMC solution will be more higher.

So in that case the entrainment of that kerosene will be more difficult, more resistance will come by that liquid, so their contact of that kerosene and the carboxymethyl cellulose, high viscous liquid will be that less, in that case mass transfer will be very less. Even more interfacial area will not be produced whenever you are using high viscous liquid. Also there energy supplied will be requiring more. In that case you have to consume more energy to get that more entrainment. So that is why, you can say that this depends on that entrainment characteristics, it depends on the physical properties of the system as well as the geometry of the system.

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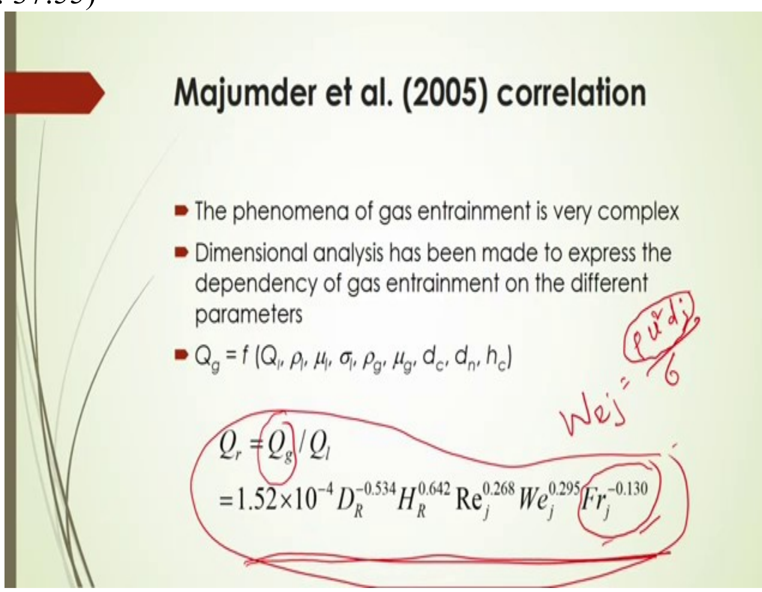

Now there are several correlations also available that I have shown in the table. In the downflow systems, we have developed one correlations based on the different operating parameters and in that case, it is very difficult to get that one you know that mechanistic model to interpret the entrainment characteristics of the gas, what the gas liquid operations. For the gas liquid operations, you can actually interpret this or you can predict that entrainment of the gas, how much gas is entrained there by that making empirical correlations

$$Q_r = Q_g / Q_l$$
$$= 1.52\times10^{-4} D_R^{-0.534} H_R^{0.642} \mathrm{Re}_j^{0.268} We_j^{0.295} Fr_j^{-0.130}$$

So for that what you have to do? You can do dimensional analysis based on the different operating variables. Now different operating variables for this downflow system for the entrainment of the gas is like liquid velocity, density of the liquid, viscosity of the liquid, surface tension of the liquid, gas density, if you are using air, then air density, viscosity of the air or gas, column diameter and also you know that is called the nozzle diameter, even also you can say that pool of the liquid, that is you know that height of the pool of the liquid inside the column.

So that should be also considered because if you have more pool of the liquid there, you will see that more resistance to drag of that droplet or gas into the liquid. So based on which you have to you know do the dimensional analysis either by relate method or that Buckingham Pi Theorem to get that different dimensionless groups because you can get different dimensionless groups for that like Q_r that is Q_g by Q_l. Here Q_g is in this slide, it is shown that Q_g is volumetric rate of gas entrained there in the column and Q_l is the liquid flow rate, volumetric liquid flow rate which is that allowed through that rotameter and through the nozzle and creating that liquid jet.

And then, other groups like D_R here in that case you know that nozzle diameter to the column diameter is one important factor. If you increase the nozzle diameter to column diameter, then you can get less energy supplied there, then entrainment will be less. And also, H_R is one important, in that case you know that height of the liquid and also that diameter of the column, that is H_C by D_N, you can say that H_R. And Re_J, Reynolds number based on the jet velocity is another group, this is very important because in this case if you are having more jet velocity, then your Reynolds number will be very high, so your turbulent conditions will be created and based on which you can have the breaking up of the bubbles, the bigger bubbles whatever forms in the impend or plunging region or intense mixing zone there.

So you can get more finer bubbles at high Reynolds number of this jet. And also another important factor is waver number of the jet. In that case, this waver number is basically that $\rho u^2 d / \sigma$. In this case you know that rho is the density of that liquid and u is the jet velocity here, it should be considered and then d_j that means here jet diameter will be considered here. So waver number of jet will be considered as that rho u square d_j by that sigma.

