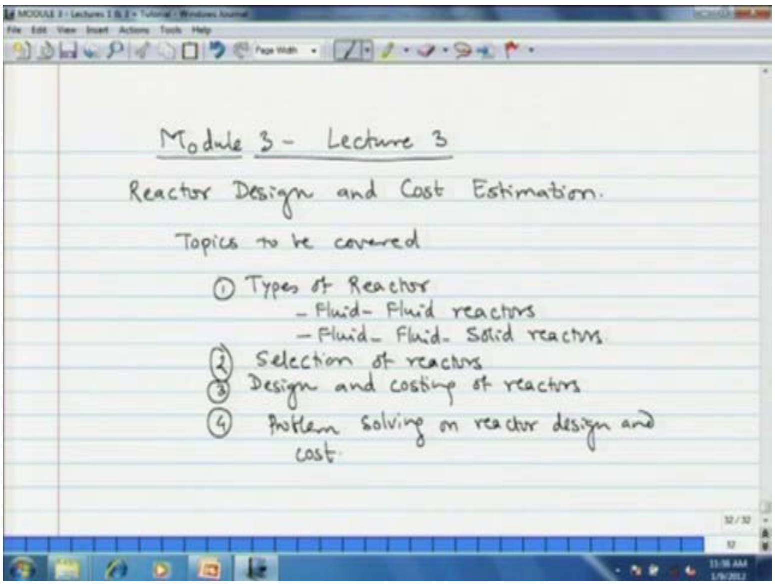
Process Design Decisions and Project Economics
Prof. Dr. V. S. Moholkar
Department of Chemical Engineering
Indian Institute of Technology, Guwahati

Module - 3
Reactor Design and Cost Estimation
Lecture - 15
Types of Reactors and Selection Criteria

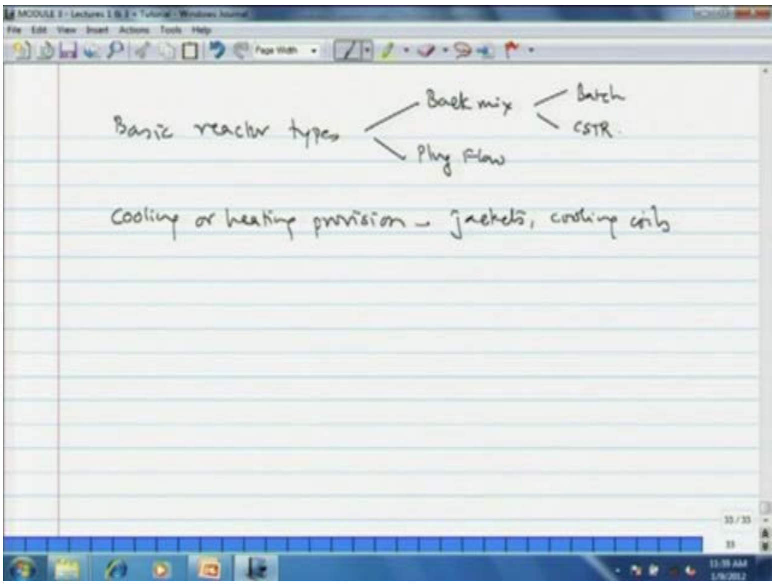
Welcome, we are in module 3 Reactor design and Cost estimation. In that two previous lectures, we saw the basic rector types or the design equations for the reactors, then in the previous lecture we saw various types of chemical reaction. And then whether we can generalize these reactions into certain categories like elementary, non elementary, reaction biological reaction so on and so forth. Then we saw the catalytic reactions what are the typical characters characteristics of the catalyst that are used in industry.

(Refer Slide Time: 00:58)



And in this lecture we continue the theme and then we shall see now the types of the reactor in better detail, basically the design of the reactor. The previous reactor type or the general type like a back mix reactor or plug flow reactor or continuous stud reactor, but in this lecture we shall see specific reactor types and design depending on the applications. We characterize these reactors into two sections; the fluid flow reactors the reactors that treat either two liquids or gas liquid or gas gas. And the second type of reactor is the heterogeneous that is fluid fluid solid reactors, then we shall see the criteria of our selection of rectors for particular application we take the theme further to see the design and costing of the reactor. And finally, we shall solve the problem for the design and reactor cost estimation.

(Refer Slide Time: 02:03)

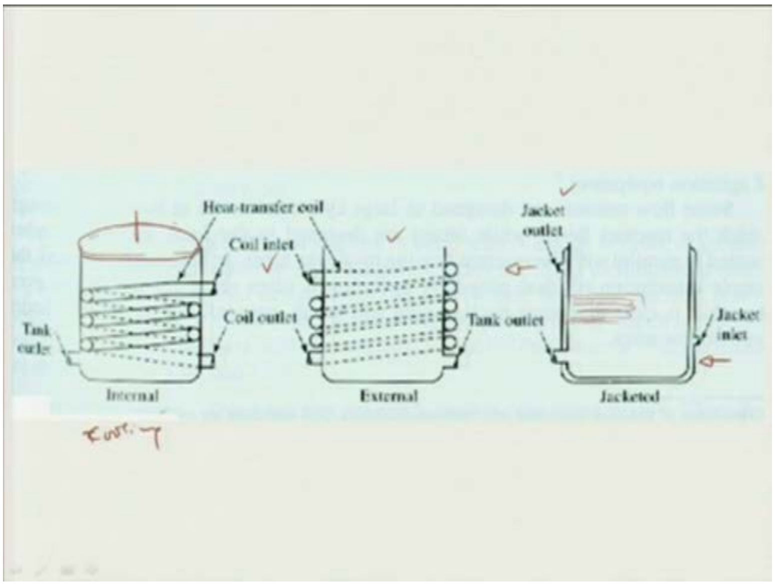


So, let us see the first topic that is the type of reactor I already told that the basic type reactor are two the back mix reactor and the plug flow rector. The back mix reactor are either batch reactor in which the reactance are taken once and the system is closed till the reaction is carried out or it could be the continuous stud reactor, whether the contents are mixed like the batch reactor. However, the reactors are continuously added and the products are continuously withdrawn.

