Fluidization Engineering
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Lecture – 30
Heat transfer Characteristics

So, welcome to a massive open online course on fluidization engineering. Ah today's lecture will be on heat transfer characteristics. So, earlier we have discussed about the mass transfer characteristics for two phase and three phase systems and there we have discussed the different mechanisms and the different models to represent the mass transfer characteristics; how the component of certain inert or you can say reactive component is transferred with reactive mode from gaseous phase to the emulsion phase or vice versa by the interchange that we have discussed.

So, in this case, we will discuss about some heat transfer phenomena in this fluidization mode in this case.

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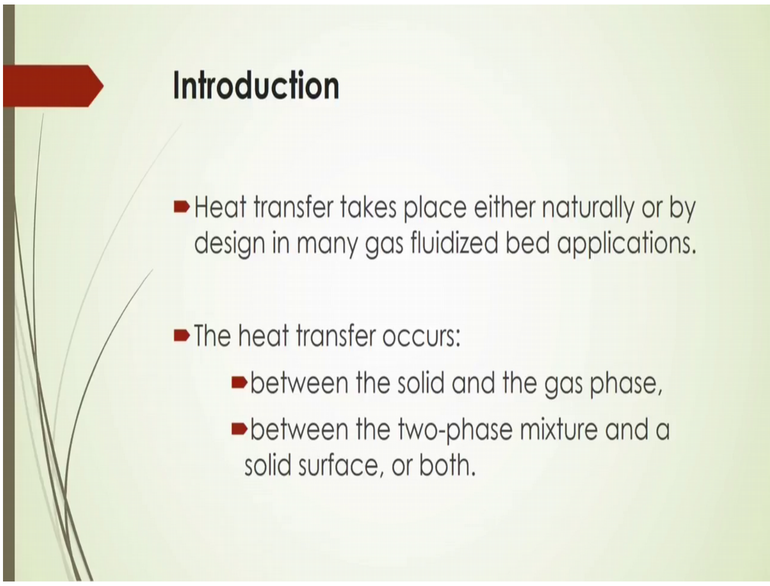

Then we should know what is the heat transfer characteristics inside the bed before going to design any well fluidized bed and also the ideal fluidized bed system and since the heat transfer characteristics has different application because this characteristics will govern the reaction mechanism as well as the transfer characteristics during the physical operation in a fluidized bed operation.

Now, you know that the heat transfer takes place either naturally or by design in many gas fluidized bed applications, they are in physical operations, you will see whenever we are going to dry the wet solids in the fluidized bed by fluidization operation, then there should be transfer of heat from one phase to the another phase and at a certain temperature; the heat transfer will be maintained in such a way that at optimum heat load the that is drying or other absorption or some other applications in fluidized bed can happen.

And that during the heat transfer you know that that the heat transfer occurs between the solid and the gas phase if there is a gas and solid fluidized bed system and also this heat transfer occurs between the two phase mixture and a solid surface or both also, if you are using the gas liquid solid system, they are will see that heat transfer will be occurring ah this two phase of gas and liquid mixture and the solid particles. Even sometimes, you will see that the heat transfer will be occurring between gas and the liquid solid slash slurry systems there.

So, in that case, the whatever mass transfer characteristics, we have learned earlier almost in all mechanism you will you can apply for this heat transfer also; there instead of mass component will be transfer here heat component will be transferred from one phase to another phase and there, we have seen that one important design parameter is called mass transfer coefficient here we will get the heat transfer coefficient.

In this case also, you will see that during that heat transfer that will be occurs by certain mechanism.

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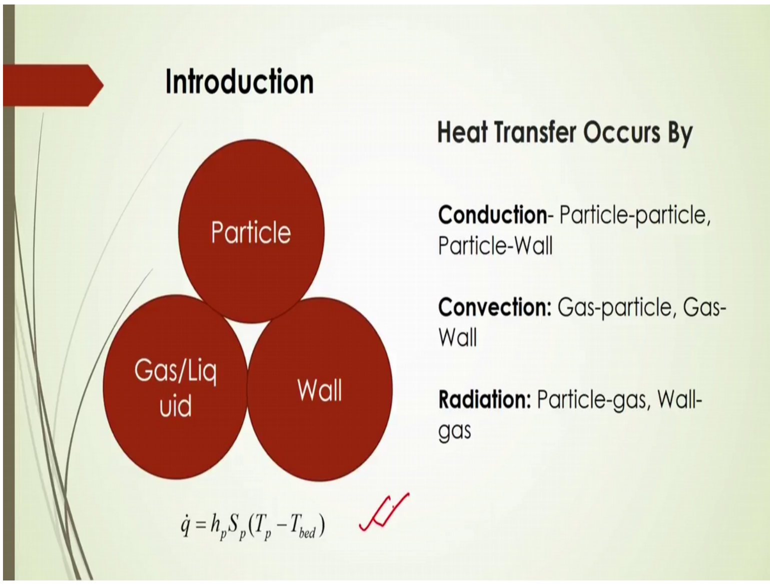

And it is well known that there are 3 types of heat transfer mechanism are there; one is conduction, another is convection and other one is called radiation. So, both 3 mechanism may happen in the fluidized bed during this heat transfer operation.

Now, conduction will may occur between particle-particle and particle wall contact and then convection will be happened within the gas particle and gas wall system and radiation will be of course, the particle gas and the wall gas system they are inside the bed and here in this picture, you will see that if we consider here this is a particle and wall and then gas liquid phase here, then there will be a heat transfer between this particle and gas liquid or gas liquid mixture, here gas liquid or gas liquid mixture with wall even particle and wall. So, the three way this heat transfer will occur inside the fluidized bed.

Now, this heat transfer how or what will be the amount of heat is transferred what is the rate of heat is transferred that can be estimated by this equation here. So, this will be denoted by q dashed q dashed in main q dot means here rate of heat transfer and h p is the heat transfer coefficient to the particle or from the particle to the medium and S p is the surface area of the particle, T p is the temperature at the particle surface and T b is the bed temperature of the fluidized system.

So, by this equation, this is the basic equation, you can calculate; what will be the rate of heat transfer there, but it may not be the conduction, it may it is called the convective heat transfer and also radiative heat transfer will be there that will be considered later on.

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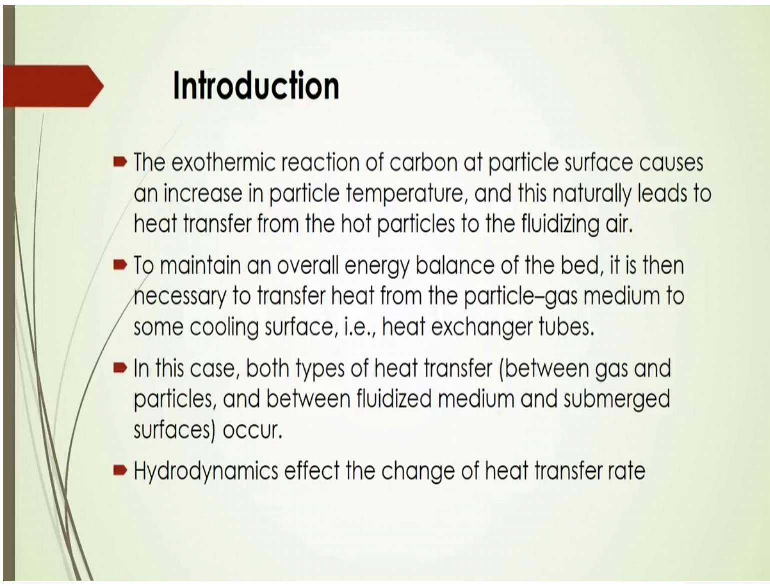

Now, where then this heat transfer characteristics will be important because anyway, we are going to study this heat transfer characteristics that should be utilized this knowledge to be utilized somewhere. So, that this heat transfer characteristics are important to say here in this fluidization operation.

Now, you know that exothermic reaction of carbon at particle surface that causes an increase in particle temperature and this naturally leads to heat transfer from the hot particles to the fluidizing gas. Now, if you want to maintain an overall energy balance of the bed, then what is necessary to actually there to know that you have to know that; what is the actually heat transfer from the particle gas medium to some cooling surfaces and; that means, heat transfer heat exchanger tubes.

So, to maintain an overall energy balance of the bed, it is necessary to transfer heat from the particle gas medium to the some cooling surfaces and how to do that may be some heat, but exchanger devices to be used for this purpose.

Now, in this case, both types of heat transfer between gas and particles and between fluidized medium and submerged surface will occur and very interesting that whatever hydrodynamic characteristics we have learned earlier, like flow pattern, hold up characteristics and the entrainment characteristics, even the mixing characteristics of the solid particles segregation and elutriation all those mechanism, all those hydrodynamics will be actually affecting the change of heat transfer rate inside the fluidized bed.

And the mechanism of heat transfer are significantly different for different fluidization regimes and generally 2 regimes of gas fluidization are mostly actually encountered in industrial of applications; one is called dense bubbling fluidized bed, another is called first circulating fluidized bed.

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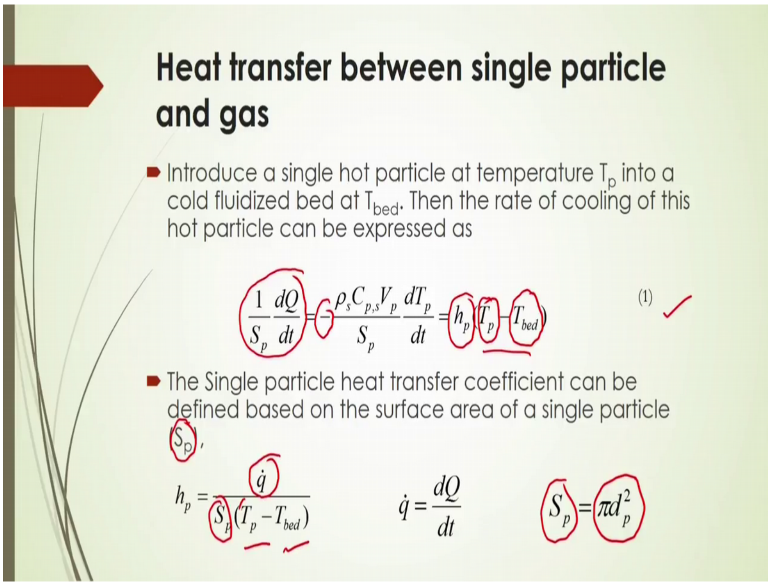

Now, anyway what should be the then heat transfer between single particle and gas because we have to know the basic fundamental law of the heat transfer from one phase to another phase, if we consider one single particle, then how heat will be transferred from this single particle to the gas there.

Now, if we introduce a single hot particle at temperature suppose T p into a cold fluidized bed at a temperature of T bed, then the rate of cooling of this hot particles can be expressed by this equation number 1 here, in this case this left hand side of this equation will be S equal to 1 by S p into d Q by d t; that means, here the rate of heat transfer that will be is equal to minus rho S C p S into V p by S p rho S is called particle density or solid density C p S is called the specific heat capacity of the solid and V p is the volume of the particle S p is the surface of the particle and d T p by d T means here with respect to time how or what will be the amount of temperature of the particle is changing.

Now, here changing; that means, hot particle will be going to the cold one that is it will remove its temperature to the lower temperature that is why here a negative sign is coming. So, this rate of heat transfer can be expressed by how what is the; then what will be the temperature of the bed that you have to know. Now if we supply the gas or liquid inside the bed, then of course, you will see for the single particle that heat will be removed from this single particle to the medium.

Now, if the medium temperature is T bed; that means, bed fluidized bed temperature is T bed and the particle temperature is T p, then what will be the temperature difference is there, then it will be T p minus T bed,, this is the driving force of the heat transfer and then this of course, heat rate of heat transfer will be proportional to this driving force of this temperature and this proportionality constant will be called that heat transfer coefficient. Now since we are applying this on this single particle, then it will be called as single particle heat transfer coefficient.

So, the single particle heat transfer coefficient can be defined based on the surface area of the single particle that is denoted by S p. So, h p will be is equal to q dot; q dot means d Q by d T that divided by surface area of the particle into here this temperature driving force here T p minus T bed and here S p; S p is the surface area of the particle which will be calculated by this equation here that will be pi d p square; that means, here particle diameter if we know, then the surface area will be is equal to pi d p square if we consider that particle is a spherical one.

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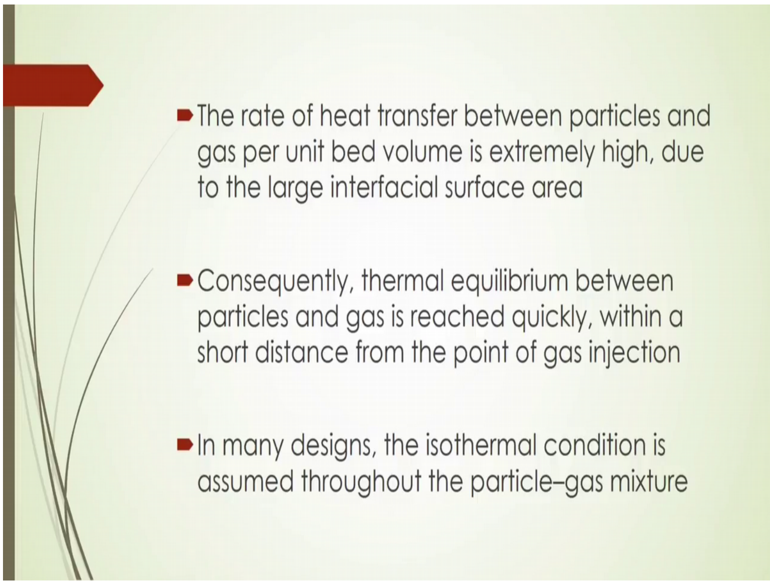

Now, the rate of this heat transfer between the particle and gas per unit bed volume is extremely high. So, due to the large interfacial surface area, if we decrease the if we decrease the size of the particles, you will see that more surface area of the particles will be inside the bed and because of which you will get the more surface area for the transferring of heat from this sub particle to the medium.

