

Fluidization Engineering
Dr. Subrata K. Majumder
Department of Chemical Engineering
Indian Institute of Technology, Guwahati

Lecture - 25
Solid segregation: Gas-fluidized bed

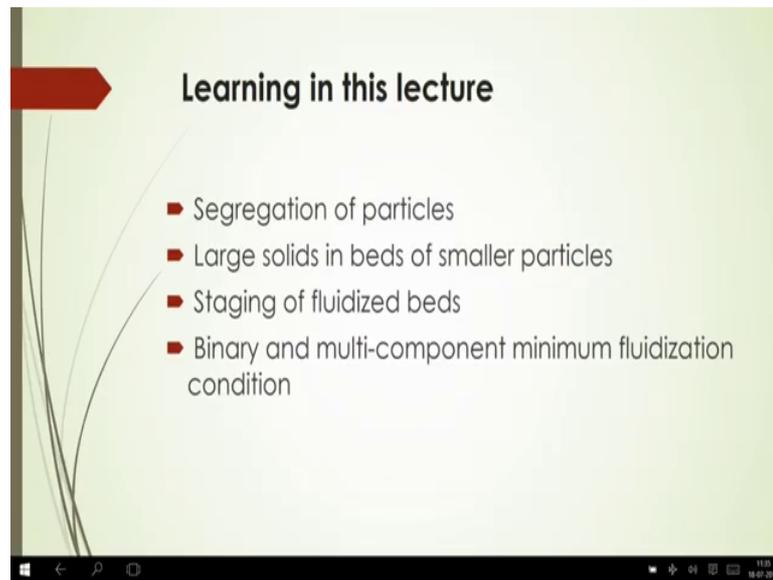
So welcome to a massive open online course on fluidization engineering. So, today's lecture will be on solid segregation based on gas solid fluidized bed. And I think we have discussed about the solid mixing, and also a solid movement in the gas solid fluidized bed and that mixing I think we have seen that there will be the solid circulations at the bed and, because of that circulation cell formation.

There will be the actually mixing of the solid vertically and horizontally; and not only that by circulation cells, there is other mechanism like the bubbles will entrain the solid particles and then get downwards on solid particles and the solid particles moving from the emulsion phase to the wake region and in some solids also coming down from the wake region.

In that case, there are some other mechanism also is responsible for this solid mixing. Now, in this lecture will be discussed about that the due to that; mixture of the solid particles may be a with different sizes or the same sizes given in different densities or the same densities, and during that mixing there will be the segregation of the solid particles of different sizes there.

And let us see here what should be the factor actually, when that the solid segregation is happened inside a bed and also how it can be represented; mathematically; this phenomena inside the how gas solid fluidized bed.

(Refer Slide Time: 02:31)

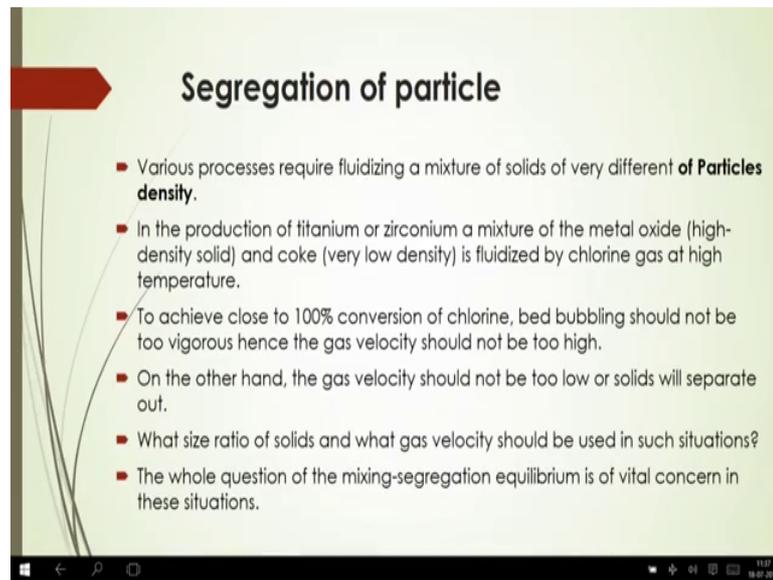


So, what we learn in this lecture that segregation of the particles how it happens and the largest solids in the beds of a smaller particles, if it is there then how that segregation will happen even if is there in the staging of fluidized bed, then how this segregation can be actually of understand on that basis.

And if there is I think different sizes particles and different type of particles in a mixture, then what should be the minimum fluidization for a binary and multi component fluidization condition. In earlier we have learned only the single type a particle and the same size of particles, what should be the minimum fluidization velocity there in the fluidized bed, but in this lecture we will also learn about and extent of that minimum fluidization velocity based on binary and multi component mixture in the fluidized bed.

Now, what is that segregation of particles you will see that various process of course, is required for fluidizing a mixture of solids of very different of particles density.

(Refer Slide Time: 03:58)



Segregation of particle

- Various processes require fluidizing a mixture of solids of very different of **Particles density**.
- In the production of titanium or zirconium a mixture of the metal oxide (high-density solid) and coke (very low density) is fluidized by chlorine gas at high temperature.
- To achieve close to 100% conversion of chlorine, bed bubbling should not be too vigorous hence the gas velocity should not be too high.
- On the other hand, the gas velocity should not be too low or solids will separate out.
- What size ratio of solids and what gas velocity should be used in such situations?
- The whole question of the mixing-segregation equilibrium is of vital concern in these situations.

So, in that case you will see that there will be a some reactions parallelaly and because of with some segregation will be happened in such way that conversion of some materials in the bed and whether the bed is vigorous or; that is particulate then what should be that the velocity of that fluidized bed so, that their segregation will not be that much, but the conversion will be optimum.

And also in that case you will see that in the production of titanium, as an example or zirconium a mixture of the metal oxide ah; that is it is density is very high and coke, where it is density is very low.

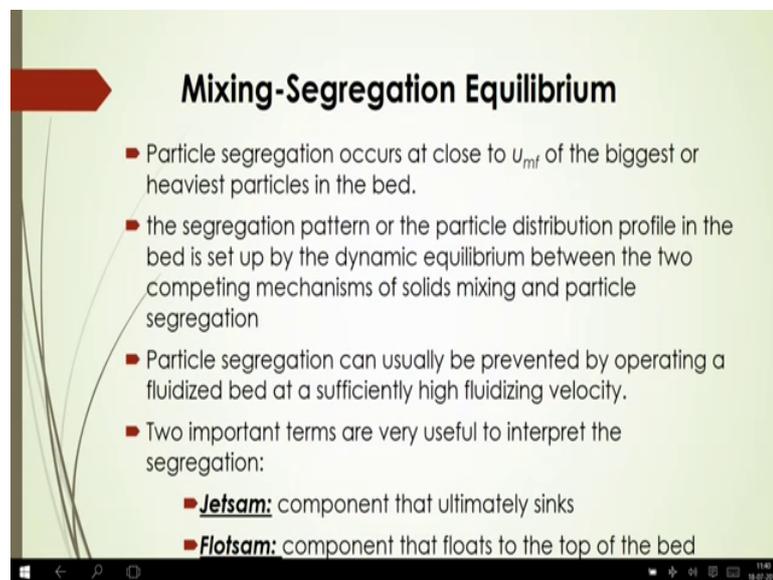
So, in that case if it is fluidized by chlorine gas high temperature there will be some segregation of the particles mechanism will happen or phenomena; will happen inside the bed and to achieve close to 100 percent conversion of chlorine bed bubbling should not be too vigorous, hence the gas velocity should not be too high.

So, on the other hand you will see that gas velocity should not be also too low. So, that the solids will segregate out there and what size ratio of the solids and of what gas velocity should be actually by utilized to serves I think situations that we have to know; and the whole questions of the mixing segregation equilibrium is of important criteria in these situations.

Now, what should be that mixing segregation equilibrium? So, main one important aspect of that whenever you are judging or you are analyzing the mixing or segregation some equilibrium condition to be known by which you will be able to know what should be the extent of that segregation or mixing inside the bed. Now, particle segregation occurs that close to minimum fluidization velocity of the biggest or you can see heaviest particle in the bed.