Second reactor is the plug flow reactor where the reactants flow continuously in one direction in a tubular cylindrical vessel that is what the plug flow reactor is. Depending on the type of reaction, we have to provide the cooling or heating either in the form of jacket or in the form of cooling coils that is either inside or outside the reactors surrounded by reactor. And the reactor should be show design that it withstands the operating condition especially in case of reaction that is harsh operating conditions such as high temperature high pressure.

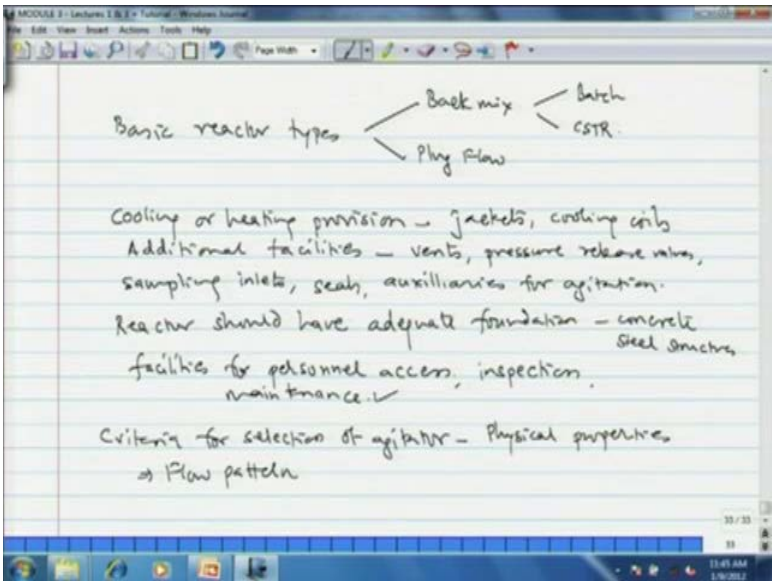
Material of construction is another issue that we are going to address later, but we here reactor should be so designed that it with stands the operating pressure and temperature. NPTEL also have special courses on process equipment design, so this topic is covered in a greater detail in those course; so I do not included here we shall see only the process design of the reactor.

(Refer Slide Time: 03:51)



Let us see what are the means of providing heat or removing heat from a particular reactant. Here you can see three types first is the internal cooling, internal cooling coils that you see here, the coils are especially on the periphery if you see this as the 3D reactor cooling coil is especially on the periphery and the adjudicator is provided in the center. Then the cooling coils can be also attached externally and here there are again on the surface of the reactor or it may be on the cooling jacket the water inlet is at the bottom and flows at outlet. Now, depending upon the exothermocity of the reaction term you can provide either a jacket or coil or both. In some cases the extended surfaces are also provided like certain surfaces which have the cooling coils attached on the periphery. So, those are for the highly exothermic reactions like polymerization fisher talk synthesis.

(Refer Slide Time: 05:02)



In addition to these we have to provide certain facilities for addition and removal of the reactant like for example, you have to provide rents in case of pressure research the pressure release valves, then sampling inlets, seals and auxiliaries for agitation. So, depending on the reactor type these addition facilities will coming into picture apart from that the reactor should have adequate foundation, either concrete or steel or both supports.

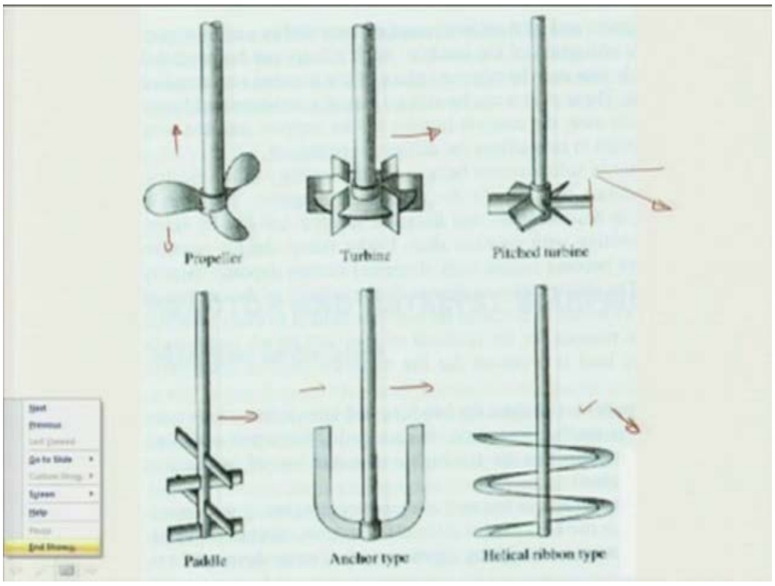
Then we have to provide facilities for personnel access like providing manholes in the reactor or inspection, we have to provide the view windows over which we can like glass windows reactor through which operator can see inside the reactor and certain provisions for the maintenance. Now maintenance means small scale maintenance it is not like shutting down the reactor and cleaning out thoroughly, small scale maintenance like providing certain holes where we can put ion the cleaning equipment and crack the hole something like that; so those maintenance provision should be made.

Then specialize attention is given for agitation in case of state tank reactive design. Now most of the reactors are reactors because the reactant should be agitated and correct agitation is critical for reactor performance. Now, criteria for correct agitation, criteria for selection of agitation we have to first see the physical properties of the reactants, what is the density, what is the viscosity, the reactants are highly viscous we can not provide agitation at high rates.

Secondly, if you want to have like for example, like juice concentration, if you want to have operation for thermally degrade reactant then we have to the agitator of some special type which do not cal cause mechanical damage. Like for example, in case of biological reactions like pharmaceutical reactions etcetera, if the mechanical agitator is rotated at high RPM then it can have cause damage to the cells. So, usually the agitation in those of the process provided by the gas flow, so that it does not create any sphere stress on the reactants.

So, depending on the physical properties, depending on the sensitivity of the reactants to agitation, their mechanical stability, delicacy or if the reactants are very ferzile type, then also the agitator has to be design properly. For example, many catalytically reactions the catalyst particles tries to breakdown, because to support is not sufficiently strong the catalyst get make it fragmented due to collision on the reactor wall in case of intense agitation. Therefore, we have to select the agitator accordingly like criteria for selection is physical properties of reactants plus the flow pattern that is needed in the reactor. I will show you certain standard agitators that are used in industry.