So in this case, if you are having more that narrow liquid jet, you can get more finer bubbles also or more entrainment there. Even if you are allowing that multi-nozzle jet there, so in that case you can get more entrainment of the gas there. So that is why it is very important. Also surface tension effect also important there. If you are considering the constant jet velocity and that liquid velocity and also you can that jet diameter is controlled. Then if you are increasing more surface tension or if you are adding some surfactant, there you will see the surface tension will be less.

Then you can have that more finer bubbles there, more stable bubbles will be there. More finer bubbles will be produced, the swarm of bubbles will be produced. The population of the bubbles will be more, then gas entrainment will be more there, because of which that more finer bubbles you can get there. So this is one important factor and sprout number is also important there if it is there any gravity effect or not. If suppose this liquid jet is producing from the long distance there, so in that case gravity effect will be more, whereas if it is actually produced in the near about that plunging liquid position, then you can have that less gravity effect there.

So that gravity effect will give you that you know that by this dimensionless groups sprout number. So we can have this correlation based on that operating conditions and the entrainment characteristics based on the experimental observations and we have proposed here one empirical general correlations by which you can say that at which liquid jet velocity give you the what amount of entrainment of the gas in the downflow system for getting the more contact area between gas and liquid there. So that depends on that entrainment amount of gas there.

So based on these correlations, you can of course obtain the you know that amount of gas entering the pool of the liquid by this liquid jet system where ejector will be used for that creation or development of the bubble there in the downflow system.

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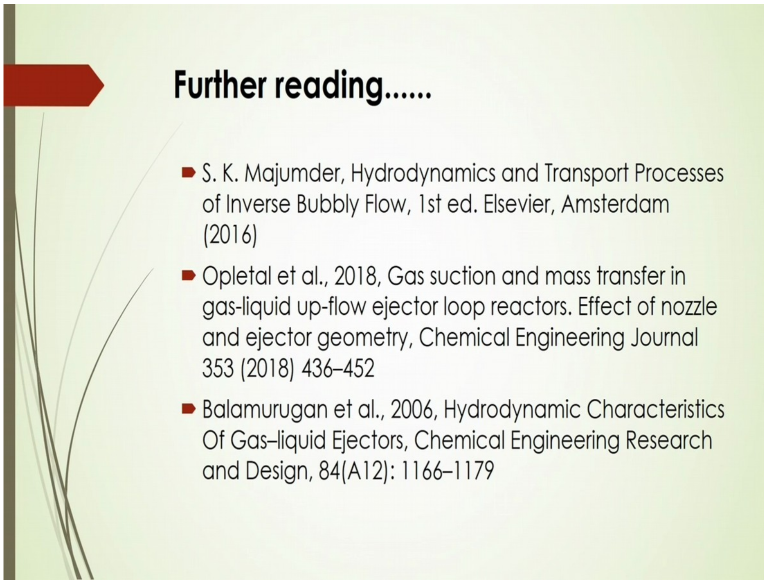

So we have discussed how that ejector can be used for process intensification, for getting more contact between gas and liquid, more finer bubbles formation, more droplet formation, more finer droplet formation for that chemical engineering operation. Like one example I am giving that here, like suppose droplet formation, if you are suppose extracting some propionic acid from the waste liquid, so in that case, that water which is reached by propionic acid and if it is actually in contact with the paraffin or some other organic liquid, aromatic ether or some other alcohol e.g., decanol if you come, if you make a contact with that, what propionic acidized water with that decanol, then you can get that contact area between that immiscible liquid of decanol or you can say paraffin. And then through that interfacial area of that droplet where that propionic acid will be transferred from that liquid to the decanol.

So this process you can apply for the separation of that propionic acid from the liquid to the organic. After that, then you have to distillate it then so that you can separate those propionic acid. So this can be utilized here in the downflow systems also by ejector system.

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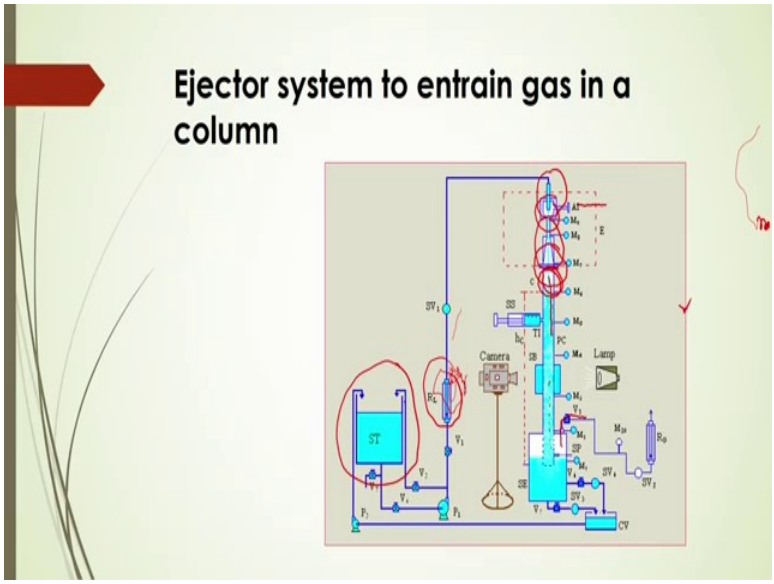

In this case what you have to do that in this case, that propionic acidized water should be supplied through this in this column as a jet and then it will be plunging into the pool of the liquid where that one portion, volumetric portion of the paraffin or decanol should be that there.