So, either it by size or by the density of the particles and the segregation pattern or the particle distribution profile in the bed is set up by the dynamic equilibrium between the two competing mechanism of solids mixing and particle segregation in the bed.

(Refer Slide Time: 06:50)



Mixing-Segregation Equilibrium

- Particle segregation occurs at close to u_{mf} of the biggest or heaviest particles in the bed.
- the segregation pattern or the particle distribution profile in the bed is set up by the dynamic equilibrium between the two competing mechanisms of solids mixing and particle segregation
- Particle segregation can usually be prevented by operating a fluidized bed at a sufficiently high fluidizing velocity.
- Two important terms are very useful to interpret the segregation:
 - **Jetsam:** component that ultimately sinks
 - **Flotsam:** component that floats to the top of the bed

And also it is very important that; you have to some extents prevent that segregation, because of getting that optimum conversion in the bed.

So, particle segregation can usually be prevented by operating a fluidized bed at a sufficiently high fluidization velocity. So, in that case you have to know the what should be the minimum fluidization velocity; if you are having the mixture of different type of particles, that is binary or multi component mixers there and then you have to operate the fluidized bed beyond that minimum fluidization velocity at a certain condition so, that that you can you can be able to or you can be design you will be able to design or you can be design in such a way that segregation of the particles should be minimum there.

And two important terms are very useful to interpret this segregation one term is called jetsam another is called flotsam. Now jetsam actually the component that ultimately sinks that is called jetsam; that means, the particles will come downward and it will be settled and it flotsam is nothing, but the component of that materials those will be floats to the top of the bed.

So, these tools terms will be very important or to analyze the segregation criteria there. Before going to that we have to know, what should be that actually mechanism of that segregation generally three different mechanisms are found to be important in the relative movement of particles in the bed that is actually reported by Rowe et al., 1972.

(Refer Slide Time: 08:51)

Mechanism of segregation

- Three distinctly different mechanisms were found to be important in creating the relative movement of particles in the bed (**Rowe et al., 1972**)
- **Lifting of particles in the wake of a rising gas bubble:** -the only way the flotsam can be transported to the upper part of the bed
- **Migration down to the bottom of the bed:** - The larger and denser particles usually descend by falling through the bubbles,
- **Inter-particle percolating:**- the smaller, denser particles percolate downward interstitially.
- **The average descending distance of the aggregate was proportional to the bubble diameter and the distance from the bubble center (Tanimoto et al. 1980)**

Now, lifting of particles in the way that we have seen that earlier there will be reflection of the reflection of the emulsion to lift that solid particle to the wake, and in there it is seen that that lifting of particles in the wake of a rising gas bubbles.

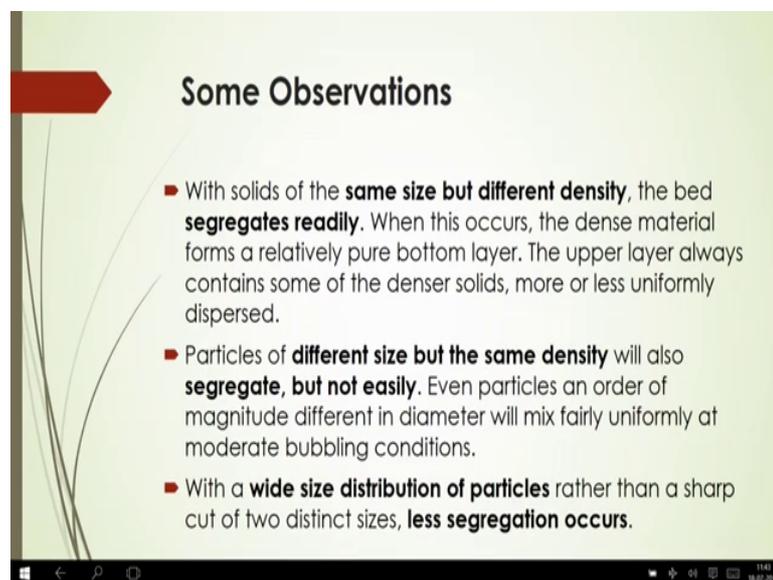
So, in that case one this is one important mechanism of this particle segregation. So, by this mechanism the only way the flotsam can be transported to the upper part of the bed. So, these particles those densities are very less and also the particle size is a small, then only those particles will be lifting in the wake when bubbles will be rising there.

Now another mechanism is called migration down to the bottom of the bed, what does it mean that; you will see that larger and the denser particles, because of their height

terminal velocity they will usually descent by falling through the bubbles. And also a inter particle percolating is one important mechanism by which that you will be able to now understand that whether the smaller or denser particles that will percolate downward interest, that is called interstitially or not.

Now, this average that is the descending distance of that aggregate of that what is that segregation actually that is proportional to the bubble diameter and the distance from the bubble center; that is stated by what is that the Tanimato et al., 1980.

(Refer Slide Time: 10:45)



Some Observations

- With solids of the **same size but different density**, the bed **segregates readily**. When this occurs, the dense material forms a relatively pure bottom layer. The upper layer always contains some of the denser solids, more or less uniformly dispersed.
- Particles of **different size but the same density** will also **segregate, but not easily**. Even particles an order of magnitude different in diameter will mix fairly uniformly at moderate bubbling conditions.
- With a **wide size distribution of particles** rather than a sharp cut of two distinct sizes, **less segregation occurs**.

Some observations are given by different investigators young 2003, but they have a stated that the, with solids of the same size but different density if you are using in the fluidized bed, then the bed segregates readily.

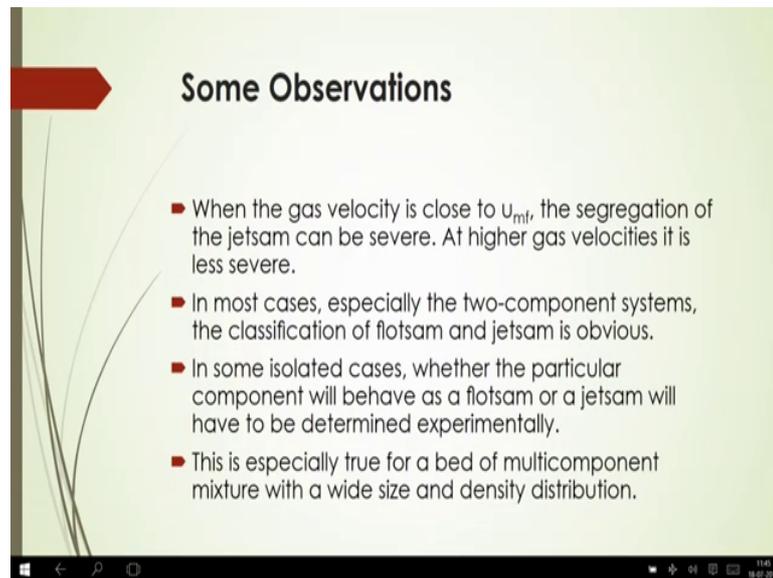
When this occurs the dense material forms a relatively a pure bottom layer and the upper layer always contains some of the denser solids and the, it this will be more or less uniformly dispersed. And particles of a different size, but of the same density will also segregate, but that will not be so, easy even particles an order of magnitude; that is different in diameter will mix purely uniformly at a moderate bubbling conditions.

Now, question is that if there is one wide size distribution of the particles are in the bed whether there will be a segregation increased or not; no there will be no actually segregation significantly, because in that case the wider size distribution means there will

be a mixture of either is very small particles will be more amount or very large particles will be more amount. There will be mixture in that case such destitution will be more wider the size range will be very low to the high. So, in that case you will see the segregation may not be that the occurs in significantly.

So, less segregation sometimes is seen there in the bed; and this can be actually rather than a shortcut of two distinct sizes there may be obtained there.

(Refer Slide Time: 12:42)



Some Observations

- When the gas velocity is close to u_{mf} , the segregation of the jetsam can be severe. At higher gas velocities it is less severe.
- In most cases, especially the two-component systems, the classification of flotsam and jetsam is obvious.
- In some isolated cases, whether the particular component will behave as a flotsam or a jetsam will have to be determined experimentally.
- This is especially true for a bed of multicomponent mixture with a wide size and density distribution.