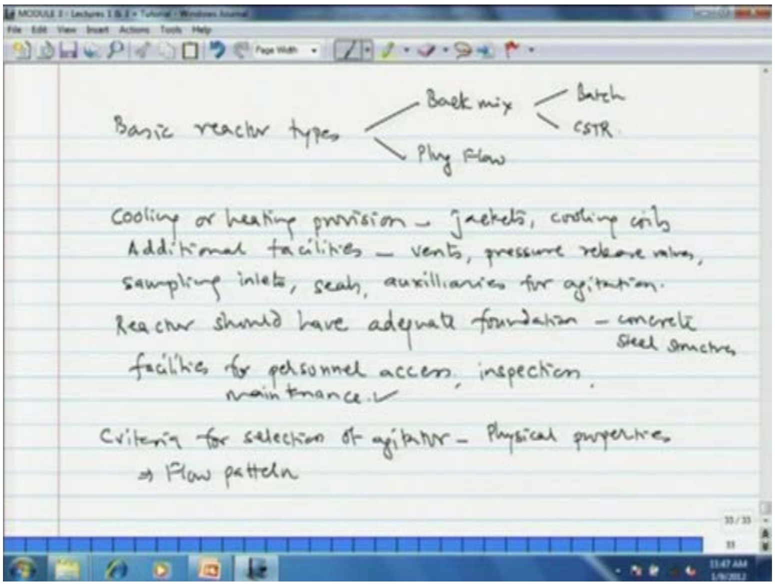
(Refer Slide Time: 09:15)



The first one is the propeller, which creates basically an actual flow of the reactants, the turbine this is flat plate turbine which creates basically a radial flow of the reactants. Then the third flow pitched turbine where the turbine blade is given certain angle, now this is very much like the fans that ceiling fans that we use in our home. Now, here the flow that is created is both actual as well as radial, so it is essentially in this direction and then there is paddle will which we use in some cases then anchor type.

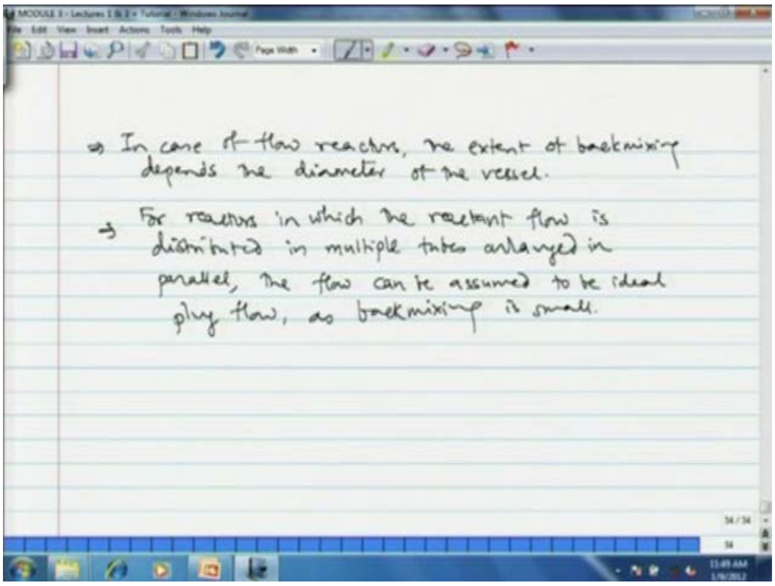
If the reactants are highly viscous and then in some case helical ribbon type of agitators, so these are some of the common agitators. Now, here anchor type creates the radial flow, paddle also creates the radial flow, helical ribbon type may create some flow in actual direction as well similar to pitched turbine so on and so forth. So, depending on the flow pattern that you want in the reactor you have to choose thus agitator.

(Refer Slide Time: 10:27)



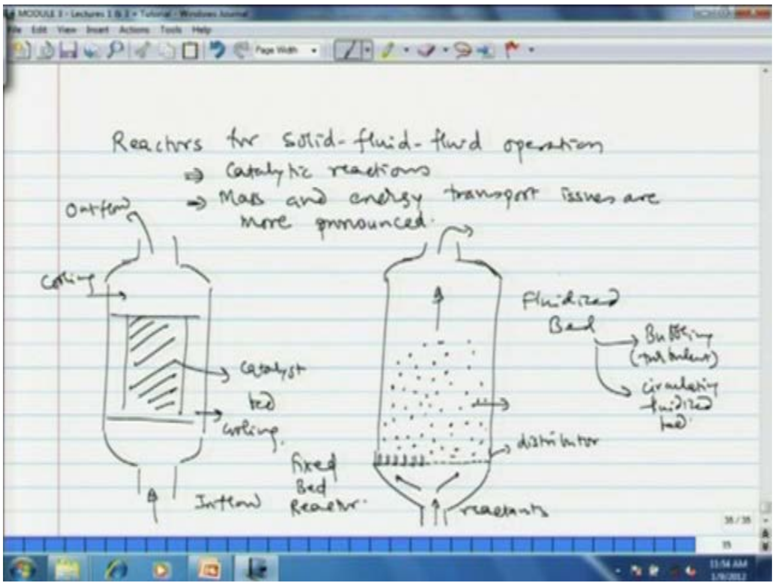
Now, this is as far as the fully fluid reactor reactors are concerned, in some cases in some flow reactors are large cylinders through which the reactants flows while others are designed in the form of multiple tubes located in the parallel with the reactants flowing inside the tubes. In these cases the reactants are distributed in the multiple tubes you can assume the reactor operation to be ideal plug flow, because the extent of back mixing is very small as the diameter of flow increases the extension the extent of back mixing also increases, so that point we note here.