So, that is why the rate of heat transfer between particles and the gas in the whole fluidized bed per unit bed volume will be very high due to the large interfacial area consequently you can say that there will be a thermal equilibrium. Now this thermal equilibrium between this particle and then gas reached very fastly within a short distance from the point of gas supply.

So, that is why you will see that there will be a thermal equilibrium rapid thermal equilibrium within a short distance from the point of gas injection in many designs; you will see that the isothermal condition is generally assumed throughout the particle gas mixture because of that uniform uniform mixture or uniformly distribution of the heat inside the bed.

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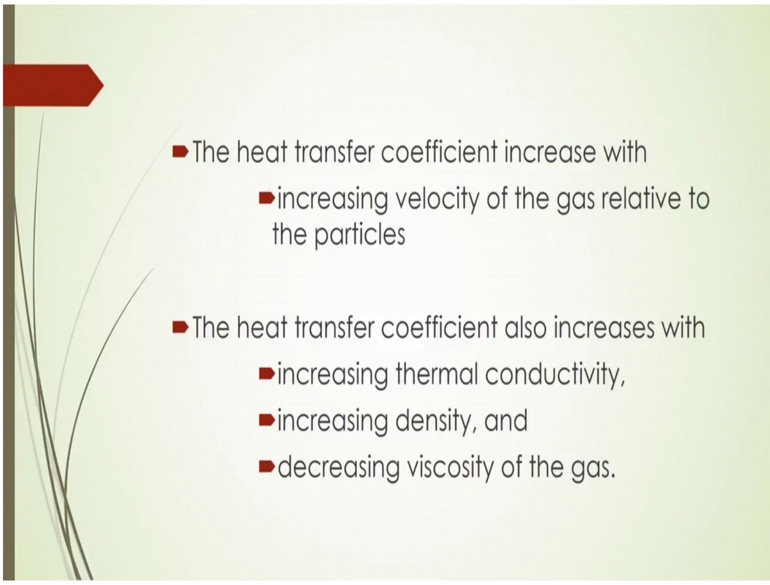

Now, the heat transfer coefficient you will see it will increase with increasing velocity of the gas relative to the particles. So, of course, this you will see whenever you are going to estimate this heat transfer coefficient, this heat transfer coefficient will be changing with different operating variables. So, gas velocity is one important operating variables, if the gas velocity related to the solid particles velocity, we know if you will see that the increasing velocity of the gas the related to that solid particles that will increase the heat transfer coefficient and also, this heat transfer coefficient will increase with increasing thermal conductivity.

That means, physical properties of the system physical properties of the particle even particle density even viscosity of the gas, you will see that this heat transfer coefficient to increase with thermal conductivity and increase with density and also, it is very interesting that the heat transfer coefficient will decrease with the viscosity of the fluid.

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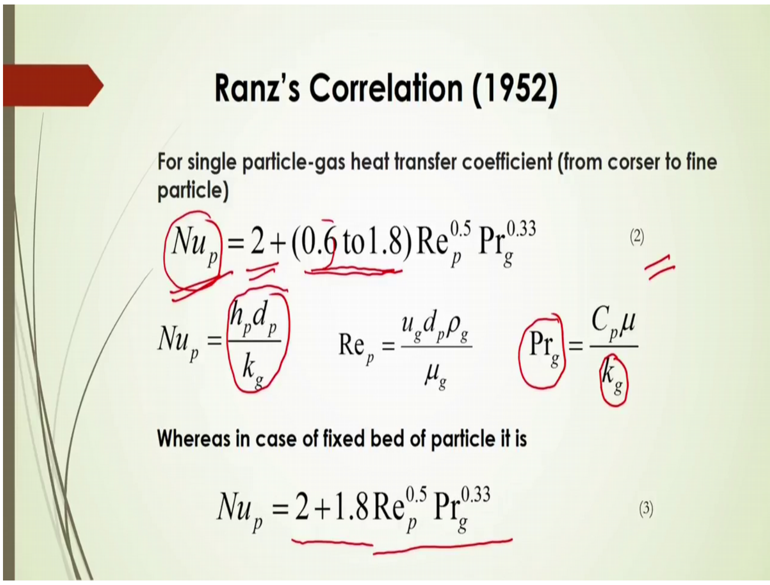

Now, for single particle gas heat transfer coefficient range; 1952, they have proposed one correlations from their experimental data and they have observed that the heat transfer coefficient will be ranging from certain value to certain value. In this case, they have expressed; they are experimental results by a correlation of equation 2 given here by this Nusselt number; Nusselt number of particle that will be is equal to 2 plus 0.6 to 1.8 into Re p to the power 0.5 into Prandtl number to the power 0.33.

In this case, you will see that the for single particles if it is finite to the course are that it will change accordingly these 0.6 to 1.8 for very fine particles, it is generally 0.6 for Corser particles, it is generally 1 point for finer particle 1.8 for Corser particle 0.6 here.

So, if there is no flow of the gas or fluid inside the bed, then there will be a natural convict convection of the heat natural transfer of the heat, then that Nusselt number will be is equal to there 2. So, this Nusselt number of particle will be defined as h p d p by k g; what is h p? H p is called the heat transfer coefficient of the single particle, d p is the particle diameter and k g is the thermal conductivity of the gas in which medium these particles are suspending and Re p; Re p is called the Reynolds number based on the particle diameter and here, it is defined as U g d p rho g by mu g here d p is the particle diameter rho g and U g are the density and velocity of the gas and mu g is the viscosity of the gas.

Here Prandtl number; Prandtl number is C p mu by k C p is the specific heat capacity of the particle and here, mu is called the viscosity of the gas and k g is the thermal conductivity of the gas. So, if you ah if you know this Reynolds number, Prandtl number and also other other operating conditions, then from equation 2, you will be able to calculate; what should be the heat transfer coefficient of the single particle from this Corser to the fine particle there.

Whereas in case of fixed bed of particle, it is seen that this Nusselt number will be is equal to 2 plus 1.8 Re p to the power 0.5 into Prandtl number to the power 0.33; that is given in equation number 3. In this case for fixed bed this also the same value, if we only consider that Corser that is finer particles of the fixed bed condition, then we can compare it that almost equals to same heat transfer coefficient for this case.

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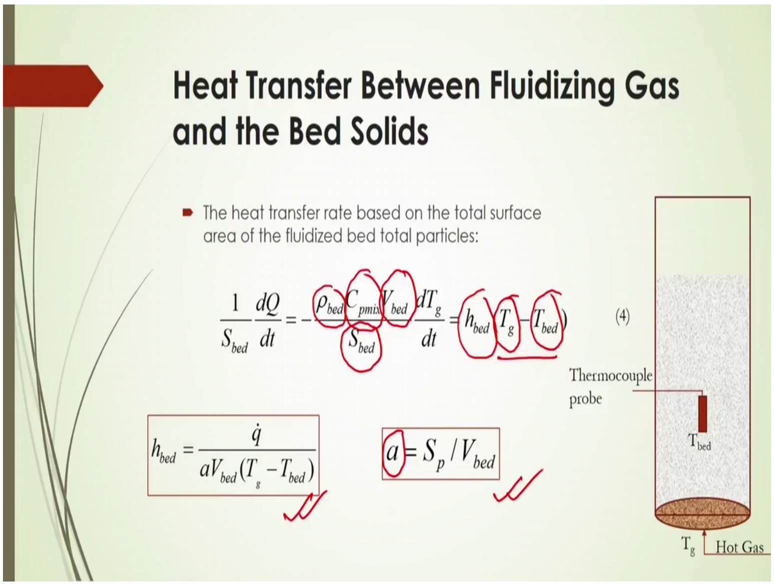

Now, heat transfer coefficient between fluidizing gas fluidizing gas and the bed solids now; the heat transfer rate based on the total surface area of the fluidized bed for the total particles can be expressed by this equation number 4. So, again the same way; we can consider here; in this case instead of single particles, we will consider the properties of the fluidized bed here like bulk density of the bed, here surface area surface area of the bed total volume of the bed the mixture specific heat capacity and then these what is that d T g by d t means here change of temperature of the gas with respect to time and here T g is the temperature of the gas and T b; T bed is called the Bed temperature.

So, what will be the difference T g minus T bed and this proportionality constant would be called as h bed, h bed is denoting the bed heat transfer coefficient instead of only single particle of heat transfer coefficient. So, h bed will be represented by this equation here, this q dot by a into V bed into T g minus T bed whereas, a small a is called specific interfacial area; that means, surface area of the particles divided by the total volume of the bed here.

So, this is called specific interfacial area. So, again if we here supply some hot gas; they are and if we measure the temperature change of that medium from its medium, then how this gas will be changing its temperature and from which will be able to calculate; what should be the heat transfer coefficient and this bed heat transfer coefficient will be denoted by this h bed.

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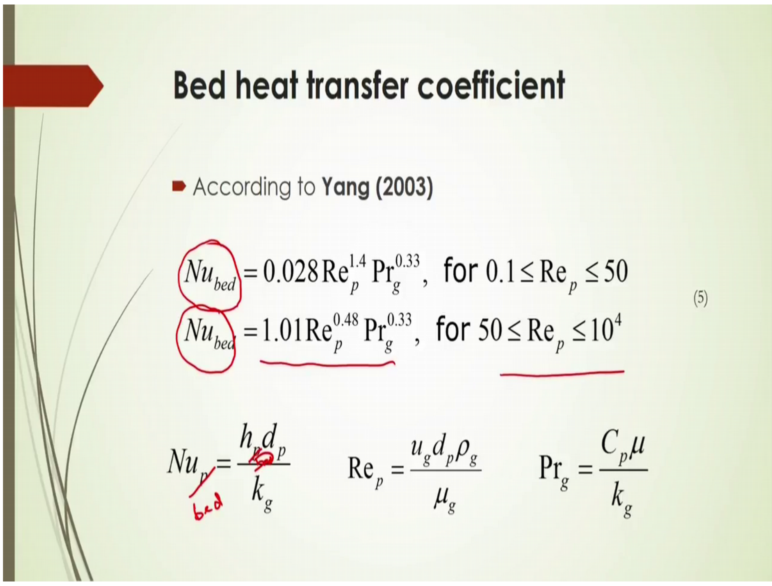

Now, according to Yang; 2003, they have proposed two correlations within a 2 operating ranges; they are to predict the heat transfer coefficient from their experimental data. So, in that case, they have expressed that Nusselt number of bed, this Nusselt number of bed that will be is equal to 0.028 into Reynolds number of particle to the power 1.4 into Prandtl's number of the gas to the power 0.33 and in this case, these correlations is applicable only for Reynolds number of particles from 0.1 to 50.

Whereas, if the Reynolds number is greater than 50 and up to up to 10 to the power 4, then this Nusselt number of bed will be represented by this correlations, here 1.01 into

Re p to the power 0.48 into Prandtl number to the power 0.33. So, by these equations, within this certain range of Reynolds number, you will be able to calculate; what should be the bed heat transfer coefficient, once you know that Nusselt number of the bed here.

So, Nusselt number of the bed instead of particle, it will be represented here p instead of p; it will be bed and here h p instead of h p, it will be is equal to h bed and others remain same here physical properties will be considered as the average temperature of that bed temperature and the gas temperature and the mixture properties and here in see in this diagram the Nusselt number of the particles and the Nusselt number of the bed is drawn with respect to Reynolds number of the particles there.

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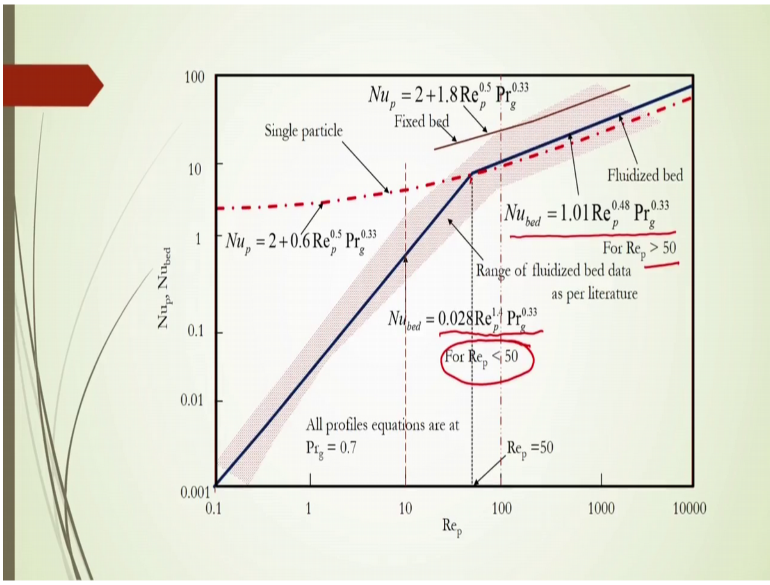

So, here we are seeing that this line this farm line is giving the heat transfer coefficient equation or Nusselt number bed equation for the fluidized bed system. So, in this case up to here Reynolds number of 50, there will be a certain increase of Nusselt number of the bed here up to this and again here this profile is actually followed by this equation of Nusselt number of bed is equal to 0.02 h Reynolds number to the power 1.4 into Prandtl's number to the power 0.33 within a range of Reynolds number of particle less than 50.

Whereas above this Reynolds number of 50, there you will see the slope of this line will be decreasing higher, this profile will be represented by these correlations here and this correlations will be applicable only for this Reynolds number is greater than 51 important aspect here, it is seen that here see that for the single particle this Nusselt number is represented by this dotted line red dotted line here.

Now, for the single particles up to Reynolds number is equal to 50, almost you will see that this single part[icle] heat transfer coefficient from the for the single particle is higher than this fluidized bed condition whereas, if Reynolds number is greater than 50; there in see that this Nusselt number of the bed will be higher than the little bit higher than this single particle fluidized bed remaining all other constants escape.

So, and here another important, if we consider the fixed bed the Nusselt number of the particles will be represented by this equation or profile and this equation is 2 plus 1.8 into Re p to the power 0.5 into Prandtl number to the power 0.33. So, in this case, you will see for the fixed bed operations the heat transfer coefficient of the single particle should be higher than the single particle fluidized bed in the single particle I transfer coefficient in fluidized bed condition.