And, when the gas velocity is close to minimum fluidization velocity the segregation the jetsam; that means, which are going downward can be severe at higher gas velocity to it is less severe. In most of the cases the two component system the classification of this flotsam and the jetsam is clear in some isolated cases it is seen that that; whether the particular component will behave as a flotsam or jetsam that will have to determine experimentally. And this is especially true when a bed of multi component mixture with a wide size and the and the density distribution will be in the bed and for two component binary systems Chiba et al., 1980.

(Refer Slide Time: 13:36)

Some Observations

For a two-component binary system, **Chiba et al. (1980)** suggested the following general rules:

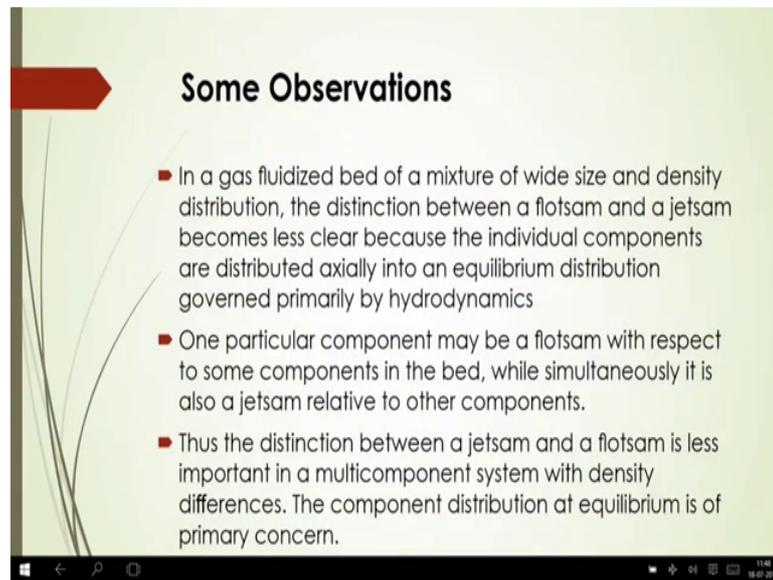
Case	Condition	Remarks
Case I	$d_b/d_s \leq 10$	
Ia	$\rho_b = \rho_s$	Jetsam = bigger component
Ib	$\rho_b \neq \rho_s$	Jetsam = heavier component
Case II	$d_b \gg d_s$ and bed material \rightarrow 100 smaller component	
IIa	$\rho_b = (\rho_b)_s$	Jetsam = bigger component
IIb	$\rho_b < (\rho_b)_s$	Jetsam = smaller component
Case III	$d_b \gg d_s$ and bed material \rightarrow 100 bigger component	
IIIa	$\rho_b > \rho_s$	Jetsam = bigger component
IIIb	$\rho_b < \rho_s$	Jetsam = either component may be jetsam
Case IV	The minor component is plate like with $\psi < 0.5$	
IVa	Plate like particle is denser	Jetsam = plate like component
IVb	Plate like particle is lighter	Jetsam = either component may be jetsam

Yang (2003)

They have suggested some following rules here given like case 1, case 2, case 3 and case 4. So, in the case 1 they have observed that if the bubble size bubble size to the solid size if it is less than 10, then you will see for the equal density of this; that means, the bed and solids you will see that jetsam will be equals to bigger component, where if the bed density; that means, bulk density if it is not that what is that solid density; then jetsam will be is equal to heavier component.

And in case 2; if suppose this bubble diameter is greater than and equal to of solid diameter and bed material things to 100 smaller component, then at a different conditions like pb that will be is equal to rho b s and pb less than equal to rho B s these two are remarks can be obtained inside the fluidized base. Similarly, for case 3, case 4; as per this table you just to see how this jetsam and flotsam of phenomena occurs.

(Refer Slide Time: 15:14)



Some Observations

- In a gas fluidized bed of a mixture of wide size and density distribution, the distinction between a flotsam and a jetsam becomes less clear because the individual components are distributed axially into an equilibrium distribution governed primarily by hydrodynamics
- One particular component may be a flotsam with respect to some components in the bed, while simultaneously it is also a jetsam relative to other components.
- Thus the distinction between a jetsam and a flotsam is less important in a multicomponent system with density differences. The component distribution at equilibrium is of primary concern.

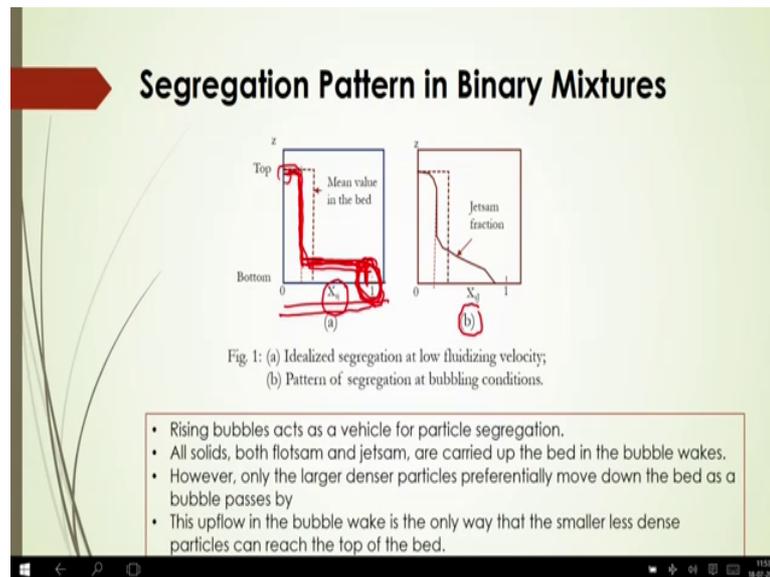
Inside the bed now in a gas fluidized bed of mixture of wide size and density distribution, the separation between a flotsam and jetsam will become a less clear because; in that case individual components that will be distributed axially into an equilibrium distribution that will be governed primarily by hydro dynamics.

So, for mixture of wide size and density distribution that be distinction between that flotsam and jetsam depends on the different hydrodynamics characteristics and.

If suppose one particular component if in a if it is in a flotsam with respect to some components in the bed, then you will see that simultaneously it is also a jetsam related to other components; there thus the distinct between if jetsam or flotsam is less important in a multi component system with density differences.

The component distribution at equilibrium is or then primary concern for over analyse the segregation mechanism inside the fluidized bed. Now, what should be the segregation pattern in binary mixture? So, it is important to know that how it will be segregated.

(Refer Slide Time: 16:49)



That jetsam and flotsam particles there in the bed; whether this how the separation between this bottom and top part of this fluidized bed will be there. Now, if we represent that the fraction of that jetsam solid this is X_j .

And, if we change that this mixture component of that; what is that X_j jetsam component to 0 to 1 it is seen that that for idealized segregation at low fluidization velocity there, it will be the pattern will be like this here in this case; what does it mean; that at the bottom you will see that for this; that is component one; that means, your X_j is equal to 1 they are you will see that the solid particles those who are floating down that those who are downward.

So, in that case maximum that your 100 percent of the solid particles will be going downward here; in this case whereas, this segregation pattern will also will be decreasing with that; constitution of that jetsam solids, but at a certain at a certain concentration, you will see there will be some constraints of that concentration of that jetsam solids that segregation will increase up to the top here.

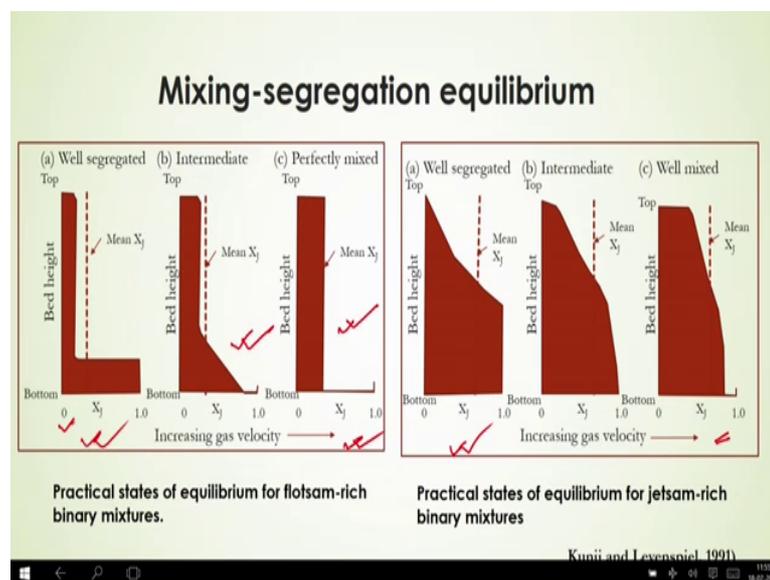
So, this is the segregation present here from 0 to 1 to bottom to top here of the fluidized bed, and this dotted line will give you this mean value in the bed.