(Refer Slide Time: 11:08)



In case of flow reactors the extent of back mixing depends on the diameter of the vessel. For reactors in which the reactant flow is distributed in multiple tubes arranged in parallel the flow can be assumed to be ideal plug flow as back mixing is small, so this is as per the fluid flow reactors are concerned. Now, the topic of fluid solid reactors these are essentially the catalytic reactors. Now use of catalyst require special reactor design to account for the mass reactors and energy transportations here the mass transfer promotions are more pronounced. There are various designs available based on the relative motions of the reactant the three basic type of reactor are either a single fixed reactor, I will show you a basic sketch of the reactor type.

(Refer Slide Time: 13:02)



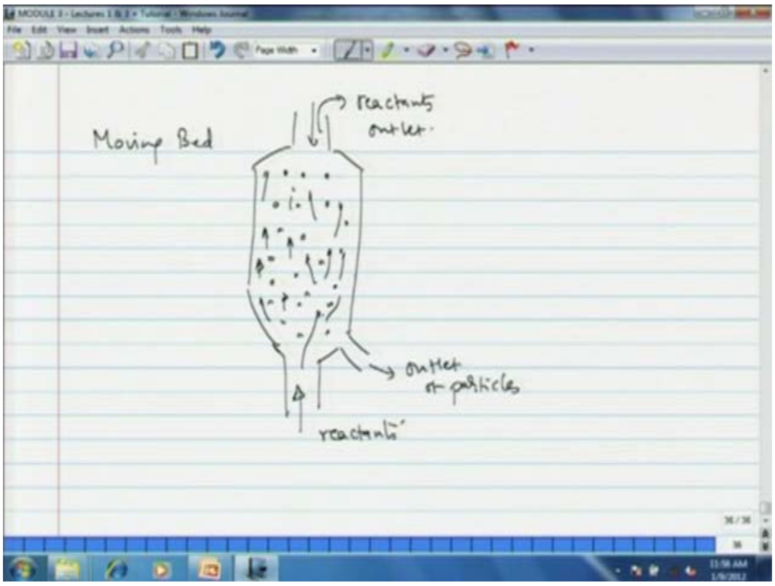
First basic reactor type is the fixed reactor in which the grade of the catalyst is enclosed in a shell and the reactants flows over head. Below and above the bed there is a distributor, now if the reactor is exothermic then the cooling may be provided simultaneously this is the basic fixed bed type of reactor. In case where the amount of heat that is released is the quite high than fixed bed reactor may not be very useful, because the conviction in this type of reactor is very small. Therefore, the transport or properties are not very high, so for example, you are not going to get very high transfer coefficient in these kind of reactor therefore, we have to go for fluidize bed reactor.

Now, fluidize bed reactor means that contains fluids that are suspended in flow of the reactant it has been reactant essentially the vessel, which has at the top and bottom. The reactants enters and are in the form of basically gas or liquid or mixture and these are distributed into the reactor through the distributor plate. The distributor plate could be of different type it could be a simple peripherated plate or it could be have certain like a to arrange or caps double caps those details are included as per the need.

But basic thing is that you have the distributor through which the reactant fluid is spread into the reactor and then small particles of catalyst are suspended in it. Now, if we have to suspend this catalyst particles into the flow of; obviously, the flow the velocity of the reactants has to be higher than the minimum fluid flow velocity that is determined by another like force balance on the particle. So, those things we are not going to include in the course you have a separate course on production engineering where these things are covered in greater detail.

Now, depending on the velocity of the reactant this particle move around. So, you get different resumes of fluidization like bubbling regime, shear regime or fast fluidization, turbulent fluidization. And in case the flow of reactant or the velocity of the reactants exceeds turbulent setting velocities of the particle, then these catalyst particle are this may get carried away and then you have to at outlet you have to capture these particles in a cyclone separator and return back to the bed. So, this is like fluidized bed reactor, fluidized bed has two operating regime bubbling bed and bubbling or turbulent and circulating fluidized these reactor have everything mix so the performance of these reactants is very similar to CSTR reactor.

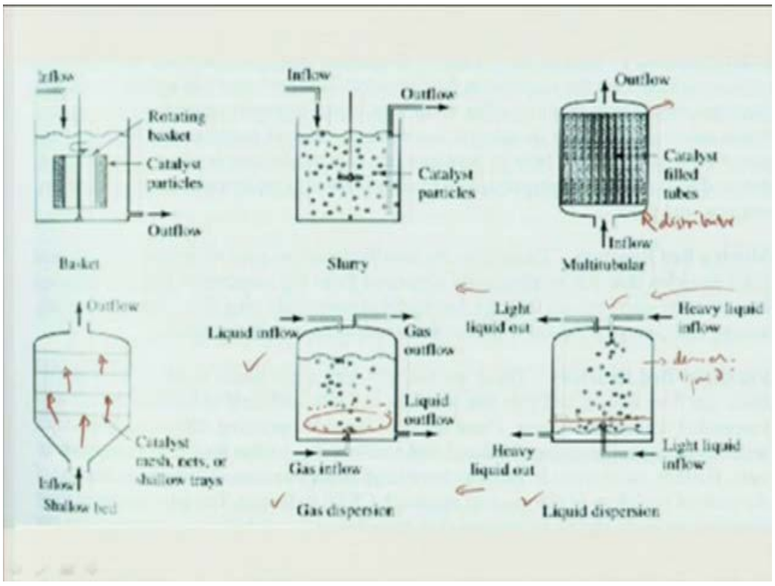
(Refer Slide Time: 17:29)



And the third type of reactor is a moving bed reactor, these are especially used when the following is high or the catalyst reactivation rate is high. So, that you can continuously remove catalyst from the reactant and then regenerate it, here the reactants and the catalyst flow particles are counter tend to each other, reactants enters at the bottom and the catalyst particle are headed at the top. However, unlike the fluidized bed reactor here the velocity of the reactors is sufficiently small, so that all the flow occurs between the voids and there is no movement of particle in the direction of the reactants flow.

So, the particles move continuously down slowly and these are removed a side outlet and this catalyst particle are treated and then sent back to the reactor. So, these are the general solid fluidized reactor types fixed bed, fluidized bed and moving bed. Now, depending on particular application there are several sub design or several sub categories of further detail designs that are I will show you now.