Whereas for all particles; that means, they are not a single particle conditions the heat transfer coefficient will be within the range of these the single particle to the fixed bed conditions. So, here is the beneficiation of region where that you can apply this fluidized bed condition for your application of heat transfer and for that specific application in your industrial purpose.

So, so, from this diagram will be knowing what will be the flow regime; what will be the flow condition at least that we can get the higher mass transfer heat transfer coefficient in a fluidized bed.

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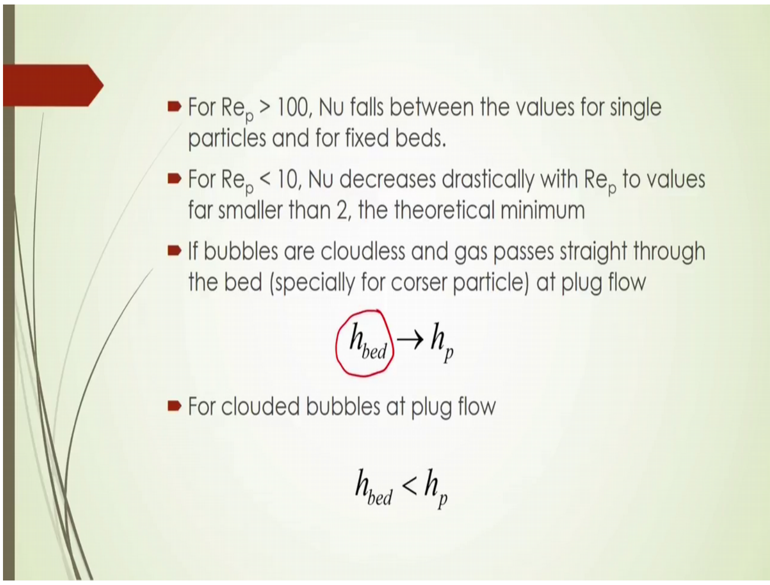

And then for Reynolds number is greater than 100 Nusselt number falls between the values of single particles and for fixed bed that we have discussed and for Reynolds number less than 10 here, it is seen that this Nusselt number decreases drastically with Reynolds number of particle two values for smaller than two here and the theoretical minimum value which is shown.

If bubbles are in this case, if we are considering the bubbling fluidized bed if bubbles are cloudless and gas phase passes straight through the bed especially for the Corser particles at plug flow condition, then you can say that heat transfer coefficient of the bed will tends to the heat transfer coefficient of the single particles whereas, for clouded bubbles at plug flow condition these always the heat transfer coefficient for the bed will be less than heat transfer coefficient for the single particle there.

Now, what should be the heat transfer between bed and surface now whole bed coefficients can be estimated by both steady state and unsteady state techniques at steady state.

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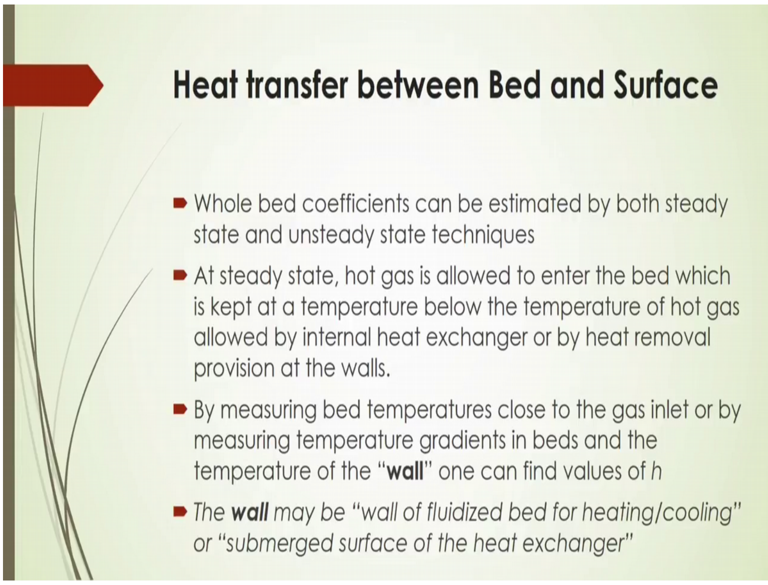

You will see that if we supply hot gas to enter the bed which is kept at a temperature below the temperature of hot gas that is allowed by internal heat exchanger or by heat removal provision at the walls then by measuring bed temperatures; that is close to the gas inlet or by measuring temperature gradient in the bed and the temperature of the wall, one can find values of the heat transfer coefficient. This wall may be are defined as wall of fluidized bed for heating or cooling or you can say is there any submerged surface are there in the fluidized bed for that heat transfer as a heat exchanger device or not so; in that case, this wall to be actually considered for that submerged surface of the heat exchanger also.

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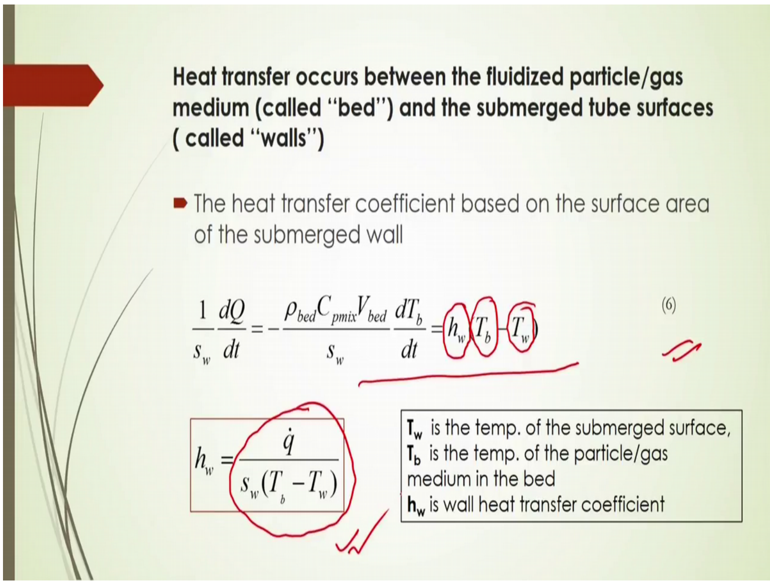

Now, heat transfer occurs between the fluidized particle or gas medium; that is called bed and the submerged bed surfaces that is called walls the heat transfer coefficient based on the surface area of the submerged wall; that will be represented by this equation number 6 here. So, in this case submerged wall, then heat transfer coefficient will be represented by this h w that is called Heat transfer coefficient wall heat transfer coefficient here.

So, based on that previous equation; exact to the same way you can say here this, what should be the wall temperature and what should be the bulk temperature there the T b is the temperature of the particle or gas medium in the bed and T w is the temperature of the submerged surface and h w is called wall heat transfer coefficient. So, from this equation 6, you can calculate the heat transfer coefficient of wall that will be denoted by this equation.

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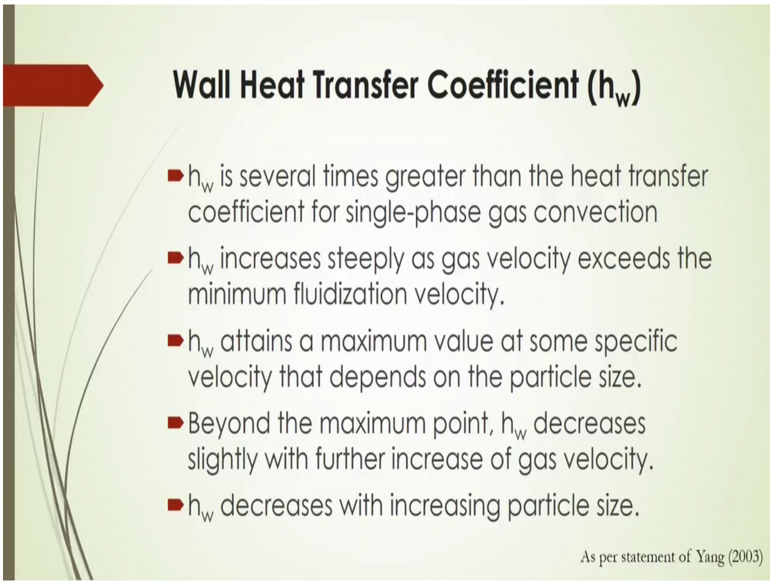

And this wall heat transfer coefficient; of course, there will be a change because of different operating conditions and it is seen that that wall heat transfer coefficient will be several times greater than the heat transfer coefficient for single phase gas convection and this wall heat transfer coefficient increases very steeply as gas velocity exceeds to the minimum fluidization velocity.

Now, this wall heat transfer coefficient again, it will gain a maximum value at some specific velocity that depends on the particle size beyond the maximum point h w; that means, wall heat transfer coefficient decreases slightly with further increase of gas velocity and this also wall heat transfer coefficient decreases with increasing particle size.

So, in this case, you will see that wall heat transfer coefficient will decrease with increasing particle size because of the surface area here in this diagram, it is shown; how this wall heat transfer coefficient will be changing with the relative velocity of the gas to this minimum fluidization velocity with respect to different pressure and particles there.

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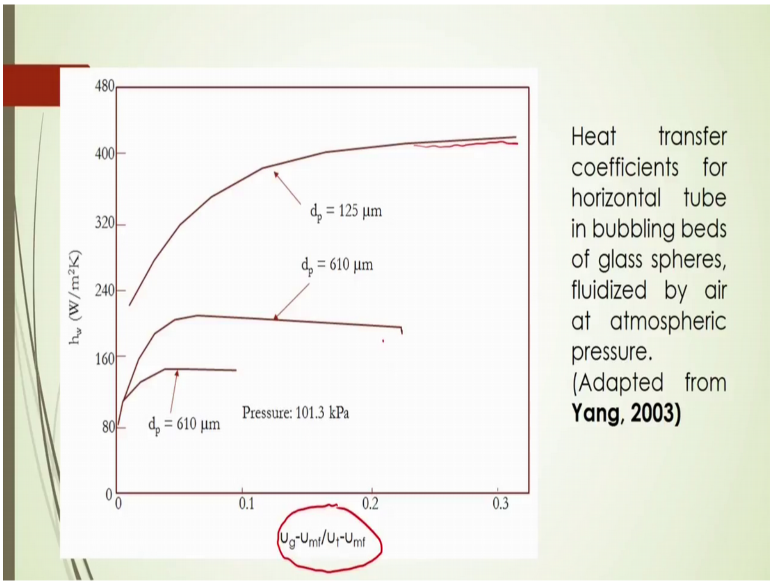

Now, if we consider this x axis at U g minus U m f by U t minus U m f U t means terminal velocity of the particles and minus U m f U m f means minimum fluidization velocity uses the gas velocity, then you will see that heat transfer wall heat transfer coefficient initially increases and then it will be again increasing bar to the slope will be decreasing there, here in this case, here again the same trend will come. So, with this value heat transfer coefficient will increases and then it will come to the saturation there will be increase there, whereas, this heat transfer coefficient will increase with the with the decreasing particle diameter here because of the surface area.

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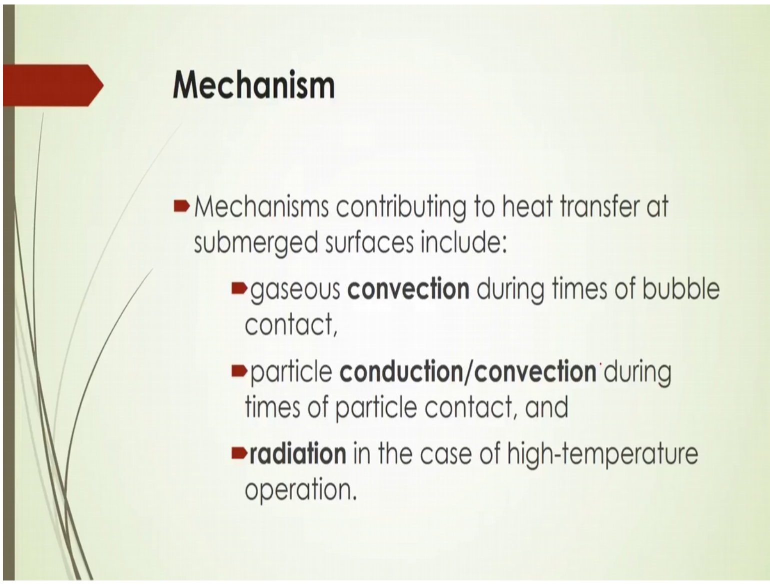

Now, what are the different mechanism of this heat transfer at the submerged surface that will include to the includes the gaseous convection during times of bubble contact and the particle conduction or convection during times of particle contact and radiation in case of high temperature operation.

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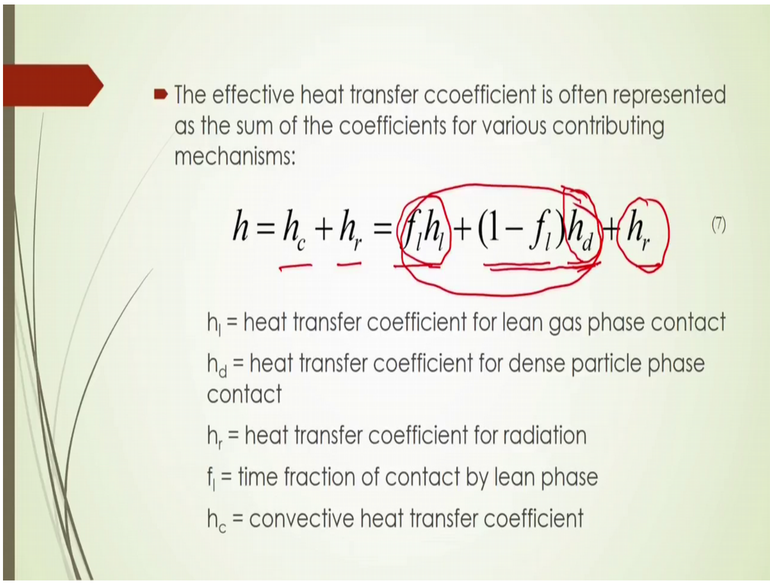

Now, the effective heat transfer coefficient is often represented as the sum of the coefficients for various contributing mechanisms like h will be is equal to h c plus h r; what is h c? H c is called convective heat transfer coefficient and h r; h r is called the heat transfer coefficient for radiation. Now, this can be denoted by this h c is nothing, but f l into h l plus 1 minus f l into h d plus h r here.