So, when this well mixed solids are there with some concentration or that volume fraction or you can say mass fraction of the solid fraction, then this segregation pattern will be like; this for idealized segregation case whereas, for pattern of segregation.

In bubbling condition you will see this figure b as shown that; how do we look like do not be exactly that; what is that is idealized condition. So, here this pattern will become deviate from this idealized condition, because of hydrodynamic behaviour in the bubbling conditions there.

So, in this case rising bubbles acts as a vehicle for particle segregation and all the solids both the flotsam and jetsam are carried up the bed. In the bubble wakes; however, only the larger denser particles preferentially when to we will move down the bed as a bubble it will passes by and this up flow in the bubble wake is the only way that the smaller dense ah; that means, less dense particles can rich the top of the particles there in the bubbling fluidization condition.

(Refer Slide Time: 19:59)



Now, here also it is seen that Kunii and Levenspiel that they have observed some phenomena; that mixing segregation equilibrium condition here for part for the particular condition; if the equilibrium for flotsam rich binary mix and what will be the flow pattern and the equilibrium jetsam rich binary mixture, what should be the mixing segregation equilibrium patterned there.

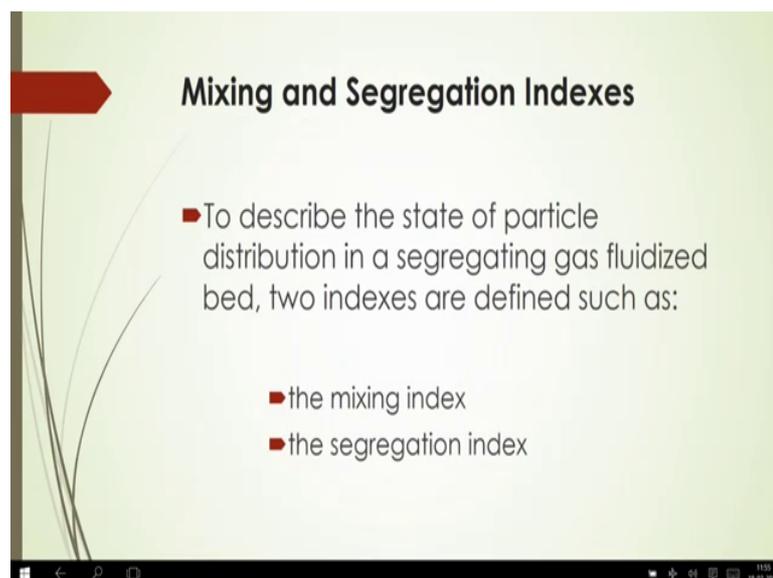
So, in this figure you will see that in this figure the practical states of equilibrium for flotsam rich binary mixtures there, in this case flotsam; how this well segregated condition this flotsam behaviour like this; and for intermediate condition here this flotsam rich the binary mixture, how a flow pattern for the segregation is giving and then here also for perfectly mixed mixture how this segregation pattern will give you. So, this will change when increase the gas velocity from this lower to the higher value.

Similarly, for this here equilibrium for jetsam rich binary mixers, how it will become rich it will rich to that equilibrium condition here by this, figure you can observe or you can understand, how this pattern will change when it will be less segregated and we will be intermediate the segregated or well mixed segregated to there.

And in the figure the dotted line will give you that jetsam much fraction of the solids as a mean and this change would bed high; that is bottom two top here. Again and the jetsam must fractions to be varies from 0 to 1 there; that means, here pure binary mixture of that flotsam and the jetsam there by 0 and 1 respectively.

So, this figure you can observe how this flow pattern it changing; when gas velocity will change and for that intermediate case also, how it will be there deviated from this well segregated and well mixed condition.

(Refer Slide Time: 22:32)



Mixing and Segregation Indexes

- To describe the state of particle distribution in a segregating gas fluidized bed, two indexes are defined such as:
 - the mixing index
 - the segregation index

Now, to analyze the mixing and segregation; in the fluidized bed two important parameter is called that indexes. So, there mixing indexes and the segregation indexes are two important parameters, which are defined there and based on which you will be able to actually analyze how and what extent of that mixing and segregation happens inside the bed and Rowe et al., 1972.

(Refer Slide Time: 22:58)

Mixing Index

- Solids mixing index defined as (Rowe et al., 1972)

$$M = \frac{\text{Mass fraction of jetsam in the top portion of the bed}}{\text{Jetsam mass fraction in a perfect mixed bed}} = \frac{X_{s,j,top}}{\bar{X}_{s,j}}$$

M = 0 : complete segregation
M = 1 : complete mixing

The jetsam fraction in Fig. 2 is practically constant in a large portion of the bed, using this value an approximation for M can be:

$$M \cong \frac{X_{s,j, \text{straight-line portion}}}{\bar{X}_{s,j}}$$

Actually they have defined this solid mixing indexes are here M this M is equal to mass fraction of jetsam in the top flotsam of the bed divided by the jetsam mass fraction in the perfect mixed bed here; this is defined by this $X_{s,j,top}$ and by mean value of this $\bar{X}_{s,j}$. Now, in this case if M is equal to 0 there will be a complete segregation and if M is about 1, then there we will be a complete mixing.

So, this jetsam fraction in the figure two is practically constant in a larger flotsam of the bed using this value on approximation for M can be is equal to this year. In this earlier that figure we have shown there and they are see here this M, then it is very interesting that you have to obtain this M value to actually analyze whether there will be the complete segregation or the complete mixing is there or not to describe the degree of particle separation in the bed.

(Refer Slide Time: 24:11)

Segregation Index

- To describe the degree of particle separation in the bed, the segregation index defined by Chiba et al. (1982) may be more convenient
- The segregation index for a binary system, S , is defined as

$$S = \frac{\text{Mass fraction of floatsam in the top portion of the bed}}{\text{Flotsam mass fraction in a perfect mixed bed}} = \frac{\bar{X}_{sf, top}}{\bar{X}_{sf}}$$

$S = 1$: a state of perfect mixing
 $S = 1 / \bar{X}_{sf}$: a state of complete segregation

Since for binary system

$$\bar{X}_{sf} = 1 - \bar{X}_{sj}; \quad M = \frac{1 - S\bar{X}_{sf}}{1 - \bar{X}_{sf}} = S + \frac{(1-S)}{\bar{X}_{sj}}$$

No general and useful mixing index has been suggested for multicomponent systems yet

The segregation index defined by Chiba et al., 1982 may be more convenient to analyze this segregation mixing behaviour inside the bed. The segregation index for a binary mixture that is S is defined as that S will be is equal to mass fraction of flotsam in the top flotsam of the bed by flotsam a mass fraction in a perfect mixed bed here this is based on the flotsam; whereas, in the earlier case mixing index is defined based on that jetsam.

So, here this segregation index defined by that flotsam. So, X_{sf} top by mean or this excessive will be there.

So, if S is equal to 1 what does it mean that; will be a perfect mixing step whereas, S is equal to 1 by mean of that mass fraction of this float solid will refer to the state of complete segregation there; and since for the binary mixture you will see that X_{sf} bar that will be equal to 1 minus X_{sj} bar that will mean of these flotsam solids that will be is equal to one minus mean of the jetsam solid fraction.

So, M and S what is the relationship that M will be is equal to 1 minus S into X_{sf} bar by 1 minus X_{sf} bar. So, it will be is equal to S plus 1 minus X_{sf} bar by X_{sj} bar. So, they are you will see you can then similarly you can actually analyze by that segregation phenomena by this parameter S in the fluidized bed.