(Refer Slide Time 18:58)



What design is that for basket reactor in which the catalyst is put in a porous baskets that basket rotates in a reactor at high velocity. So, the reactant can access the catalyst particle through the pours of the basket and the products flow out, reactants flow can be unidirectional the flow enters at the top and leaves at the bottom. And then second is slurry type of reactors here the reactions which slurry continuously solid particles that can be physically separated by suspension fluid or carried out the tank is agitated tanks.

These reactors are simple in designed and they have good transport properties especially for highly exothermic reaction. And then control can be provided a sufficient control can be provide over the reactor convergence reactor performance without any compromise to catalyst access. In fact, catalyst particles can be added or removed also continuously through the flow off slowly; however, the one major demerit is the this origin in this reactor the reactor origin occurs because of the continuous the speed of agitation is high.

And therefore, impeachment of the reactor particle over the reactor wall can cause certain erosion of the reactor wall as well as it can cause fragmentation of the particles.

Then the next is the multitubulor reactor, multitubular reactor as I already mention earlier the catalyst the reactant distributed reactant flow is not through single bed, but distributed through different tubes there is a distributor down here which plates reactants almost be formally over the all the tubes and the catalyst is packed in this tubes.

So, this are multiple fixed bed units where multiple bed are catalyst filled tubes are arranged in parallel and heat conducting fluid can flow outside this tubes you can achieve good thermal control and uniformity of resistant time distributions in this type of reactors. Then comes the circulating flow, reactor circulating bed with adjustment is like the moving bed reactor this are essential same as prudile bed reactor, but creates suspicion of particles through fluid impeachment.

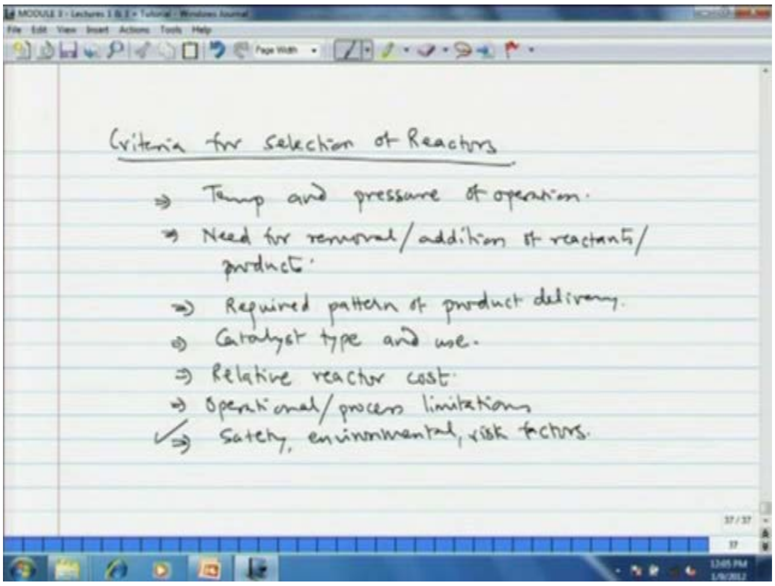
Like some cases are used where the reactant flows to the shell bed of closed particles and than lifts catalyst particles slightly so as to create as more wide or more mixing. So, this are the moving beds are sometimes called the spouted bed reactors these are like the family members of fluidal bed reactor itself. However, the velocity of the fluid motion is relatively small than they are like the thin or shallow bed reactors in which a rector bed flow flows through a catalyst mix or thin beds.

And these are suitable for fast reaction where good controller is required over the resident time distributions and temperature. These are quite simple in construction and a particular useful for catalyst reactivation, maintenance and removal of larger heat load. Then comes the category of dispersion reactor, now there are two types of dispersion characters shown here, gas dispersion and liquid dispersion. These are typically fluid containing vessel that allowed dispersion of liquid and gas flowing reactant and bubbling the later through the liquid or dripping the liquid in the gas stream or in liquid.

Like in the first reactor type the gas is bubbled through the reactor in some cases the gas burner is used a ring which distributes the gas uniformly throughout the reactor vessel. In case of large diameter the liquid flows continuously in case of liquid liquid reaction the lighter liquid is parched at the from the bottom again there is distributor here, which spreads this particular liquid in the form of droplets, which moved upward through a denser liquid. And then light liquid is taken out the bottom, the heavy liquid can also be in the flow mode it can enter continuous at the top and removed at the bottom.

In some cases film reactor are used this design is maximize the contact area for gas liquid reactions by bringing together gas and liquids as a thin field over solid support this is reactor also offer increase thermal control due to solid support. Like a pack reactors over which counter current operating packed reactor using certain packing rings like pawl rings, rush rings, dp packing. In this case the liquid spread form of a thin film that flows over or it is wet the packing surface and gas flows the bottom. And because of this spread of liquid over the packing surface very high inter facial area can be achieved, in some cases also used wetted valve column reactor were the liquid spread in over the particular column which wets the wall of that particular column this is specially for low surface tension liquids which can be easily spread in the form of film.

(Refer Slide Time: 24:35)



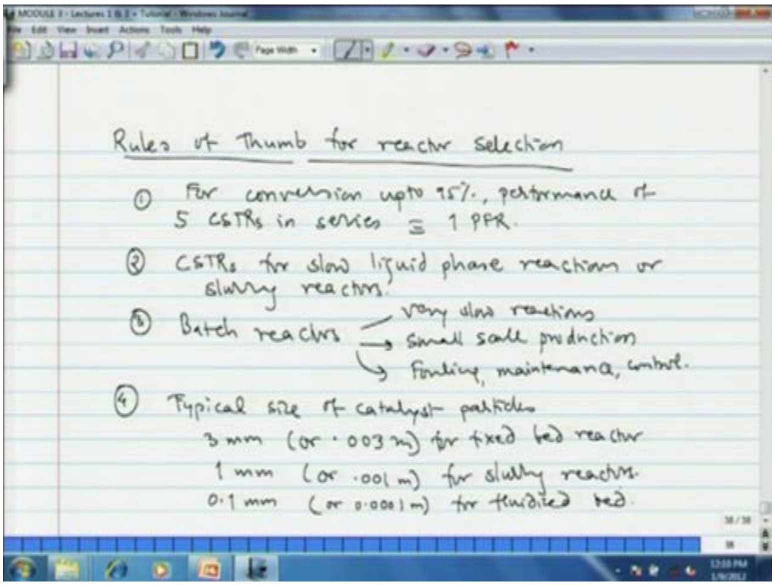
Now we shall see the criteria for reactor selection, which reactor is useful for which application, that we need to consider are temperature and pressure of the reactor. Then second need for removal and addition of the reactants and products, then third required pattern of product delivery with the batch or continuous. Then the catalyst type and use required for solid catalyst replacement and contact with fluid reactant and products, then the relative reactor cost, then the operation or process limitation. And then safety environmental factors, so on and so forth. Now, you NPTEL also have two courses on safety and risk assessment, so that point will be treated as better last point it will be treated as better detail in those courses.