So, this one is nothing, but to the h c and this one is h r. Now h c; what is this f l into h l? F l is nothing, but the time fraction of the contact by lean phase in the fluidized bed, we have seen there will be 2 phases; one is lean phase and other is dense phase, if I consider the fraction of the lean phase as f l, then f l into h l means the heat transfer coefficient in the lean phase will be is equal to f l into h l whereas, 1 minus f l will be denoted by the by the by the fraction of the dense space. So, they are the heat transfer coefficient for that dense space will be represented by h d; so, 1 minus f l into h d that will be your effective heat transfer coefficient the dense space.

So, total heat transfer coefficient will be the summation of this convective heat transfer coefficient and the radiative heat transfer coefficient.

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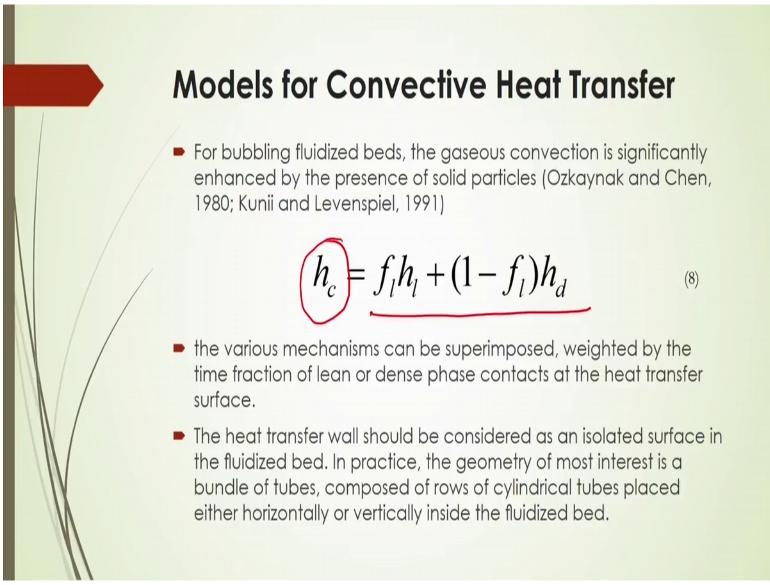

Now, what are the different models by which you can express this or analyze this heat transfer coefficients, let us consider fast that convective heat transfer coefficient for bubbling fluidized bed, the gaseous convection is the significantly actually enhanced by the presence of solid particles and because of which there will be a enhancement of the heat transfer are in this bubbling fluidized bed phenomena.

So, in that case, this heat transfer coefficient to be denoted by this f l h l plus 1 minus f l into h d. Now the various mechanisms that we have already discussed that the in that case may be superimposed that is weighted by the time fraction of the lean or dense phase contacts at the heat transfer surfaces, they are now heat transfer wall that should be considered as an isolated surface in the fluidized bed.

In this case, it is very common to know that or common that the geometry of the most interest is a bundle of tubes here composed of rows of cylindrical tubes that is placed either that is horizontally or vertically inside the fluidized bed for the heat transfer operation.

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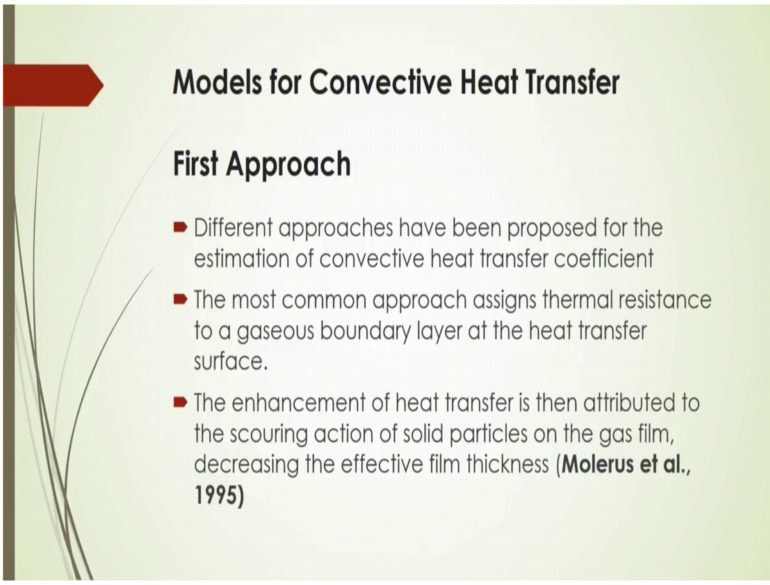

Now, for convective heat transfer coefficient; there are several approached actually by which you can represent these convective heat transfer mechanism, they are they are the one; let us see that first approach; what is that; based on these, they are different approaches have been proposed for the estimation of the convective heat transfer coefficient and this first approach is the common one; the most common approach assigns here that thermal resistance to a gaseous boundary layer at the heat transfer surface the enhancement of the heat transfer is then attributed to the scouring action of solid particles on the gas film who is decreasing the effective film thickness.

So, first approach; what is told that the first approach demonstrates the enhancement of the heat transfer in the bubbling fluidizing bed by scouring action of the solid particles on the gas film and because of which that that will decrease the effective film thickness and hence the heat transfer will enhance Wender and Cooper's.

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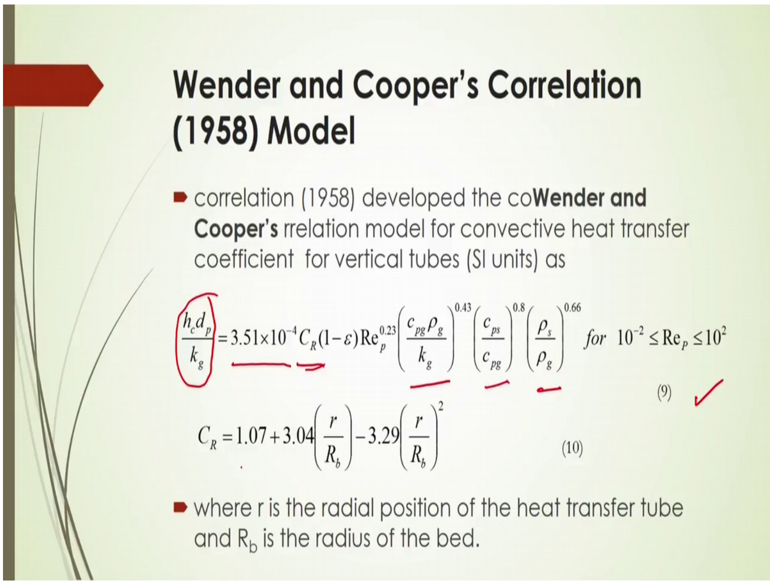

They have developed one correlations from their experimental data, based on this approach and they have suggested this equation 9 to ah analyze or you can say predict the heat transfer coefficient for convection or it is called convective heat transfer coefficient by this equation 9. So, they represent it in terms of C (Refer Slide Time: 00:00); one important correction factor that is actually, they have considered when the heat is supplied to there; there will be some radial distribution of the flow inside the bed and because of which that heat transfer distribution will be accordingly.

So, they have considered that correction factor and also other operating variables; they have also considered to ah develop these correlations. So, they have according to their correlations, it is a multiple of this number into C R into 1 minus epsilon into Re p and then these groups also and some other dimensionless groups, they are here; C R is called that correction factors and these correction factors considered the radial variation of the heat transfer and this is a function of this r from the central axis to the radial direction of the fluidized bed.

So, C R will be is equal to 1.07 plus 3.04 into r by R b and minus 3.29 into r by R b square. Here R b is the radius of the bed where small r is the radial position of the heat transfer tube and R b is the radius of the bed. So, from equation number 9 and 10, you will be able to calculate; what should be the convective heat transfer coefficient based on this approach of thin gas film thickness.

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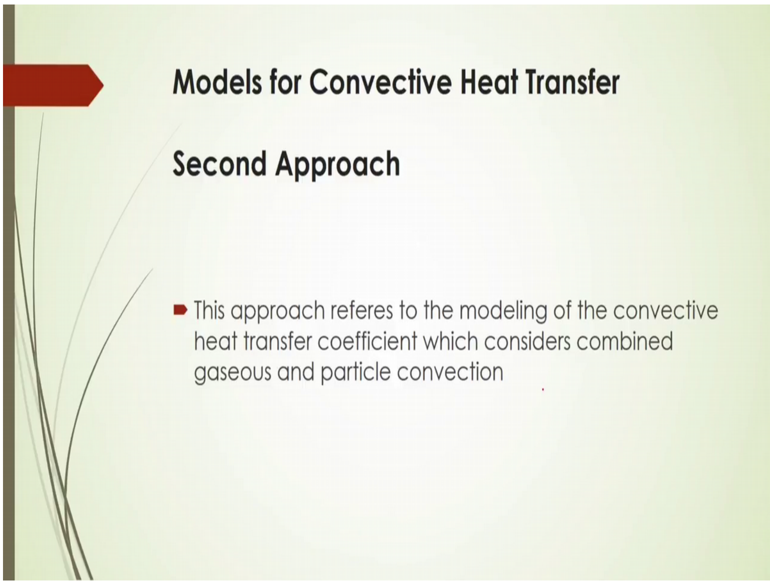

Second approach is that who is refers to the modeling of the convective heat transfer coefficient which considers the combined gaseous and particle convection there.

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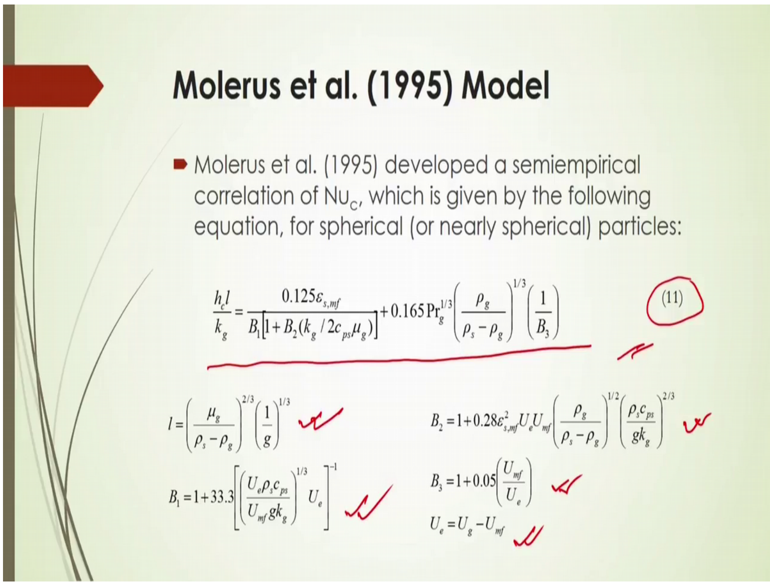

So, in this case; based on this consideration of this gas and particle movement, Molerus et al 1995; they have developed one semi empirical correlations for this Nusselt number of this convective heat transfer coefficient, in this case, they have given this equation for spherical or nearly spherical particles by equation number 11.

Now, as per equation number 11, it is seen that this transfer coefficient h c is a function of this sum factor of this B 1, B 2 density of the gas density of the particle and also the factor B 3 there and other physical properties like specific heat capacity of the solid and specific heat capacity of the gas and also the thermal conductivity of the gas here and also this l is the length of the bed this length of the bed also is one important factor there.

So, according to their correlations l is defined as here and B 1 is defined as this equation and B 2 like this B 3 and U e is the effective gas velocity; that means, relative to the minimum fluidization velocity there. So, from this equation number 11, one can easily calculate; what should be the convective heat transfer coefficient based on the concept of both gas and particle movement inside the bed.

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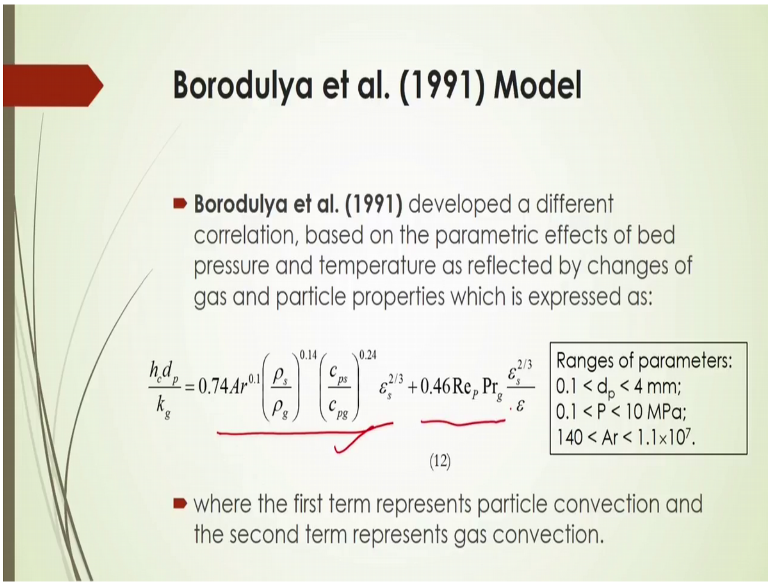

Whereas Borodulya et al, 1991; they have developed different correlations based on the parametric effect of the bed pressure and temperature which is reflected by changes of gas and particle properties which is expressed as here. So, in this case, what is very important that they have considered here the temperature and pressure which may affect the physical properties of the particles and gas and based on which they have developed another empirical correlations which is represented by equation number 12 and this equation number 12 valids only within the range of 0.1 to 4 millimeter of particle diameter and pressure will be within 0.1 to 10 mega Pascal and the Archimedes number will be within the range of 140 to 1.1 into 10 to the power 7.

In this case, the first term represents the particle convection and the second term represents the gas convection here in this equation of equation 12. So, this one is called the particle convection, the second term is for gas convection.