(Refer Slide Time: 26:07)

Nienow et al. (1987) Model:

Mixing index M correlated with the gas velocity by :

$$M = \frac{1}{1 + e^{-z}}, \quad z = \left[\frac{u - u_{t0}}{u - u_{mf,F}} \right] e^{u/u_{t0}} \quad \text{Nienow et al. (1987)}$$

The takeover velocity u_{t0} , where $\frac{dM}{d(u - u_{mf,F})} = \text{Maximum at } M = 0.5$

$$\frac{u_{t0}}{u_{mf,F}} = \left[\frac{u_{mf,J}}{u_{mf,F}} \right]^{1.2} + 0.9(\rho_R - 1)^{1.1} d_{ER}^{0.7} - 2.2(\bar{X}_J)^{0.5} (H^*)^{1.4}$$

Where $\rho_R = \rho_J / \rho_F$, $d_{ER} = (\phi_J d_J) / (\phi_F d_F)$, $H^* = 1 - \exp(-H / d_{bed})$

ρ is density, ϕ is sphericity, H is height and d_{bed} is diameter of bed
J refers jetsam and F refers flotsam

And now Nienow et al., 1987 they have actually developed one model based on this mixing index they have correlated with the gas velocity with this mixing index like this year.

So, they have correlated to the as this they have given this correlation as M is equal to 1 by 1 plus e to the power minus z; where z is the parameter, which is the depending on the gas or fluid velocity inside the bed and this will be defined as the that will be equals to u minus u t 0 by u minus umf f into e to the power u by eight zero. So, in this case a terminal velocity at this ah; that is take over velocity it is called that take velocity u t 0; where this u t 0 will be obtained from this correlations; that is given by Nienow et al., 1987.

So, in this case very interesting that rho R is 1 parameter; that is the ratio of that density of that jetsam flotsam and density of that flotsam of the solids inside the bed whereas, dER is another one important parameter, which is defined as that phi J d J d J by phi F d F what is this phi; that is sphericity of that jetsam particles and d J is called here the diameter of that solid particles which is the in the class of jetsam.

Whereas, this F will represent that flotsam of that particular a diameter of that flotsam and the phi F for R sphericity for that flotsam particle and H star this is defined as that; what if the in terms of ratio of their total height of that of bed to the a bed diameter there. So, H star should be is equal to 1 minus exponent of minus H by d bed.

So, by this equation here as far this Nienow et al., 1987, you will be able to calculate, what will be the mixing index; when the fluidized bed is operated under a certain gas velocity.

(Refer Slide Time: 28:31)

Wu and Baeyens (1998) Model

- The excess gas flow rate required to prevent segregation in a fluidized bed with a wide size distribution of powder can be calculated from the mixing index expression shown in the equation (Wu and Baeyens, 1998)

$$M = 1 - 0.0067 d_R^{1.33} \left(\frac{G_B}{A} \right)^{-0.75};$$

$d_R = d_B / d_s$ // $d_B =$ bigger particle diameter
 $d_s =$ smaller particle diameter

- For $d_{ER} \approx 2$, good mixing ($M \geq 0.9$) can be achieved when the visible bubble flow G_B/A is larger than about 0.094 m/s.

There another important model that is given by Wu and Baeyens 1998 they have developed their model with the excess gas flow rate that should be required to prevent; that segregation in a fluidized bed with a wide size distribution. And in that case they have calculated that mixing index from their actually bubble flow of phenomena.

So, they have correlated this mixing index with that; what is that bubble flow rate; like this here M will be equals to 1 minus 0.0067 dR to the power 1.33 into GB by A to the power minus minus 0.75; what is GB; is they call here a bigger particle diameter this dR here; in this case dR is defined as d B by ds; what d B d B is called bigger particle diameter, where d s is called smaller particle diameter.

Now for d E R if it is equal to 2; that means, d R if d ER or effective this bubbled diameter ratio sorry not bubbled diameter this is called that particle diameter ratio.

If it is approximately equals to 2 then you will get the good mixing for M is greater than is equal to 0.9 whereas, when the visible bubble flow is GB by a is larger than about 0.094 meter per second.

You can also observe that good mixing inside the fluidized bed. So, this mixing index will give you the; how or what extent to the mixing of solids inside the bed without doing any experiment by pressure particle or pressure techniques also here.

(Refer Slide Time: 30:33)

Yang and Keairns (1982) Model

- According to them, the particle segregation in a fluidized bed can be simulated by two perfectly mixed fluidized beds in series with particle interchange between them.
- The particle exchange is assumed to be accomplished by bubble wakes from the bottom to the top fluidized bed and by bulk solids flow in the reverse direction
- The resulting equation is

$$\ln \left[\frac{V_1(1-C_{F,w})-V_{J1}}{V_1(1-C_{F,w})-V_{J1}^0} \right] = - \frac{(u-u_{mf2})A_w f_w (1-\varepsilon_w)}{V_1} z$$

If the bubble wake contains pure flotsam, $C_{F,w} = 0$

$C_{F,w}$ = volumetric flotsam concentration (fraction) in the wake phase
 f_w = wake fraction
 V_1 = volume of solids in fluid bed 1 excluding volume of the voids between particles
 ε_w = voidage in the wake

So, another important model; that is developed by Yang and Keairns 1982 according to their model they have assumed that the particle segregation in a fluidized bed can be simulated by two perfectly mixed fluidized bed in series with particle that will interchanged between them.

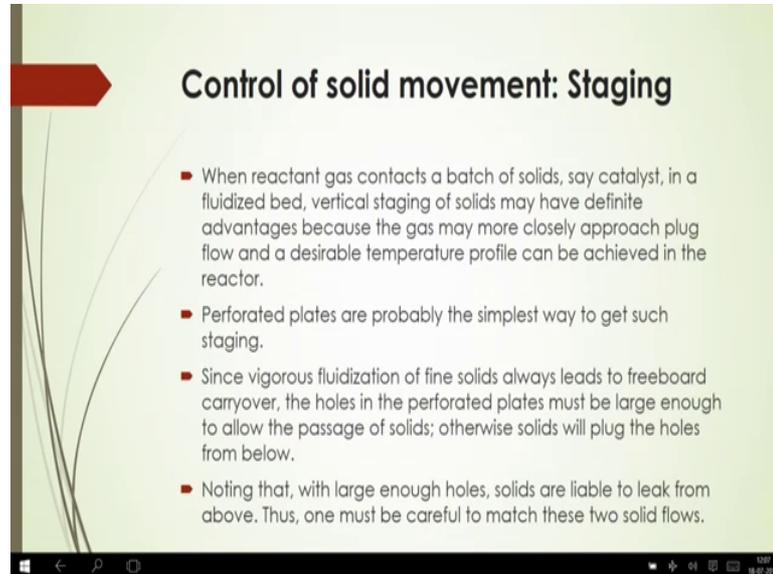
During their flow upward or downward movement in the fluidized bed; and that particle exchange that will be actually occurred by the bubble wakes from the bottom to the top; fluidized bed and and and by bulk solids flow in the reverse direction.

During the bubble flow inside the bed and they have given that final equation from their derivation like this; that \ln into $V_1(1-C_{F,w})-V_{J1}$ by $V_1(1-C_{F,w})-V_{J1}^0$ and 0 here in this case.

So, here $C_{F,w}$ is called the volumetric flotsam concentration; that is fraction in the wake phase and f_w is the wake fraction and V_1 is called volume of solids in the fluid bed, excluding a volume of the solids excluding volume of the voids between particles and ε_w is called the void is in the wake region of this fluidized bed.

And if the bubble wake contains pure flotsam particles then you can say that C_F, W will be equals to 0.

(Refer Slide Time: 32:27)



Control of solid movement: Staging

- When reactant gas contacts a batch of solids, say catalyst, in a fluidized bed, vertical staging of solids may have definite advantages because the gas may more closely approach plug flow and a desirable temperature profile can be achieved in the reactor.
- Perforated plates are probably the simplest way to get such staging.
- Since vigorous fluidization of fine solids always leads to freeboard carryover, the holes in the perforated plates must be large enough to allow the passage of solids; otherwise solids will plug the holes from below.
- Noting that, with large enough holes, solids are liable to leak from above. Thus, one must be careful to match these two solid flows.