In some situation multiple reactor types could be used depending on the consideration of the cost safety and other issues. Like the complete there may not be the complete of PFR or complete CSTR like convergence of reactor may not be achieved in a single reactor there could be reactor in series or there could be reactor in parallel. Suppose the reaction is highly exothermic like these things we seen in module 2 also, if the reaction is highly exothermic. Then the amount of heat transfer surface that can be accommodated in the single reactor is high.

Therefore, it may not be possible to treat the entire reactant in the single reactor, because of the size limitation the maximum amount of heat exchange area that you can stuff in the single reactant typically 6000 to 8000 feet square. So, accordingly you have to distribute your reactor in different reactant type, many times in case of highly exothermic reaction in case of czardas reaction, cursive reaction stand by reactant could be used.

So, that if one reactor effect mal function or if it is the under maintains the second reactant can operate or some reactions can be carried out partly in PFR or partly in CSTR those thinks also we have seen before in module 2. Where the contacting pattern depending on the order of the reaction, the kinetics of the reactions there are no explosive guidelines for selection of the reactors; but we can have some rules of thumb, which we can use in the selection of the reactor for the given application.

(Refer Slide Time: 28:36)



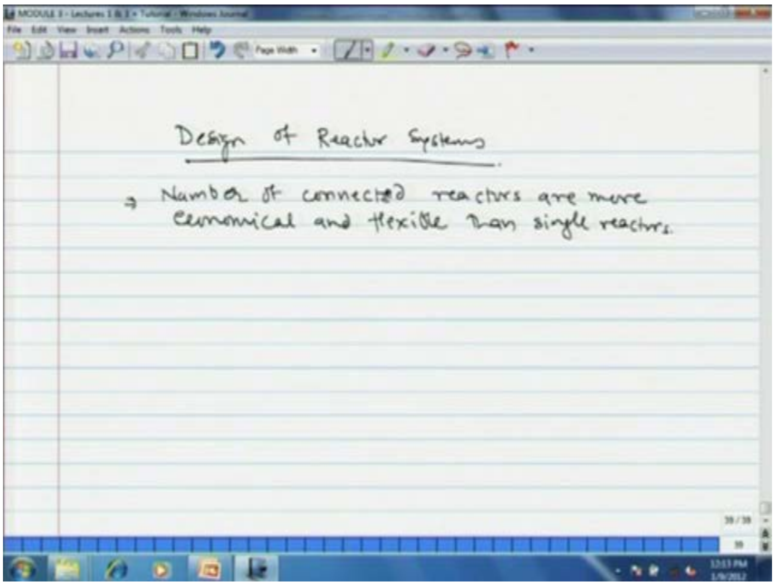
I will now summarize some of this rules of thumb for the conversion of 95 percent of equilibrium performance of fire mole CSTR connected in series equivalent to that of PFR for conversion up to 95 percent performance of 5 CSTR in series is equivalent to that of 1 PFR done. CSTR is to be used for slow liquid face reaction or steady reactor. Then third batch reactor are best suited for production in steady reaction or those found the reactor or those which required intense monitoring and control. So, three criteria batch reaction very slow reaction, which means high residence time of the reactant, that will give every high volume of PFR which in practical.

Then if the production scale is small and third fowling intense maintenance and control that is what the three criteria of batch reactor. Then in case of catalytic reaction the size catalyst particle is crucial the typical size of catalyst particles 3 millimeter or 0.003 meter for fixed bed reactor, because here we have to use the larger size. So, I have to have sufficient yardage because yardages decreases the temperature across the fixed bed reactor increases, pressure drop increase.

So, in order to have judicial choice between interfacial area pressure drop the 3 millimeter size is typical. If you go above this 10 you have higher yardage, but lesser surface area. Then for steady reactor 1 mm size and for flooders bed reactors 0.1 mm, now fluid bed characteristic the flooders bed the hydro dynamics kinetic are very finely if you use the larger particle size then the terminal velocity increase. So, the UMF increases the minimum fluidounce of velocity and then the residence time of the reactant decreases.

So, in that case the particles are characterized as C B A and D, C for cohesive, B for big particle size, A for a is the actual size which is catalyst which we use in FCC and D is the very large size that is in case of spotted bed reactors. Again you have a course in NPTEL of fluidization engineering also in particle characterization, so this topic will be treated in greater detail in these courses. So, we leave these things right here, with introduction then the designer of the reactant system.