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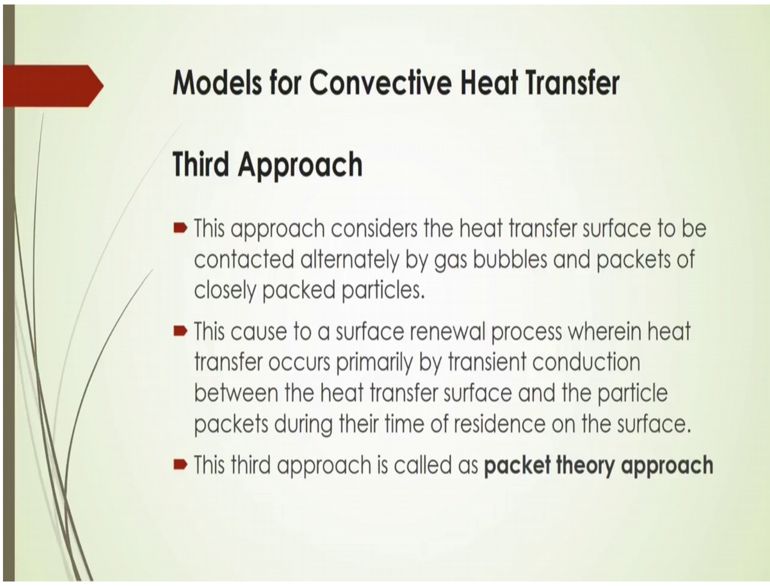

And the third approach the third approach to represents this convective heat transfer that considers the heat transfer surface that is to be contacted alternately by gas bubbles and packets of closely packed particles.

So, there are two things here; one is the packed particles, another is gas bubbles. So, there will be a contact between these gas bubbles and packet of closely packed particles there. So, this approach considered this phenomena that heat will be transferred from this bubble to the packed of packed particles there packets of packed particles there.

So, this cause to a surface renewal process where in heat transfer occurs primarily by transient conduction between the heat transfer surface and the particle packets during their time of residence on the surface. So, you will see very interesting that on the bubble surface if there will be some some packets of particles that is depositing and that packets may change their position from one from its surface to the emulsion again emulsion to the surface. So, every time there will be a continuous contact; that means, here just packets or particles will be contact to the bubble surface.

So, that surface may be renewed by these packets of that packed particles and that is why surface renewal process will be actually considered in this case for the transfer of heat. So, this third approach is called the packet theory approach. So, this packet theory approach is basically based on the surface renewal theory.

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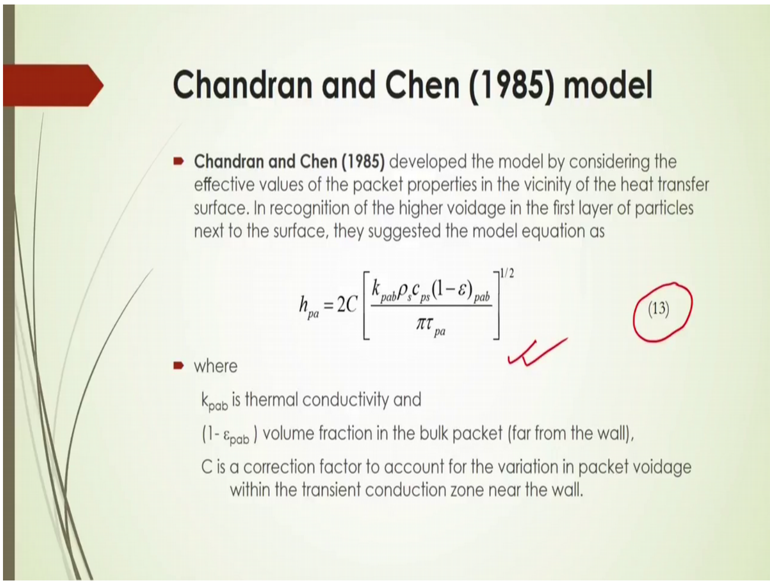

Now, Chandran and Chen, 1985; they have developed the model by considering the effective values of the packet properties in the vicinity of the heat transfer surface and in recognition of the higher voidage in the first layer of particles, next to the surface, they suggested the model equation as given by equation number 13 here. So, that they have represented this h p a, h p a is called that the heat transfer coefficient of the packet particles; that will be is equal to 2 into C into k p a b into rho s C p s into 1 minus epsilon p a b by pi T p a to the power half what does it k p a b is the thermal conductivity of the bulk packet and 1 minus epsilon p a b is the volume fraction in the bulk packet far from the wall and C is a correction factor to account for the variation in packet voidage within the transient conduction zone near the wall.

So, based on this equation, one can calculate what should be the heat transfer coefficient for the packet of packed particles; there this correction factor can be calculated by equation number 14 given here.

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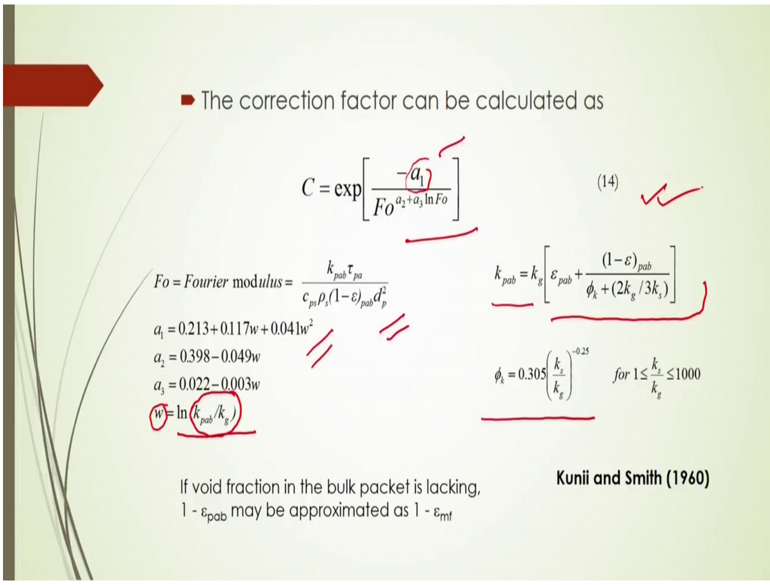

This is a function of that is Fourier modulus which is defined as by this equation here and this one important parameters like a 1, a 2 and a 3; this a 1, a 2, a 3 are a function of ah; that means, for void fraction of the solids they are in the bed and this w this w is a defined as l n k p a b by k g; this is actually the logarithm of the ratio of this; what is that that is thermal conductivity of the packet particles to the what is that gaseous.

So, here this w and other factors like particle concentration particle size they are also very important and to actually to find out this a 1, a 2 and a 3 and this k p a b; this is called what is that thermal conductivity packet particles; they are which will be actually relative to that thermal conductivity of the gas which can be denoted by this equation and in this case pi k is one important parameter; this is a actually function of ratio of thermal conductivity of the solid and to the thermal conductivity of the gas.

So, if thermal conductivity of the solid to the gas is less than 1000s, then you can apply this equation 14 to find out the C value and then substitution of C value in the previous equation of 13 here to calculate the heat transfer coefficient by this packet approach.

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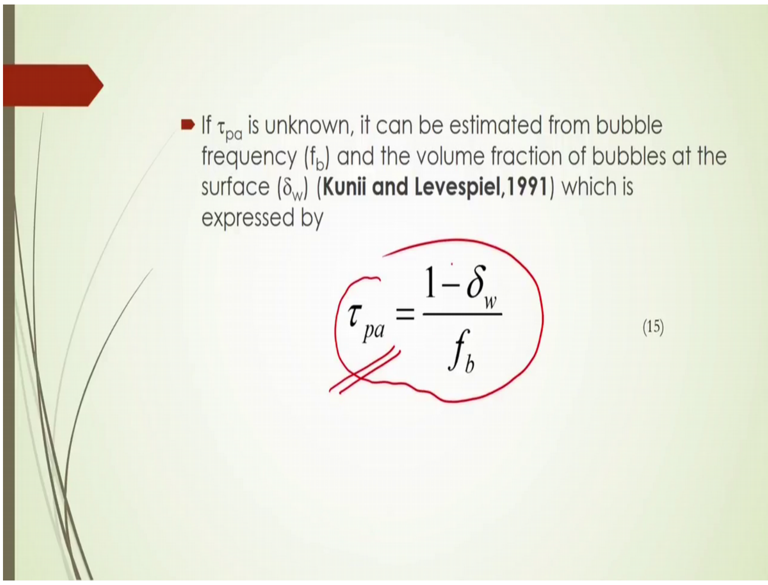

And in this case, another important factor is called that tau p a, which is unknown parameter and it can be estimated from the bubble frequency. This is f b and the volume fraction of the bubbles at the surface that is denoted by delta w; that has already been discussed in earlier classes, what will be the bubble fraction and which is expressed by this here equation 15 to actually calculate this tau p a that is this residence time of the packet particles which can be denoted by this 1 minus delta w by a b.

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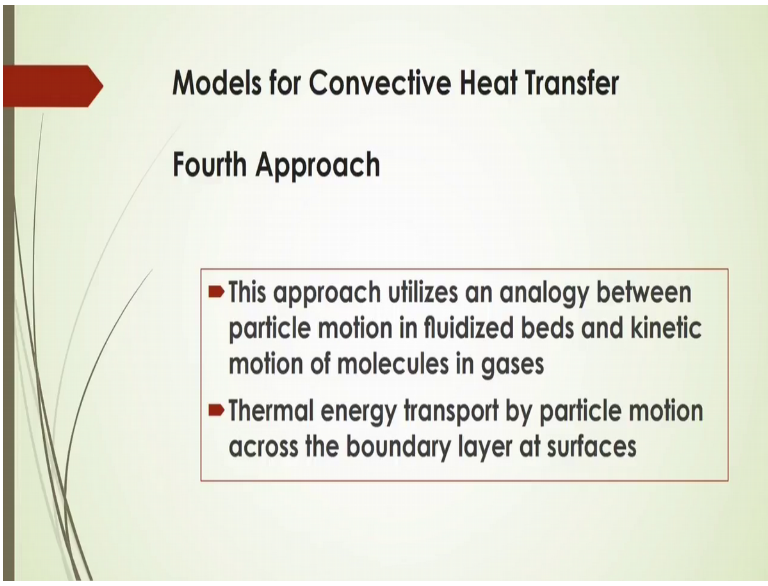

Now, as a fourth approach you can calculate the convective heat transfer coefficient, in this case utilizes an analogy between particle motion in fluidized beds and kinetic motion of the molecules. Molecules in gaseous and also thermal energy transport by particle motion across the boundary layer at surfaces.

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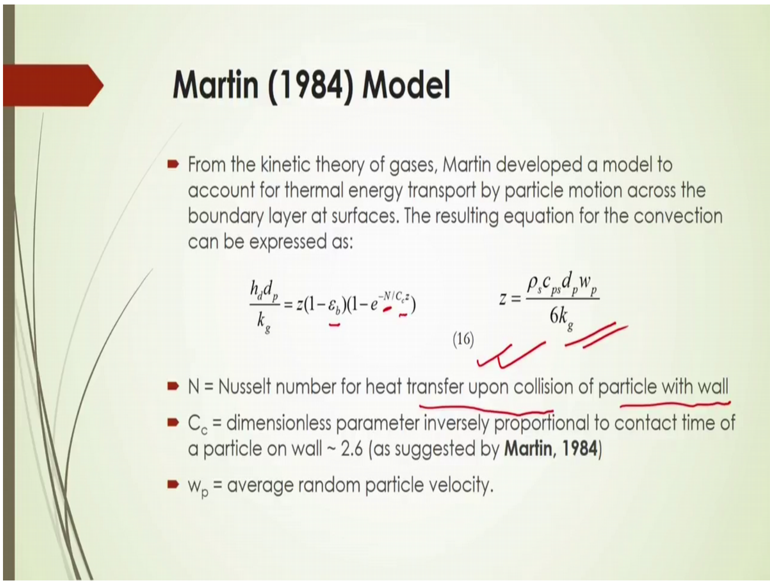

Martin, 1984; they have developed this equation to actually calculate the convective heat transfer coefficient in the dense bed medium based on the kinetic theory of gases and martin developed the model to account for thermal energy transport by particle motion across the boundary layer at surface and they have developed this equation number 16 to calculate the heat transfer coefficient.

Here n is called the Nusselt number for heat transfer upon collision of particle with wall here this N N is called Nusselt number here and C C is one dimensionless parameter which is inversely proportional to the contact time of the particle on wall and which will be approximately equal to 2.6 as suggested by Martin 1984 from the experimental data and w p is the average random particle velocity which also will govern the heat transfer coefficient inside the bed.

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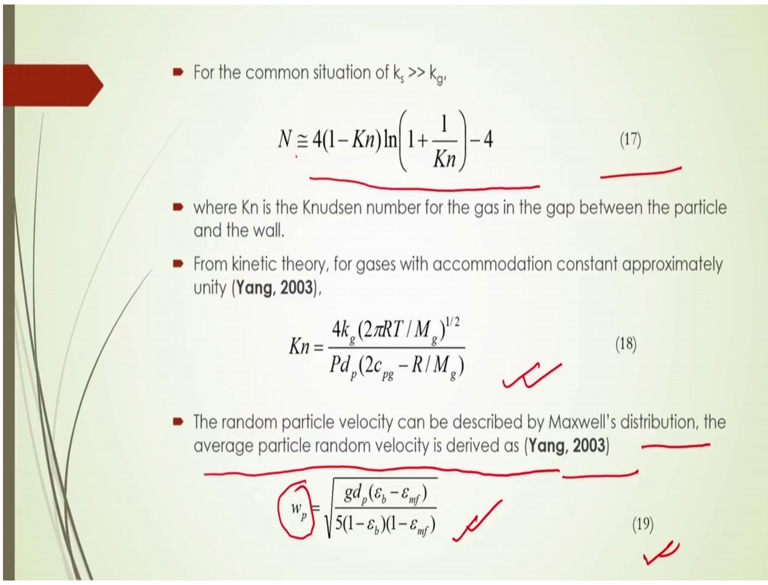

For the common situation of if suppose the thermal conductivity of the solid is greater than more greater than thermal conductivity of the gas, then this Nusselt number can be related to this Knudsen number for the gas in the gap between the particles and the wall which is denoted by this equation number 17 here and from the kinetic theory for gases with accommodation a constant approximately unity in that case Knudsen number will be expressed by this equation number 18 and the random particle velocity can be described by Maxwell's distribution and then the average particle random velocity which will be derived by this equation 19 here as given by Yang 2003.