Now, how to control this solid movement staging is important; one important actually way to that control of solid movement inside the bed, when that reactant gas contacts a gas of solids, you will see in a fluidized bed, vertical staging of solids may have definite advantage, because the gas may more closely oppose plug flow and a desirable temperature profile that can be achieved in the reactor, because of that a closely approached plug flow behaviour inside the bed.

And perforated plates are preferably preferably actually suggested the; to get such the staging phenomena to control the solid movement. And there will be of course, the vigorous fluidization of the solids when it will be operated at the first fluidization condition.

So, that may lead to the freeboard carry over and the holes in the perforated plates. In that case you have it will be design in such a way that should be large enough to allow the passage of solids there; otherwise solids will plug the holes from the below and the there will be actually clogging of that particles inside the hole of the distributor and which may actually affect the fluidization phenomena inside the bed.

And, when the large enough holes will be actually designed or will be given their solids and able to leak from above also; so, thus one must be careful to match these two solids flow which that are going up and downward to through that poles.

(Refer Slide Time: 34:38)

Control of solid movement: Staging

- Consider two stages of a multistage fluidized bed, as shown in Fig. 4.
- When equilibrium is established in terms of solid flow, the downflow leakage rate $G_{s,down}$ must just match the upflow freeboard entrainment rate $G_{s,up}$.
- Thus, the solid interchange rate per unit cross-sectional area of the baffle plate is

$$G_{s,up} = G_{s,down} = I_s f_{open} \quad [\text{kg/m}^2 \cdot \text{s}]$$

where I_s is the flux based on the open area of holes ($\text{kg/m}^2 \text{ holes} \cdot \text{s}$).

$G_{s,up}$ is related to the entrainment rate of solids from an ordinary fluidized bed having the same freeboard height Z_f

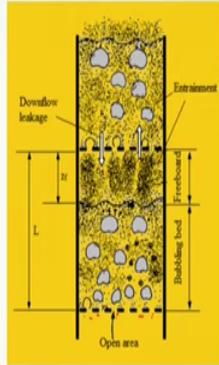


Fig. 4. Two stages of a multistage fluidized bed showing the flow of solids across a baffle plate

Kunii and Levenspiel, 1991

So, you have to optimize that design to control this solids movements around the distributor there and considered two stages of multi stage the fluidized bed as shown here in the figure 4. See here in this case this is your perforated distributor these through plate, these gases coming up and also you will see there will be a solid movement to this hole and the some through the holes also some solids also will be coming downward there.

So, there will be some entrainment of the solids through this perforated holes are and some solids will be downward; the flow due to that that is leakage it is called leakage of that solids; when will be going downward there.

So, there will be a stage in such a way that that in this stage there will be a bubbling bed and the freeboard and from that freeboard to that upper stage of this fluidized bed through the distributor hole. The entrainment of the up fine solids will be going upward whereas, some solids may go downward as a leakage there.

So, when equilibrium is established when the in terms of this solid flow the down flow leakage rate; if it is G_s down must just have just match this upward freeboard entrainment rate there in the fluidized bed.

So, in that case you will see to get this equilibrium condition one another important point to be noted here that; if is there any interchange of the solid particles during this solid movement upward or downward is there or not so, in that case the solid interchange rate also to be concluded there.

So, thus the solid interchange rate per unit cross sectional area of the baffle plate can be taken care of that. So, in that case G_s up; that means, the solid flux to that up is equal to solid flux to the down that will be is equal to is into f open whereas, is called here the flux based on the open area of holes they are through which that solid particles would be coming up and down there and this G_s up is related to that entrainment rate of the solid from the ordinary fluidized rate having the same freeboard height of Z_f there that has already been discussed in the earlier lectures also; there how the entrainment characteristics can be calculated by the model equation they are.

So, the several modern equations has been discussed there, in the earlier lectures the for this entrainment rate. So, this that entrainment rate model can be applied here, for this freeboard region where those where those solids will be coming up as per this entrainment mechanism.

Now, the most important parameters to influence this upward movement of the solids are the freeboard height Z_f and the u .

(Refer Slide Time: 37:43)

Control of solid movement: Staging

- The most important parameters to influence G_{sup} are the freeboard height Z_f and u .
- The downflow leakage of solids increases with both the hole diameter and the fraction of open area of the plate.
- Thicker plates result in less leakage.
- **Kono and Huang (1984)** suggested using long downcomer pipes at the baffle plates to reduce the downflow.

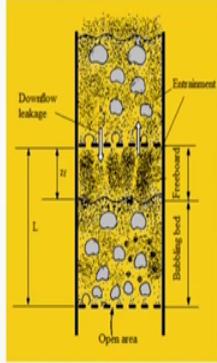


Fig. 4: Two stages of a multistage fluidized bed showing the flow of solids across a baffle plate.

And also you have to actually design that the staging operation, in such way that; that we have to give the enough space for that; freeboard there and also the down flow leakage of the solids, that will increase with the with both the full diameter and the fraction of the open area of the plate.

As per that given equation and ticker plates sometimes results in less leakage and also long downcomer pipes at the baffle plates to reduce the down flow that has been suggested by that Kono and Huang 1984.

(Refer Slide Time: 38:18)

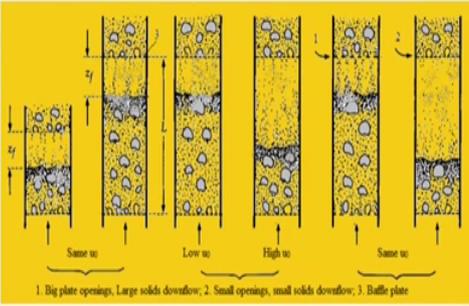


Fig. 5:

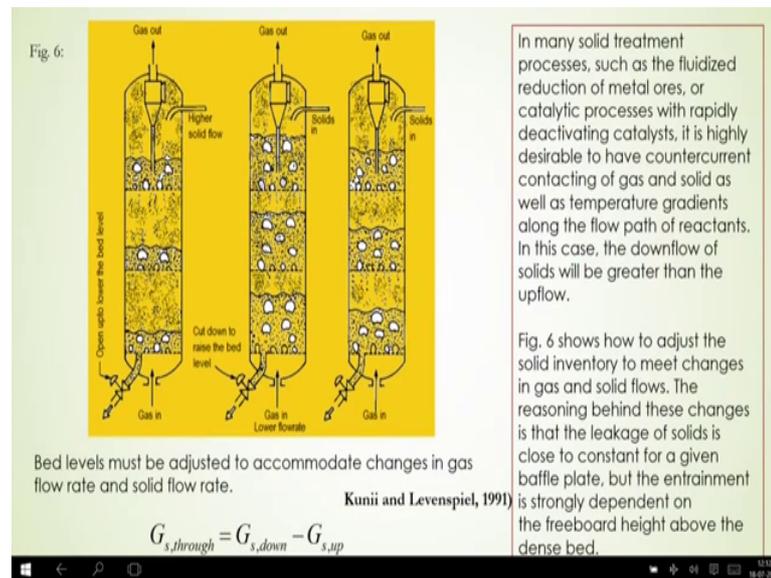
Kunii and Levenspiel, 1991)

- Figure 5 illustrates how changes in the different variables will influence the interchange rate of solids between stages.
 - (a) For different baffle spacing L , the same freeboard height gives the same solid interchange,
 - (b) High gas velocity must be matched with an increased freeboard,
 - (c) Bigger baffle openings must be matched by smaller freeboard.

Figure 5 here in this case shows that that; how change in the different variables will influence the interchange rate of solids between stages there.

So, for different weapon spacing L , you will see that the same free board height gives the same solid interchange. And the high gas velocity must be matched with an increased freeboard; whereas, the bigger baffle opening must be matched by the smaller baffled or freeboard.