(Refer Slide Time: 32:11)

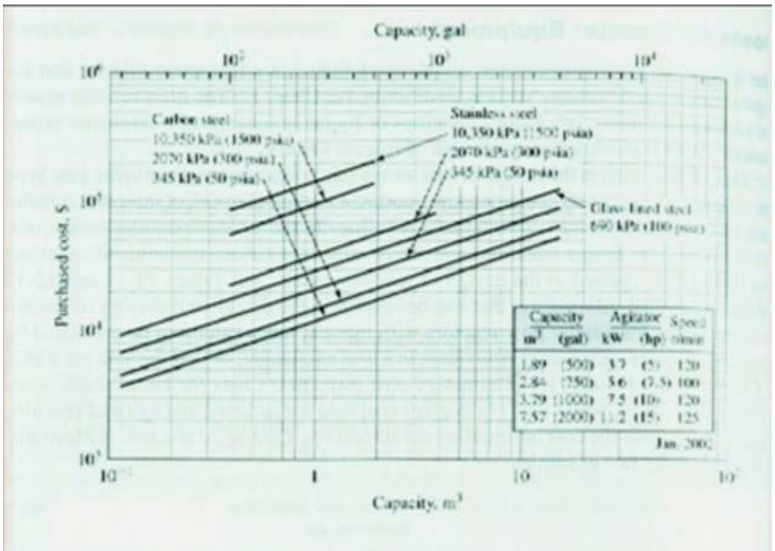


Usually the number of connected reactor are more economical than the single reactor this also gives you certain flexibility for maintenance and product distribution. Reactor combination or the arrangement for a optimal production of the product is subject of analysis criteria is same as for single reactant with added issue of arrangement of this reactors. So, if you split 1 CSTR into 3 CSTR then you have to adjust intermediate compositions properly. So, as to have the same overall convert ion in the case of single CSTR.

Generally for nth order of the reaction where n is greater than zero reactor are connected in series reactant concentration should be kept as low as possible if the reactant order is less than 1; if n is less than one as higher possible reaction is greater than 1. For complex reaction were the reaction rate has minima or maxima with respected to reactant concentration there is no simple guide line. Therefore, these thing treated like face to faces basis different convergence for same reactant system make all for different reactor combination and arrangement.

Graphical method for reaction method are quite full again you have the course on you have two course on chemical reaction engineering in which this things will be treated in greater detail the graphical method typically for PFR for a under the reaction rate curve verses the convergent gives you the volume and incase of CSTR it is that of square that rectangle of convergent that which gives you that reactor volume. So, basically graphical method are useful for initial design and after you get order of magnitude or some idea of volume that are required then you can give further design, then comes the topic of casting of the reactor.

(Refer Slide Time: 34:46)

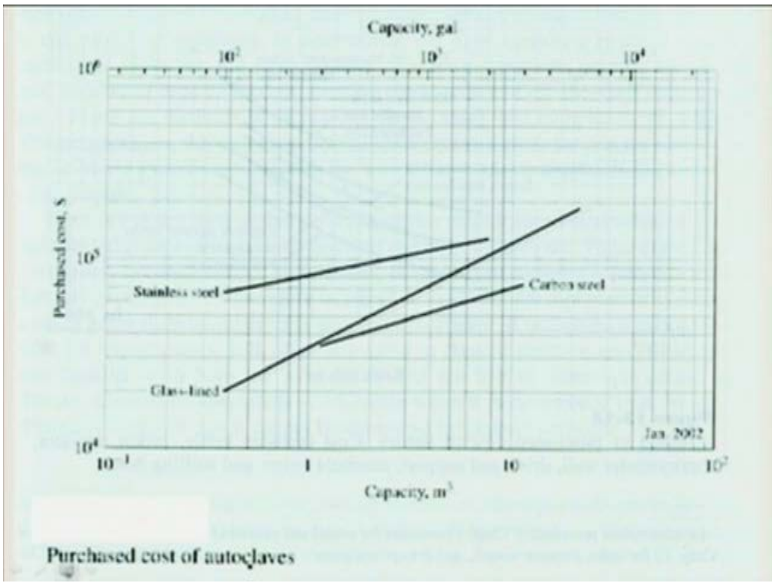


Purchased cost of jacketed and stirred reactors

Designer and the cast of reactor vessel are handled in the similar manner as further pressure vessels. Now, there are several cost coral available what we see on the screen now is installed or purchased cost of kettles cost includes the kettle, jacket, agitator thermometer well, drive and support, manhole cover and stuffing box. And you can see that the cost of varies with respect to the metal of construction you can have 316 stain and steel kettle in case the corogine is high.

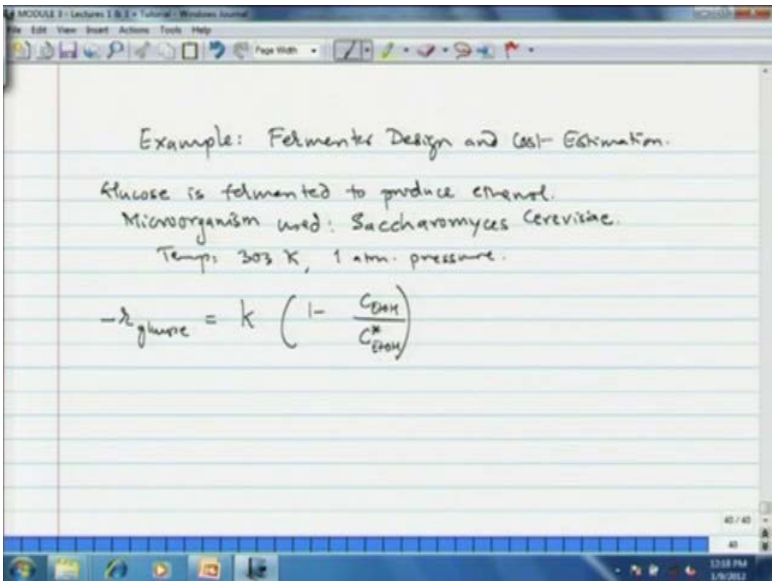
You can have the gas line kettle were the corogine is medium, homogenizes red line steel cattle's you can have cost line jacket were the corogine is minimum. And then what is show here is installed cost and purchased cost, purchased cost is somewhat high, because of other things that comes in creation of support, creation of electricity, connection, insulation, paintings so on and so forth. This things we will see in greater detail in the module of project economics, then you also have the cost of jacketed and stud vessel here depending on the type of agitation that is use that kilowatt or the power of agitation the speed and the metal of the construction, cost varies and the capacity of course, the velocity of the reactor.