So, this w p; this called the average particle random velocities will be calculated based on this equation 19, once you know this w p Knudsen number based on the properties of the fluid and the particles, then you will be able to calculate; what should be the Nusselt number from this equation number 17, once you know this Nusselt number, you substitute the value of Nusselt number here and then substitute the epsilon b c c you know that will be 2.6 and other operating variables of z z will be calculated from this equation here and finally, you will get the what will be the heat transfer coefficient based on this approach.

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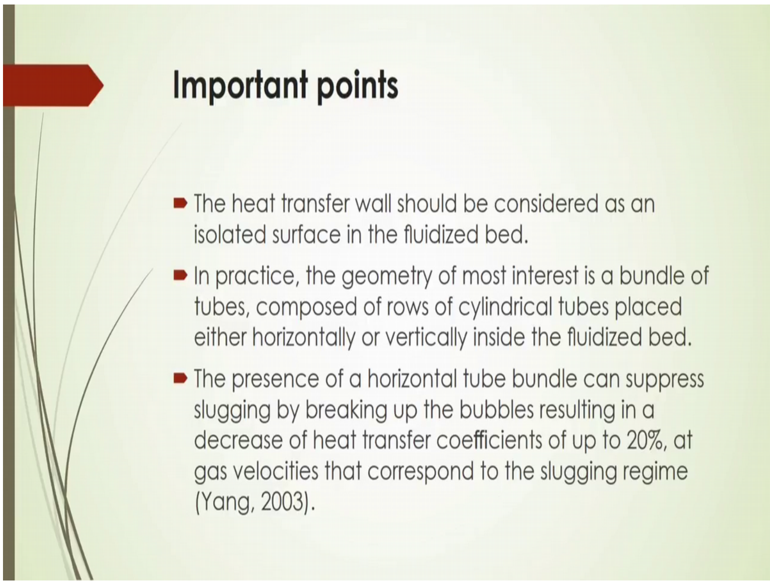

Now, some important points here that the heat transfer wall should be considered as an isolated surface in the fluidized bed in these cases, in practice the geometry of most interest is a bundle of tubes composed of rows of cylinder cylindrical tubes that is placed either horizontally or vertically inside the fluidized bed the presence of the horizontal tube bundle can suppress slugging by breaking up the bubbles which results in a decrease of heat transfer coefficients up to 20 percent at gas velocities that correspond to the slugging regime according to Yang 2003 at higher gas velocities.

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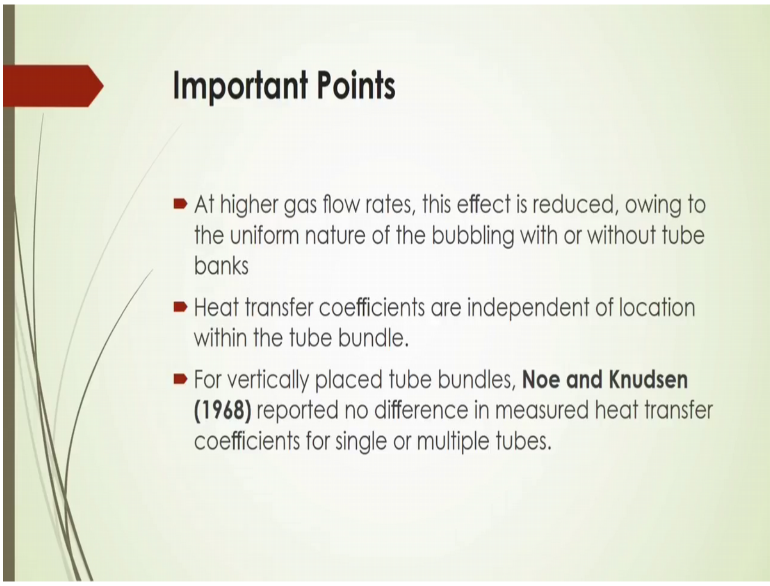

We will see the effect is reduced that will owing to the uniform nature of the bubbling with or without tube banks heat transfer coefficients are independent of location with the tube bundle for vertically placed tube bundles, Noe and Knudsen, 1968; reported that there will be no difference in the measured heat transfer coefficients for the single or multiple tubes.

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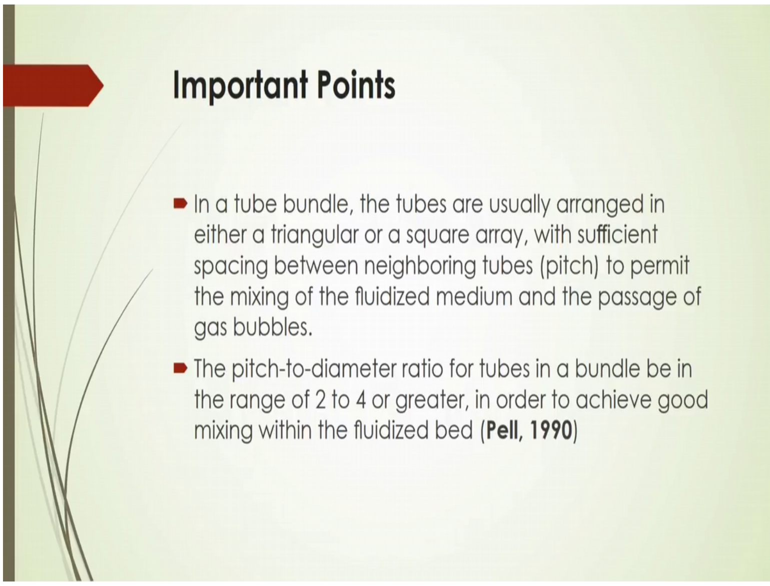

In a tube bundle, the tubes are usually arranged in either a rectangular or triangular or square array with sufficient spacing between neighboring tubes pitch that is called pitch to permit the mixing of the fluidized medium and the passage of gas bubbles now the piece to diameter which will affect the heat transfer coefficient and this ratio for tubes in a bundle be in the range of 2 to 4 or greater in order to achieve good mixing within the fluidized bed and hence the good heat transfer distribution.

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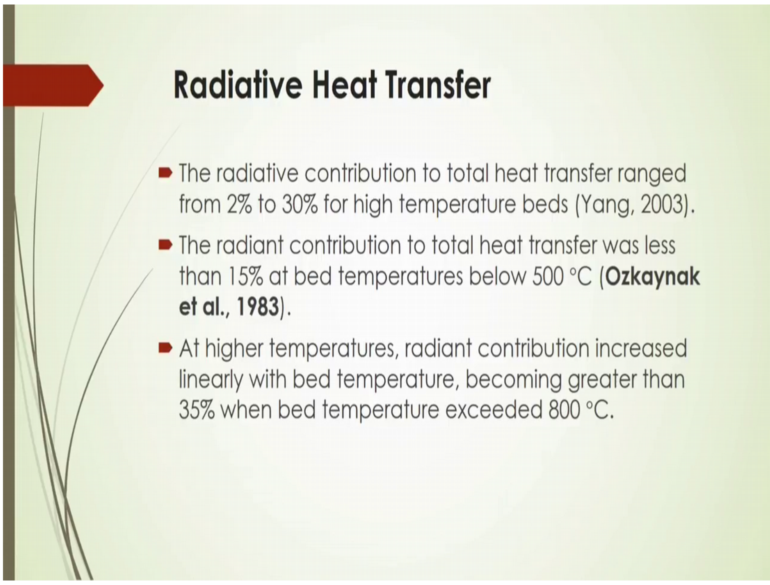

Till now, we have discussed about the convective heat transfer coefficient what about the radiative heat transfer coefficient because total heat transfer coefficient is the summation of convective heat transfer coefficient and radiative heat transfer coefficients; the radiative constitution to the total heat transfer will be ranged from 2 percent to the 30 percent for high temperature beds and the radiant contribution to total heat transfer that will be less than 15 percent at bed temperature below 500 degree centigrade as reported by Ozkaynak et al; 1983.

At higher temperatures, the radiant contribution increase linearly with bed temperature becoming greater than thirty five percent when bed temperature exceeded 800 degree centigrade that is reported by Yang 2003.

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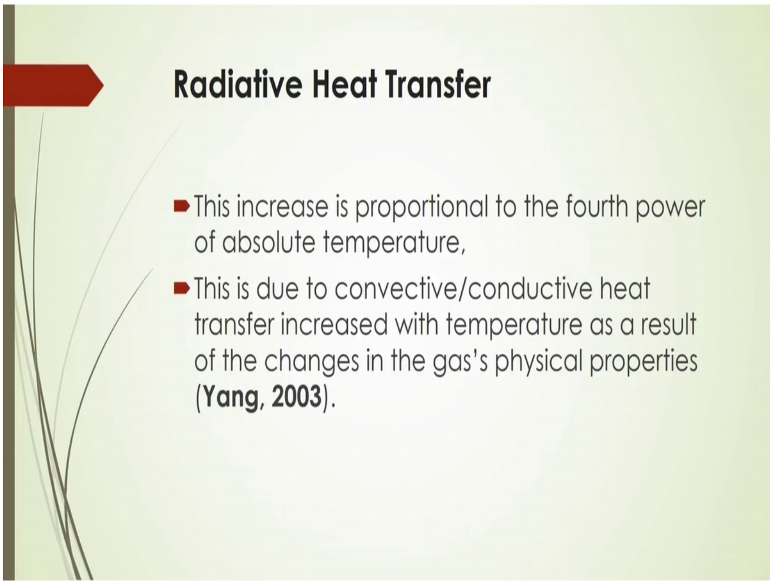

Now, this increase is proportional to the fourth power of absolute temperature. So, this radiative heat transfer is a proportional is proportional to the fourth power of absolute temperature and this is due to the convective or conductive heat transfer increased with temperature as a result of the changes in the gaseous physical properties that is reported by the Yang 2003.

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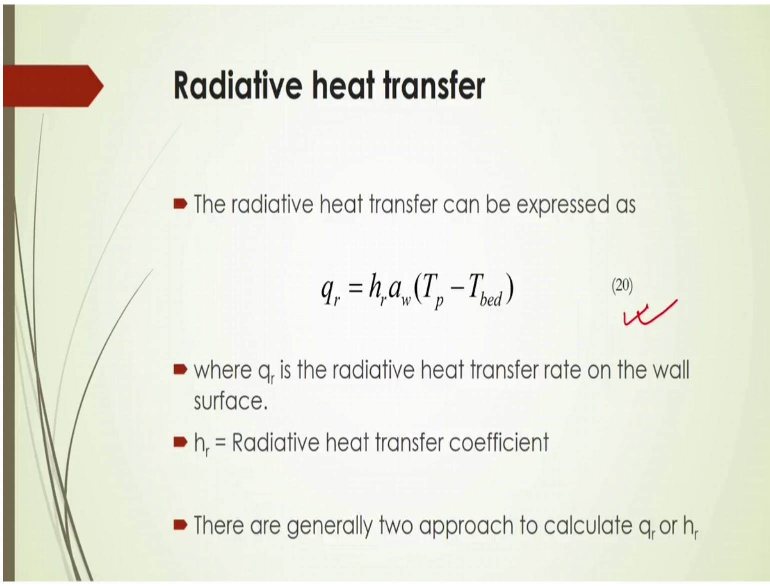

And this radiative heat transfer can be expressed by this equation number 20, this is the standard equation to represent and where q r is the radiative heat transfer rate on the wall surface and h r is the radiative heat transfer coefficient there are generally 2 approaches to actually analyze this radiative heat transfer rate or heat transfer coefficient.

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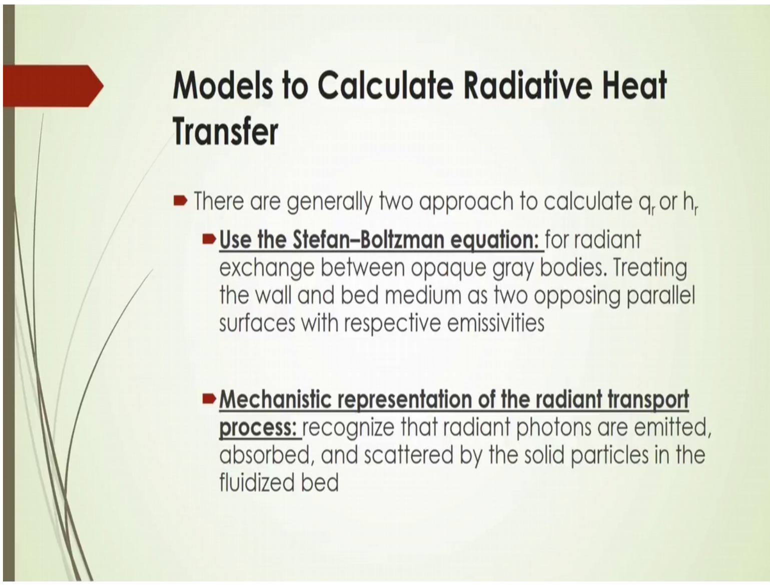

Models to calculate radiative heat transfer there are generally 2 approach to calculate this q r or h r use the Stefan Boltzman equation and mechanistic representation of the radiant transport processes the Stefan Boltzman equation, in that case, radiant exchange between opaque gray bodies will be considered and treating the wall and bed medium as 2 opposing parallel surfaces with the respective emissivities that is actually considered to express the radiant heat transfer rate.

Mechanistic approach in that case radiant photons are emitted, it is considered and absorbed and scattered by the solid particles in the fluidized bed and because of which there will be a radiant heat transfer and this mechanism is considered in this case mechanistic approach.