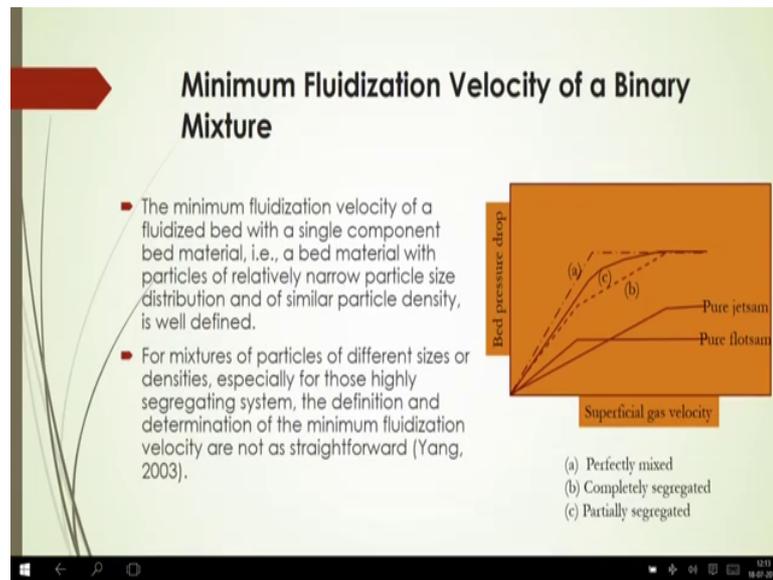
(Refer Slide Time: 38:50)



And the bed levels must be adjusted to accommodate changes in gas flow rate; and the solid flow rate by this equilibrium equation, that is; G_s through that will be equals to G_s down minus G_s up and in many a solid treatment you will see that fluidized bed that is the reduction of the metal ores, or catalytic processes with rapidly deactivating catalyst, it is highly desirable to have this counter current contacting of the gas and solid as well as temperature gradients along the flow part of the reactants.

So, in those cases the down flow of solids will be greater than the up flow and this figure 6 shows; that that how this adjustment of the solid inventory to meet changes in gas; and solid flows the reasoning behind these changes is that the leakage of solids is close to constant for a given baffle plate and, but the entrainment is strongly depending on the freeboard height above the dense rate also.

(Refer Slide Time: 40:03)



Now how to calculate the minimum fluidization velocity for a binary mixture, you will see that this jetsam and flotsam mechanism or this segregation or mixing mechanism that depends on that mixing of the solids of course, whether these solids are in a binary component mixture or single component mixture or not or even multi component mixture or not.

You will see in that case you have to know what should be the minimum fluidization value (Refer Time: 40:37) there and because of which that beyond this minimum fluidization velocity, then the segregation index are to be analyzed there now the minimum fluidization velocity of a fluidized bed with a single component material that has already been actually discussed earlier.

But for mixture of particles of different sizes or densities are especially for those have highly segregating system. In that cases the determination of the minimum fluidization velocity is, not straightforward that is stated by the Yang 2003. So, that you have to actually consider whether this perfectly mixed fluidization condition or not or completely segregated condition or not or partially it is segregated that solid particles or not.

So, based on which you will be able to calculate what would be the minimum fluidization velocity of a binary mixture there.

(Refer Slide Time: 41:38)

Goossens et al. (1971) Model for minimum fluidization for binary mixture

- Goossens et al. (1971) modified the equation by Wen and Yu (1966) on the minimum fluidization velocity for single particle size systems by substituting with the mixture particle density, $\bar{\rho}_p$, and the mixture particle size, \bar{d}_p , of a binary mixture as follows

$$\frac{\bar{d}_p \mu_f \rho_f}{\mu} = \left[(33.7)^2 + 0.0408 \frac{\bar{d}_p^3 \rho_f (\bar{\rho}_p - \rho_f)}{\mu^2} \right]^{0.5} - 33.7$$

$$\frac{1}{\bar{\rho}_p} = \frac{\bar{x}_F}{\rho_F} + \frac{1 - \bar{x}_F}{\rho_J}$$

$$R = (1 - \bar{x}_F) \rho_F (d_p)_F + \bar{x}_F \rho_J (d_p)_J$$

$$\bar{d}_p = \left(\frac{R_0}{R} \right) (d_p)_F (d_p)_J$$

$$R_0 = (1 - \bar{x}_F) \rho_F + \bar{x}_F \rho_J$$

Now, Goossens et al., 1971; they have given this model for calculating or estimating the minimum fluidization velocity for binary mixture as for their experimental the data. And they have developed this minimum fluidization velocity at this binary mixture condition as like this here.

In this case you will see that they have take a the particle density or fluid you can say bulk density as the average bulk density and also that average the what is that a particle density there. So, as far their the average fluid particle is actually calculated as $1/\rho_p$ is equal to $x_F/\rho_F + (1-x_F)/\rho_J$ here. So, in this case if there are there some float jet and jetsam flotsam and jetsam particles are there of the mixture.

Then the effective density of the fluid particle mixture inside the bed will be is equal to; that means, $x_F/\rho_F + (1-x_F)/\rho_J$ here x_F means here; the mass fraction of the solid particles of those flotsam particles and ρ_J is called that the density of the jetsam particle and ρ_F is called the density of the flotsam particles there.

And respective concentration of that jetsam and flotsam will be is equal to x_{FJ} and x_{FF} for that jetsam and flotsam and here the effective particle diameter of those mixture will be calculated as here $R_0/R \cdot d_{pF} \cdot d_{pJ}$ here d_{pF} is called the particle diameter of those particle of that flotsam and d_{pJ} is called the particle diameter of those jetsam particles there in the bed where this capital R; we is defined as that what should

be the value of this effective; what is that effective particle size based on their concentration of the jetsam and flotsam particles there.

So, it will be defined as $1 - x_F \bar{\rho}_F d_p F + x_F \rho_J d_p J$ here. So, R_0 will be is equal to; there if there only this flotsam and jetsam particles are equals to 1 there. So, it will be like this will be is equal to R_0 there for this.

So, you can calculate the minimum fluidization velocity for binary mixture of this flotsam and jetsam particles by having their mixture particle density of ρ_p bar and; that means, a was is a particle density and the mixture particle size as you know particle diameter of a binary mixture from this equation here and Cheung et al., 1974.

(Refer Slide Time: 45:16)

Cheung et al. (1974) Model

- Cheung et al. (1974) proposed an equation for binary systems with particles of similar density and with particle size ratios of less than 3. The equation for the minimum fluidization velocity of the mixture is expressed as

$$(u_{mf})_M = (u_{mf})_F \left[\frac{(u_{mf})_J}{(u_{mf})_F} \right]^{x_J^2}$$

They have also proposed an equation for binary systems with particles of similar density and with particle size ratio; when it is less than 3. The equation for that minimum fluidization velocity of the mixture can be expressed as u_{mfM} that will be is equal to u_{mfF} into u_{mfJ} by u_{mfF} to the power x_J square here.

So, u_{mfM} means here mean minimum fluidization velocity for this mixture that will be equal to u_{mfF} ; that means, here minimum fluidization velocity; if the fluidized bed is operated with this flotsam particles only and also if the minimum fluidization velocity is operated under jetsam particles.

So, once you know this minimum fluidization velocity for that, individual class particles of that jetsam and flotsam and from those values of these jetsam and flotsam minimum fluidization velocity you can calculate the minimum fluidization velocity for that mixture in the fluidized bed.

(Refer Slide Time: 46:43)

Chiba et al. (1979) Model

- Chiba et al. (1979) also proposed two equations to estimate the $(U_{mf})_M$ for a completely mixed bed and the $(U_{mf})_S$ for a totally segregated mixture.
- By utilizing the Ergun equation and the constant voidage assumption, they proposed to estimate the $(U_{mf})_M$ for a completely mixed binary system as

$$(u_{mf})_M = (u_{mf})_F \frac{\bar{\rho}_p}{\rho_F} \left[\frac{\bar{d}_p}{(d_p)_F} \right]^2$$

$$\bar{\rho}_p = f_{VF} \rho_F + (1 - f_{VF}) \rho_J$$

$$\bar{d}_p = \left[f_{NF} (d_p)_F^3 + (1 - f_{NF}) (d_p)_J^3 \right]^{1/3}$$

where f_{VF} is the volume fraction of flotsam

Chiba et al., 1979 they have also proposed to equations to estimate the mixture minimum fluidization velocity for a completely mixed bed and the minimum fluidization velocity for the solids for a totally segregated mixture there. By utilizing the Ergun equation they have developed this equation and the constant voidage assumptions, they have taken there and they proposed the correlations to estimate this u_{mfM} that is mixed and minimum fluidization for completely mixed binary system as this equation here.