(Refer Slide Time: 36:23)



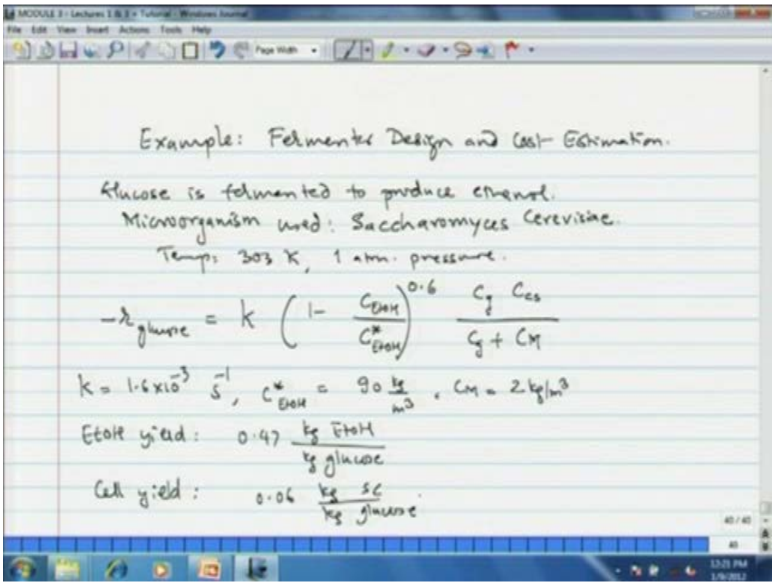
Then you have the for high pressure reaction the purchase cost of auto claves, you have the glass stand vessel, carbon steel and stainless steel. So, you have cost coronation available, so do calculations estimate the volume of the reactor and depending on what kind of reaction do you have to select the metal of the construction and you have the another issue that again it will be covered in the courses of safety and risk assessment. We are going to have brief introduction of it, there are several grade of stainless steel 304, 306 depending up on the temperature and pressure tables are available which gives the extent of that occurs the reaction over the period of time. And then you have to select the proper metal of construction for the reactor operation, now again there is a trade of if you choose the low cost material then price is low then the durability of the reactor is also small, so you have to go for a trade of. With this theory we will solve the small example on reactor size and cost estimation.

(Refer Slide Time: 37:35)



I have chosen example on fermentation, I will first give you the problem statement glucose is fermented to produce ethanol the micro organism used is saccharomyces cerevisiae. The temperature of the operation is 303 Calvin close to ambient condition under eight expression with respected to glucose the main reactant is K into 1 minus c ethanol divided by c star ethanol. Now, ethanol fermentation is inhibitory which means the ethanol that produce raptures or it basically it damages the membrane wall of the cells and it kills the cell. Therefore, the ethanol concentration in the fermentation broth increases the cells die and there is an inhibitory concentration at which all the cells die that is what is c star ETOH that is inhibitory concentration.

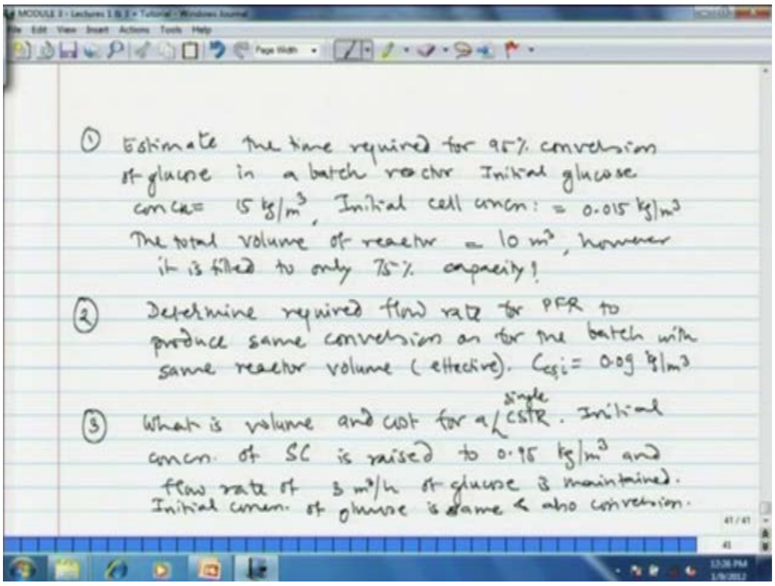
(Refer Slide Time: 39:14)



Inhibit factor given by this particular bracket one minus ETOH, which is the incent concentration of ethanol divided by the inhibitory concentration S 2 exponent 0.6, then Cg glucose concentration C c s the concentration of the micro organism saccharomyus cervisiac and the concentrate C m. So, essentially we have mono kinetics with an inhibitory factor K is the rate constant.

So, we shall list all the values K is given as 1.6 into 10 to the power minus 3 second inverse, c star ethanol is given as 90 kg per meter cube, C m is given as 2 kg per meter cube constant C m ethanol yield is 0.47 kg ethanol per kg glucose consumed. Then cell yield is 0.06 kg saccharomyus cervisiac that we abbreviate by the sc per kg glucose. So, this is the information given to us.

(Refer Slide Time: 40:56)



Now, we have to first estimate time required for 95 percent conversion of glucose in a batch reactor, initial glucose concentration in the reactor is given to us as 15 kg per meter cube. Initial cell concentration as 0.015 per meter cube and the total volume of the reactor is 10 meter cube. However, it is filled to only 75 percent of volume just write 75 percent capacity that is better. So, we have to estimate the time for this condition the second is that you have to determine the required fluid for a PFR to produce same conversion as for the batch with same reactant volume reactant volume is same I will write in the that effective why I will tell you later.

Now, here the only difference is the C s the initial concentration saccharomyces cerevisiae is not 0.015 is bit higher 0.09 per kg meter cube. And third thing we have to answer is what is the volume and the cost for a CSTR continence reactor, here we write single CSTR we are going to use only one for a single CSTR here initial concentration again, initial concentration of micro organism is high further almost 10 times to 0.95 kg per meter cube; and flow rate of 3 meter cube per hour of glucose is maintained. The initial concentration of glucose is same as before and conversion wizard also same.

So, this problem tries to analyze a biological process of fermentation of glucose to ethanol in three types of reactor in each case we have to estimate either the volume of the process or the fluoride or the time. We shall see the detail solution of this in the next lecture and we shall also try to find out or we shall also treat similar problem in case often in organic process, that is production of methanol from synthesis gas hydrogen plus carbon monoxide.