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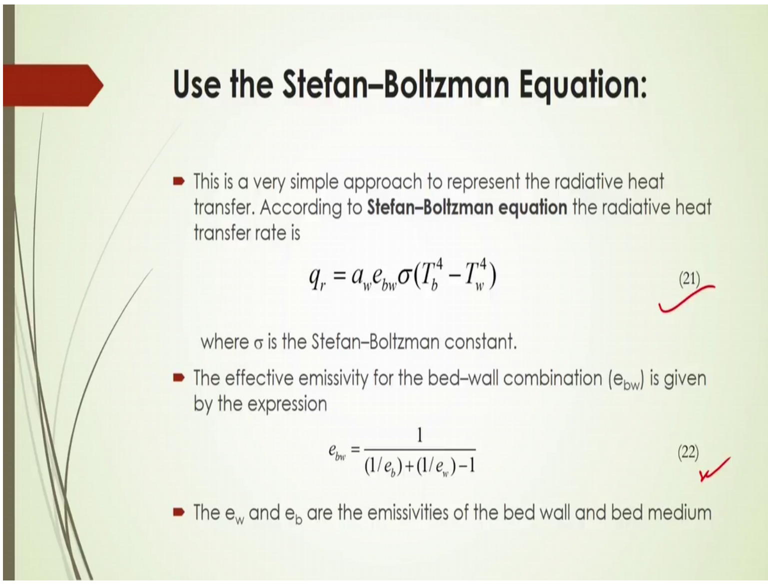

Now, if we consider that Stefan Boltzman equation very simple approach to represent to the radiative heat transfer, in this case, according to that Stefan Boltzman equation, the heat transfer rate can be estimated by this equation number 21; whereas, sigma is the Stefan Boltzman constant the effective emissivity of the bed wall combination is given by expression equation 22, here in this case, e w and e b are the emissivities of the bed wall and the bed medium.

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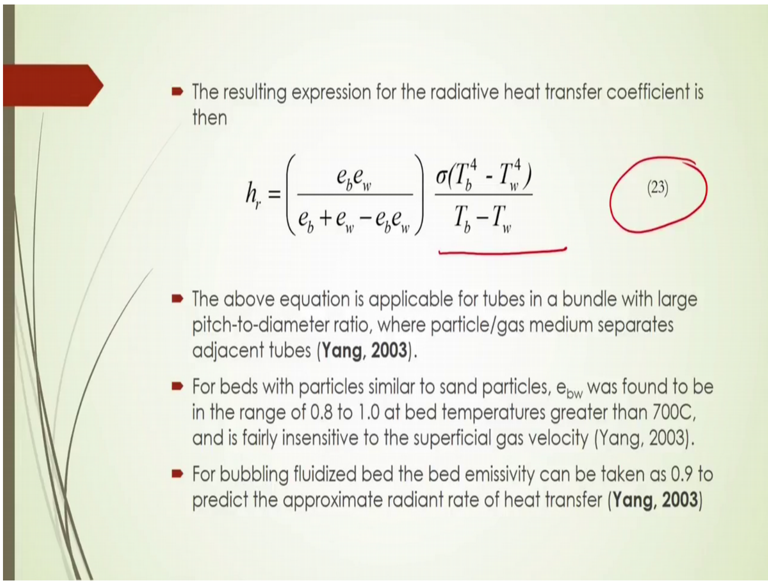

The resulting expression for the radiative heat transfer coefficient is then h r that will be is equal to e b e w by e b plus e b e w minus e b e w into this fraction that is given in equation number 23; the above equation is applicable for the tubes in a bundle with large speeds to diameter ratio whereas, particle or gas medium separates that is adjacent tubes there.

For the beds with particles similar to sand particles that is e b w that will be found to be in the range of 0.8 to 1.0 at the bed temperature which is greater than 700 degree centigrade, whereas, this will be purely insensitive to the superficial gas velocity as stated by Yang 2003 for bubbling fluidized bed the bed emissivity can be taken as 0.9 to predict the approximate radiant rate of heat transfer.

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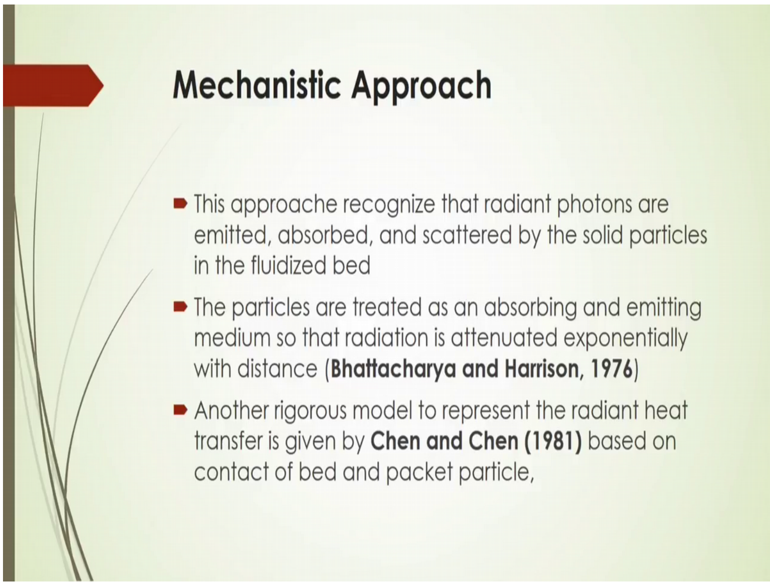

Whereas, in this mechanistic approach; that recognize that the radiant photons will be emitted and will be absorbed and will be scattered by the solid particles in the fluidized bed the particles that are treated as an absorbing or emitting medium. So, that the radiation is attenuated exponentially with the distance another rigorous model that is developed to represent to the radiant heat transfer given by Chen and Chen, 1981; which is based on the contact of bed and packet particles.

Now, according to that Chen and Chen; 1991, they have developed their model by modifying the Mickley Fairbanks packet model to include simultaneous radiative and conductive heat transfer during attenuating contact during alternating contact of the heat transfer surface by gas bubbles and particle packets, the gas phase is taken ah to be the transs transparent to thermal radiation, while the particle packet is treated as a radiatively participative medium with absorption emission.

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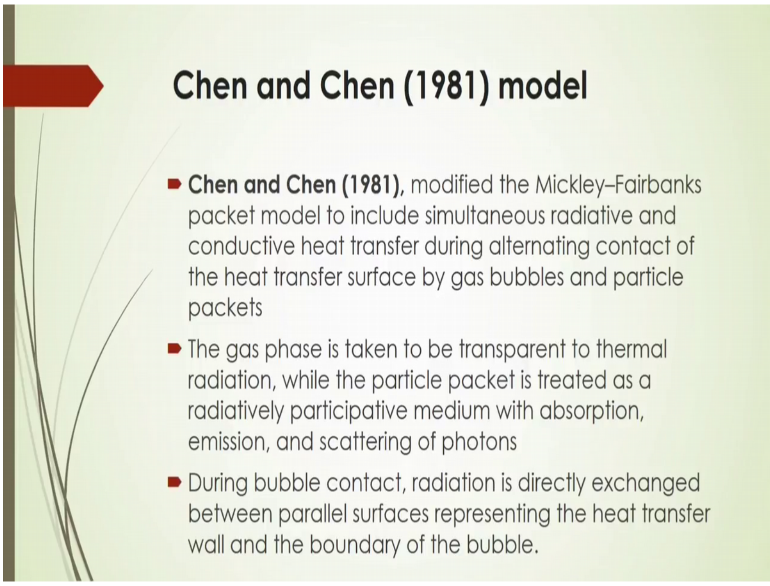

And scattering of photons during bubble contact the radiation is directly exchanged between parallel surfaces representing the radiant heat transfer wall and boundary of the bubble.

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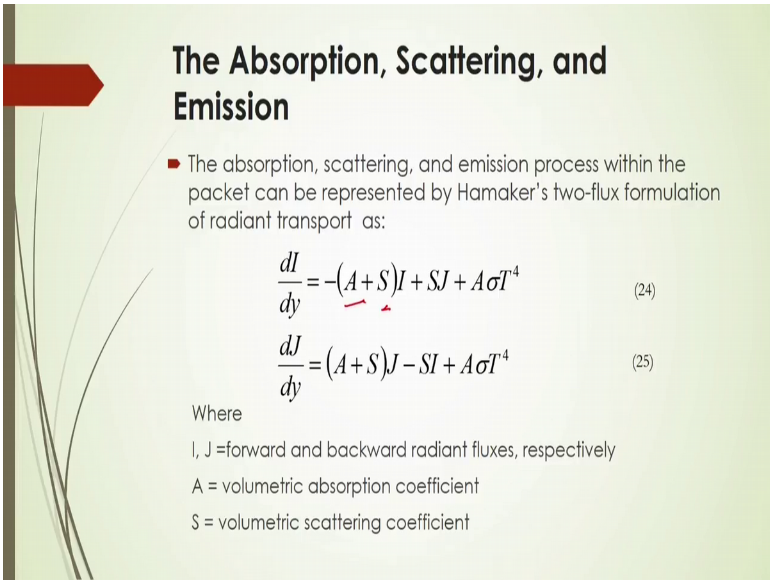

Now, how to actually estimate this absorption scattering and the emission the absorption scattering and emission process within the packets can be represented by the Hamaker's two flux formulation of radiant transport which can be given by this equation 24 and 25 for the forward and backward radiant fluxes and this forward and backward radiant fluxes is represented by this or denoted by this I and J.

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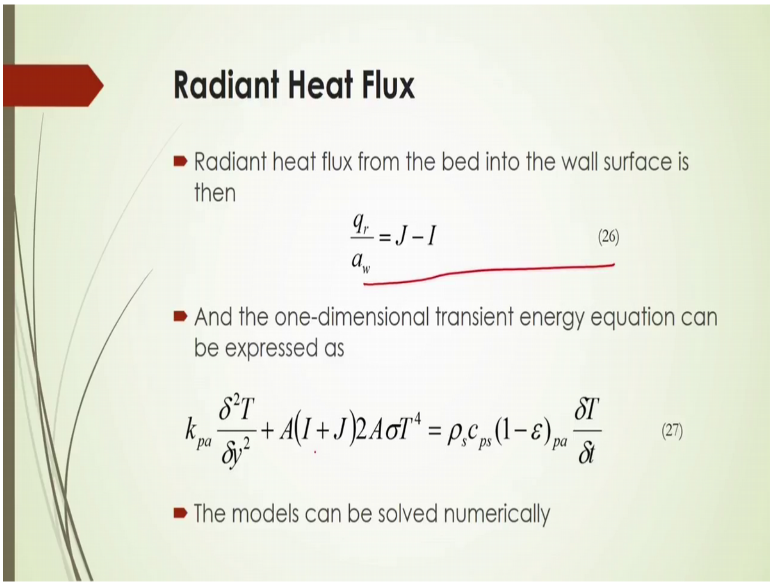

Whereas in this equation A and S are the volumetric absorption coefficient and volume volumetric scattering coefficient respectively the radiant heat flux from the bed into the wall surface is then calculated by this equation number 26. Once you know that this forward and backward radiant fluxes and one dimensional transient energy, equation can be expressed by the equation number 26 with respect to that what is that this backward and forward radiant heat fluxes.

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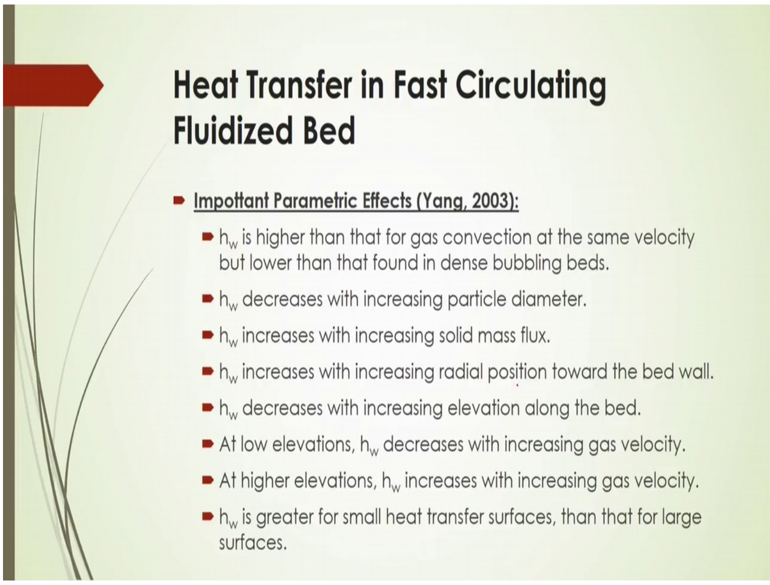

Now, what should be the heat transfer then total heat transfer coefficient once you know this radiant heat transfer coefficient and the convective heat transfer coefficient then total heat transfer coefficient inside the bed can be easily calculated. So, other than this circulating fluidized bed.

Now, in case of first circulating fluidized bed, now important some parametric effect are observed that is given by Yang 2003 that they reported that this wall heat transfer coefficient will be higher than that for gas convection at the same velocity, but lower than that found in a dense bubbling fluidized bed there, whereas, in first circulating fluidized bed this wall heat transfer coefficient will be decreases with increasing particle diameter, and also it increases with increasing solid mass flux it increases with increasing radial position towards the bed wall and decreases with increasing elevation along the bed at low elevations.

This wall heat transport coefficient decreases with increasing gas velocity and also at higher elevations, this wall heat transfer coefficient increases with increasing gas velocity and also this wall heat transfer coefficient, in the case of first circulating fluidized bed will be greater for small heat transfer surfaces then that for large surfaces.

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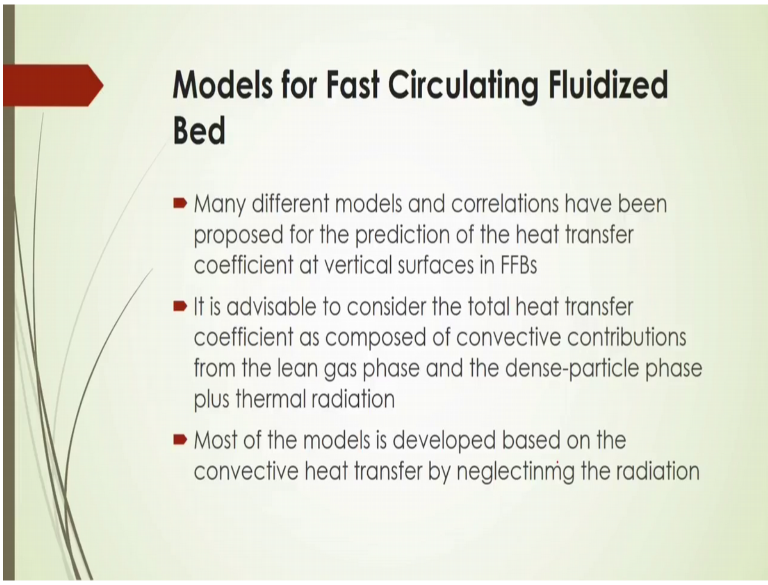

Now, many different models and correlations have been proposed for the prediction of the heat transfer coefficient at vertical surfaces in first circulating fluidized bed condition it is advisable to consider the total heat transfer coefficient as composed or convective contributions from the lean gas phase and a dense particle phase plus thermal radiation most of the models is developed based on the convective heat transfer by neglecting the radiation.