And whenever this liquid will be plunging, there will be formation of droplet of that droplet of that decanol or paraffin there and whenever this droplet will be forming and it will be coming downward again its buoyancy effect, it will reside for longer time and then that you can get the more contact time and more contact surface area and then you can get more mass transfer of this extraction of this propionic acid to the you know that decanol. After that, you have to separate it by this distillation process.

So this is very interesting application where you can intensify the process, chemical engineering process by this ejector system in the downflow system.

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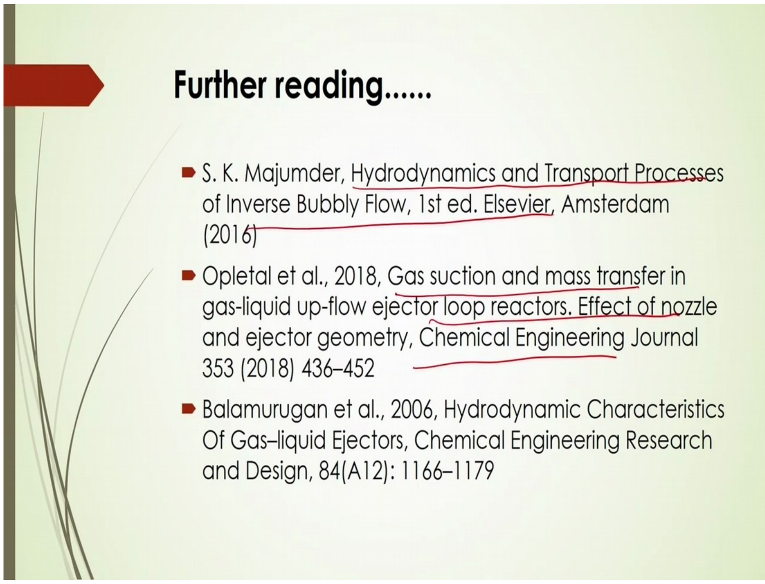

So I would suggest you to read further about this ejector system, how it can be applied, in this book here in the inverse bubbly flow system how these bubbles are forming and how it will be you know that inversely flowing and how it can be applied for different chemical engineering process for their intensification. Even I can suggest some more references to go further to get the more information about this ejector system for the chemical engineering operation there. So I think we have discussed a lot of things about this ejector system for the chemical engineering process intensification.

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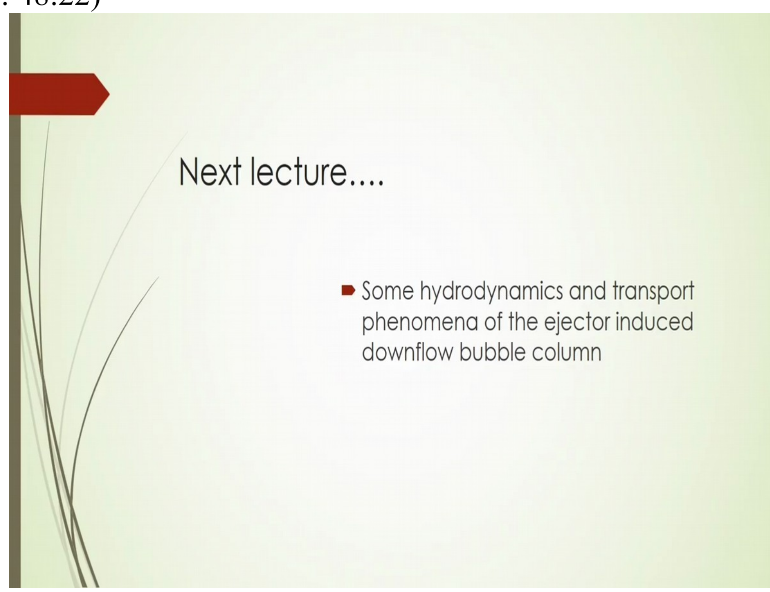

In the next lecture, we will discuss something more about the hydrodynamics and transport phenomena of the ejector induced downflow bubble column system based on which that how mass transfer actually effective and how intensified that chemical engineering operation in this system based on hydrodynamics and transport phenomena. So thank you for this lecture today.