In this case also they have defined these mixture particle density and the; what is that; effective particle diameter based on that a fraction of that non fraction of that, that is called flotsam and jetsam particles there, and this f_{VF} is the volume fraction of the flotsam is represented in this case here.

(Refer Slide Time: 47:55).

f_{NF} is the number fraction of the flotsam particles and can be evaluated as

$$f_{NF} = \left\{ 1 + \left(\frac{1}{f_{VF}} - 1 \right) \left[\frac{(d_p)_F}{(d_p)_J} \right]^3 \right\}^{-1}$$

For a completely segregated bed, the following equation should be employed

$$(u_{mf})_M = \frac{(u_{mf})_F}{\left[1 - (u_{mf})_F / (u_{mf})_J \right]^{1/f_{VF}} + (u_{mf})_F / (u_{mf})_J}$$

f_{NF} is the number of fraction of the flotsam particles and can be calculated here as by this equation. For a completely segregated bed the following equation can be employed.

(Refer Slide Time: 48:14).

Uchida et al. (1983) Model

- Uchida et al. (1983) modified the equation by Cheung et al. (1974), substituting the volume fraction for the weight fraction in the original equation and introducing an additional empirical constant, m and suggested the following equations.

$$(u_{mf})_M = (u_{mf})_F \left[\frac{(u_{mf})_J}{(u_{mf})_M} \right]^{(1-f_F)^m}$$

$$m = 0.17 \left[\left(\frac{d_J}{d_F} \right) \left(\frac{\rho_F}{\rho_J} \right) \right]^{0.437}$$

The volume-mean particle diameter rather than the harmonic mean diameter should be used in the above equation

And Uchida et al., 1983 they have developed the correlation or model based on the modification of the equation given by Cheung et al., 1974. They have substitute the volume fraction for the weight fraction in the original equation; and introduce introduced to the additional empirical constants that is defined by M here and suggested the

following equations to calculate the minimum fluidization velocity for the binary mixture here.

And this m is correlated to get particle diameter of jetsam and the flotsam and also the density of that flotsam particle and jetsam particles in the bed. And this volume in particle diameter rather than harmonic mean diameter actually should be used in this above equation they have suggested.

(Refer Slide Time: 49:12)

Minimum Fluidization Velocity of a Multicomponent Mixture

Rowe and Nienow (1975) Model

- For multicomponent particles of equal density, **Rowe and Nienow (1975)** proposed to calculate the minimum fluidization velocity of the mixture using the equation

$$(u_{mf})_M = (u_{mf})_i \left[\frac{\varepsilon}{\varepsilon_1} \left(\frac{1 - \varepsilon_1}{1 - \varepsilon} \right)^{2-n} \right]^{1/n} \times \left[\bar{x}_1 + \frac{d_{p1}}{d_{p2}} \bar{x}_2 + \frac{d_{p1}}{d_{p3}} \bar{x}_3 + \dots \right]^{1-(3/n)}$$

where n can be taken to be 1.053, an empirical value

And for multi component mixture; Rowe and Nienow 1975; they have given one important correlation for calculating the mixture minimum fluidization velocity inside the bed; so, as per their model this $u_{mf M}$; that means, mixture fluidization velocity they are the it will be is equal to that here as per this equation given in this slides.

So, here one is the important parameter is called n . n generally as per their experimental data is equals to 1.053 this will be treated as an empirical value based on the experimental data. There also it can be used to actually calculate the for multi component binary mixture to calculate this minimum fluidization velocity.

(Refer Slide Time: 50:07)

Kumar and Sen Gupta (1974) Model

- **Kumar and SenGupta (1974)** obtained the minimum fluidization velocity from the typical logarithmic plot of bed pressure drop versus fluidizing velocity for 4 single, 17 binary, 6 ternary, and 3 quaternary component mixtures
- They found that the following simple empirical equation correlated the data well. ✓

$$(\text{Re})_{mf} = \frac{\bar{d}_p u_{mf} \rho_f}{\mu} = 0.0054 (\text{Ar})^{0.78}$$
$$\text{Ar} = \frac{\bar{d}_p^3 \rho_f (\bar{\rho}_p - \rho_f) g}{\mu^2}$$
$$\bar{d}_p = 1 / \sum_{i=1}^n \frac{x_i}{d_{pi}} \quad \text{Harmonic mean} \quad \checkmark$$
$$\bar{\rho}_p = \sum_{i=1}^n \rho_{pi} \quad \text{Arithmetic mean} \quad \checkmark$$

And Kumar and Sengupta 1974 they also suggested; the minimum fluidization velocity from the typical logarithmic plot or the bed pressure drop and also the fluidizing velocity for single and also binary ternary and the quaternary component mixtures there.

And they found that the following simple empirical equation can be well fitted with the experimental data; and they have suggested this equations for prediction of that minimum fluidization velocity for those single binary, ternary and quaternary component mixture they are by taking the harmonic mean of the particle diameter and arithmetic mean of the density of the particle of that mixture.

(Refer Slide Time: 50:57)



So, in this lecture will have then actually learned something about; what would be the mixing and segregation or mechanism inside the fluidized bed; and how this mixing index and segregation index are interrelated; and how mixing index can be actually used as a tool to by interpret the extent of mixing inside the bed for this mixture solids in; and also this flotsam and jetsam parameters ah; that means, based on that there density effective density of that mixture of jetsam and flotsam and the particle diameter of that jetsam and flotsam mixture; how it actually effects on the mixing and segregation phenomena inside the bed.

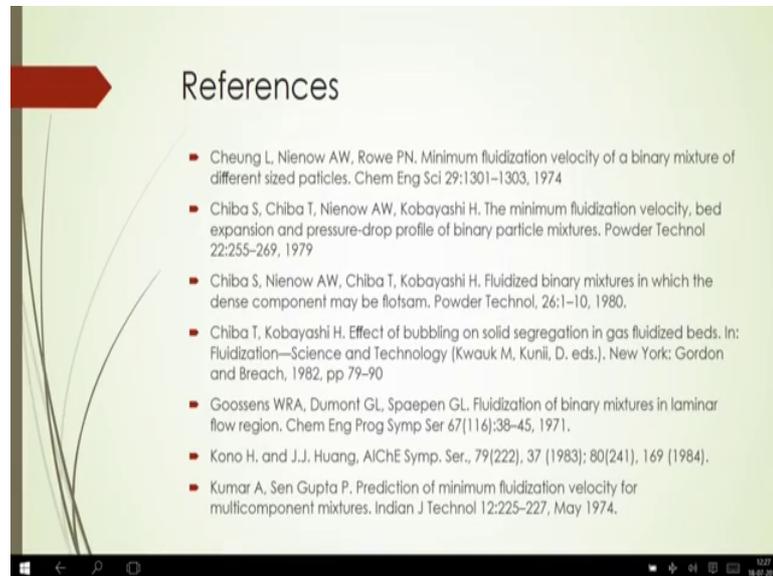
Also it is seen that that binary mixture when there will be the mixture of the jetsam and flotsam particles inside the bed, the minimum fluidization condition will be changing, it will not be exactly the same as for that when single particle single particle will be in the bed.

So, for multi component and binary component mixture, this minimum fluidization velocity to be actually calculated; before going to analyze that segregation and mixing index inside the bed and in that case the effective velocity of the fluidized bed will be based on that minimum fluidization velocity of this flotsam and jetsam, mixsam of the fluidized bed.

So, we will be discussing more about this particle mixing and segregation, if in case of liquid solid are there or for gas liquid solid system in the fluidized bed. So, this lecture

only based on that only gas solid system, but liquid solid and gas liquid solid system will be discussed in the next lecture.

(Refer Slide Time: 53:11)



Ad for this segregation and mixing phenomena for this gas solid fluidized bed you can go through more literatures for getting more information's even in more details from these references so.

Thank you.