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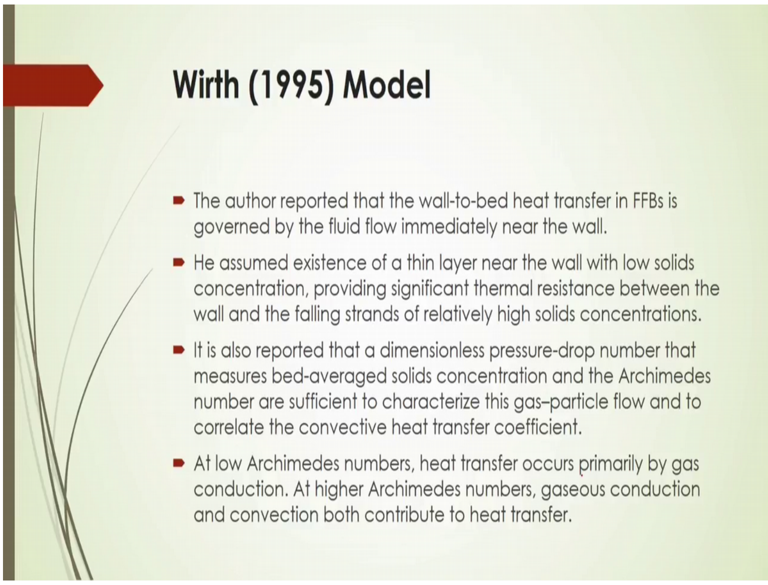

There is one important model that is called Wirth, 1995 model; this model that according to their model author reported that the wall to bed heat transfer in the first fluidized bed is governed by the fluid flow immediately near the wall he assumed existence of a thin layer near the wall with low solids concentration providing significant thermal resistance between the wall and the falling strands of relatively high solids concentrations.

It is also reported that the dimensionless pressure drop number that measures bed averaged solid concentration and the Archimedes number that are sufficient to characterize this gas particle flow and to correlate the convective heat transfer coefficients at low Archimedes number heat transfer occurs primarily by gas conduction at higher Archimedes number gaseous conduction and convection both contribute to the heat transfer as the stated.

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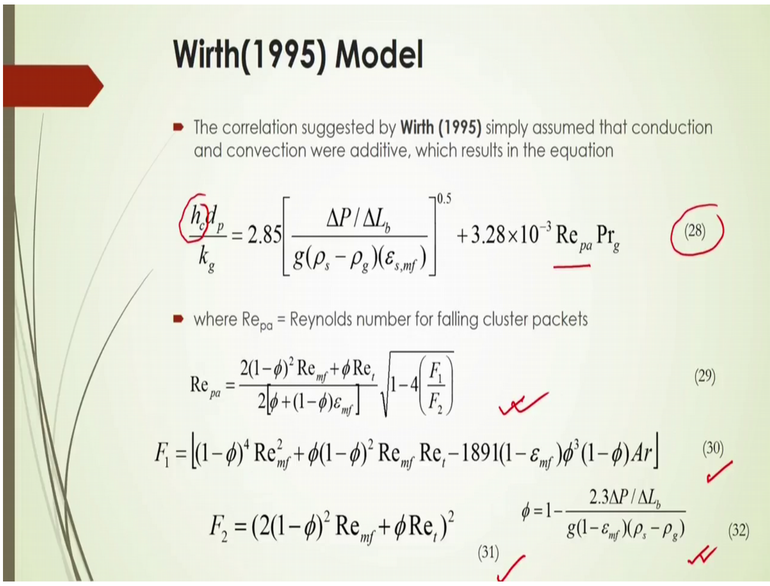

Now, as per Wirth model, they have suggested they have suggested one correlations assume that conduction and convection both will be additive in nature and which results in the equation and their equation is represented by this equation number 28 here to predict the heat transfer coefficient for convection in this case here important that their Re p a that is Re p a is called the Reynolds number for falling cluster of particle packets which will be defined by this equation number 21, again this equation number 21 is a function of some factor F 1 and F 2, which are defined by this which are expressed by this equation about 30 and 31 and here another important factor is called that phi phi is defined by this equation number 32 here.

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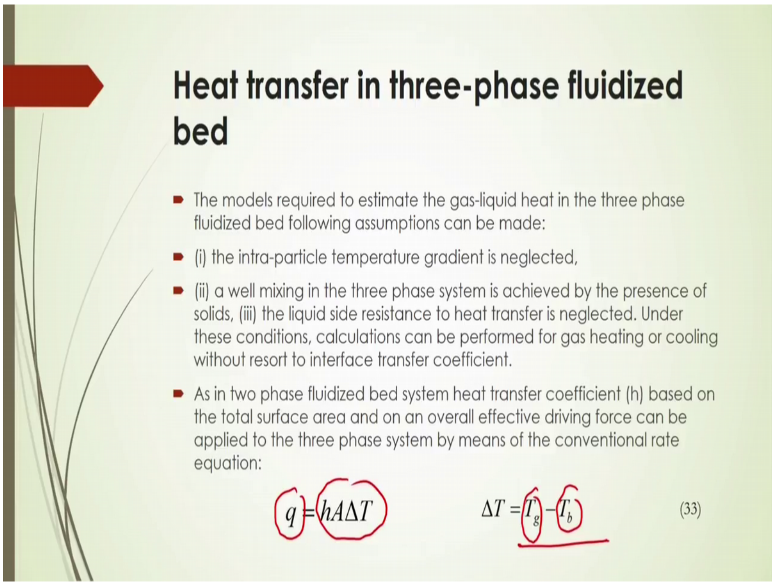

So, this first fluidized bed for first fluidized bed we can calculate what will be the convective heat transfer coefficient by this equation number 28 and what should be the heat transfer then coefficient for the three phase fluidized bed, again as per the same principle of heat transfer coefficient that is measured in 2 phase fluidized bed then three phase fluidized bed also, you can consider the same principle by just measuring the temperature differences here for the gas or liquid mixture and the bed temperature.

So, here in this case that q will be represented by this h A into delta T here delta T is the temperature difference which will be represented by this equation number here. So, in this case models required to estimate the gas liquid heat in the three phase fluidized bed by following assumptions the intra particle temperature gradient should be neglected and the wall mixing the three phase systems will be achieved by the presence of solids and the liquid side resistance to heat transfer should be neglected for measuring the heat transfer coefficient under these conditions calculations can be performed for gas heating or cooling without resort to interface mass transfer coefficient.

As in two phase fluidized bed system, heat transfer coefficient based on the total surface area and on the overall effective driving force for the temperature can be applied to the three phase systems to calculate the convective heat transfer rate or heat transfer coefficient.

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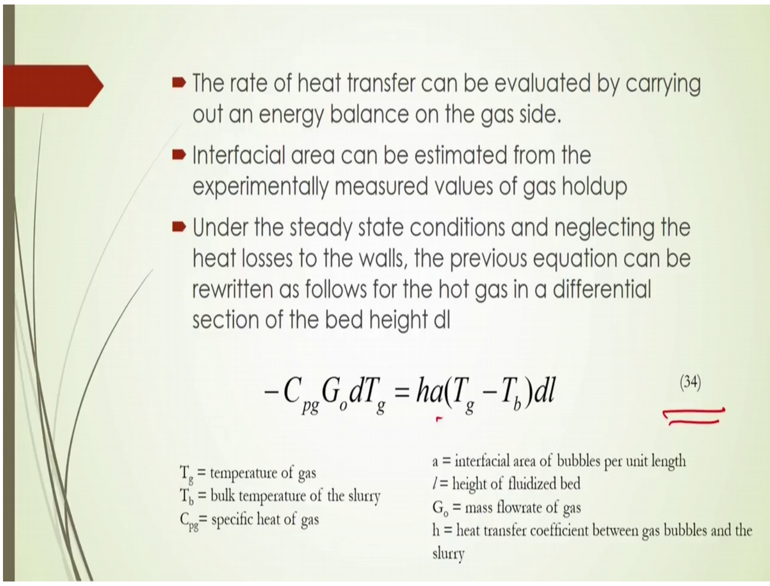

Now, the rate of heat transfer can be evaluated by carrying out an energy balance on the gas side in this case interfacial area can be estimated from the experimentally measured values of gas holdup here, in this case, gas holdup is very interesting which will govern the change of heat transfer coefficient which can be calculated from this equation number 34 here. Now a here; small a is the interfacial area of the bubbles per unit length here in this interfacial area of course, depends on that gas holdup inside the bed.

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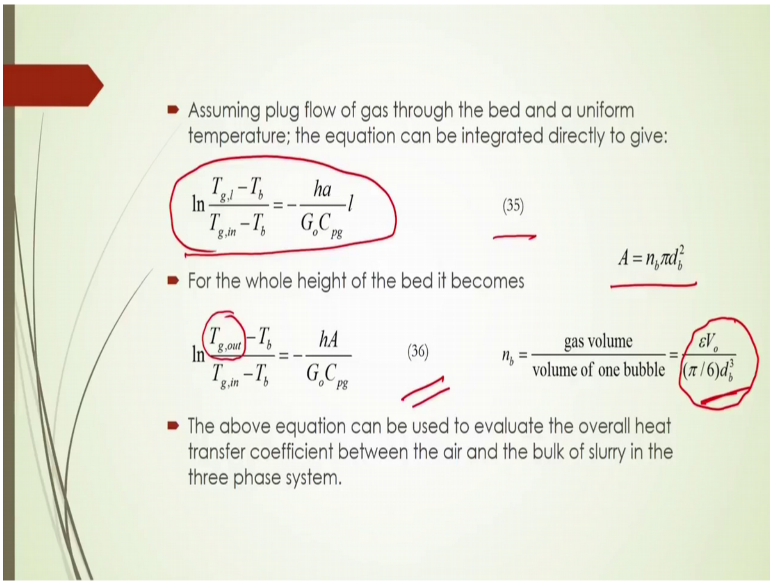

Now, assuming plug flows of the gas through the bed and uniform temperature the equation can be then integrated directly to give this equation number 35 from which you will be able to calculate what should be the temperature at a certain length of the three phase fluidized bed, once you know this equation and for the whole bed what should be the heat transfer coefficient and what should be the temperature profile, you will be able to calculate from this equation number 36.

In this case, here a is the total surface area that is given by the bubble and then n b is called the number of bubbles which will be calculated from the volume of the gas inside the bed and number of what is that what is the volume of the bubble diameter. So, this above equation can be used to evaluate the overall heat transfer coefficient between the air and the bulk of the slurry in the three phase fluidized bed.

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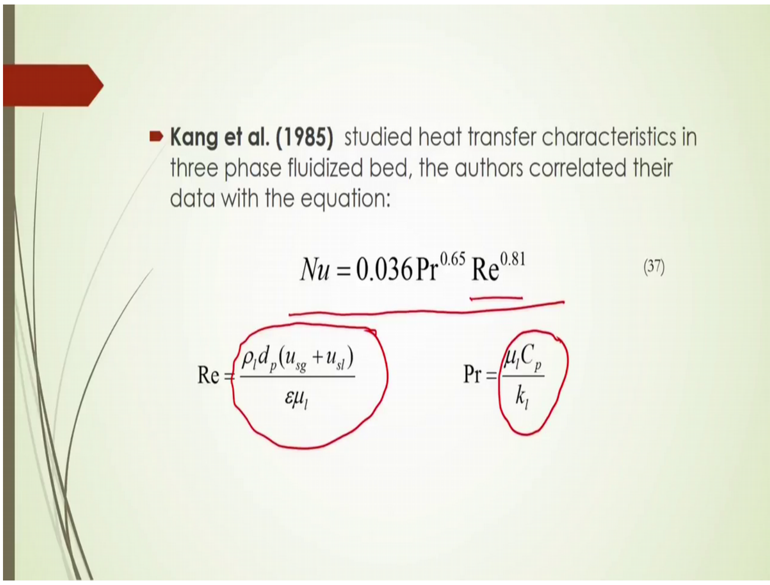

As per Kang from the experimental data, the equation 37 can be represented to predict the heat transfer coefficient in the three phase fluidized bed where this is again is a function of Prandtl number and Reynolds number, here Reynolds number will be defined as by the fluid mixture properties and the Prandtl number also, it is a mixture of the liquid here.

So, based on this equation 37 one can calculate what should be the heat transfer coefficient in the three phase fluidized bed. So, in this lecture what we observed that how to estimate the heat transfer coefficient and what is the rate of heat transfer and what is the different mechanism of heat transfer in the fluidized bed in the bubbling fluidized bed how this fluidized heat transfer is happened whether the conduct conduction or convection or radiation is there that we have discussed in this lecture.

And also in three phase fluidized bed that the same mechanism can be applied to calculate the heat transfer coefficient also if you do the research on this field then you will be able to do some experiment and you have to do some experiments with further systems for fluidization systems how this heat transfer coefficient will be changing if you change the systems. So, the heat transfer coefficient depends on the system properties geometrical properties of the fluidized bed as well as the particle property size all these parameters.

So, I think, this lecture will be helpful for you to estimate the heat transfer coefficient and heat transfer rate in the fluidized bed once you know the gas velocity liquid velocity or fluid properties, liquid properties, etcetera and I think we have discussed this transport processes earlier mass transfer operation and here in this lecture by heat transfer operation more details of the heat transfer operations you can get from different textbook also we have given and references that given here in this lecture.

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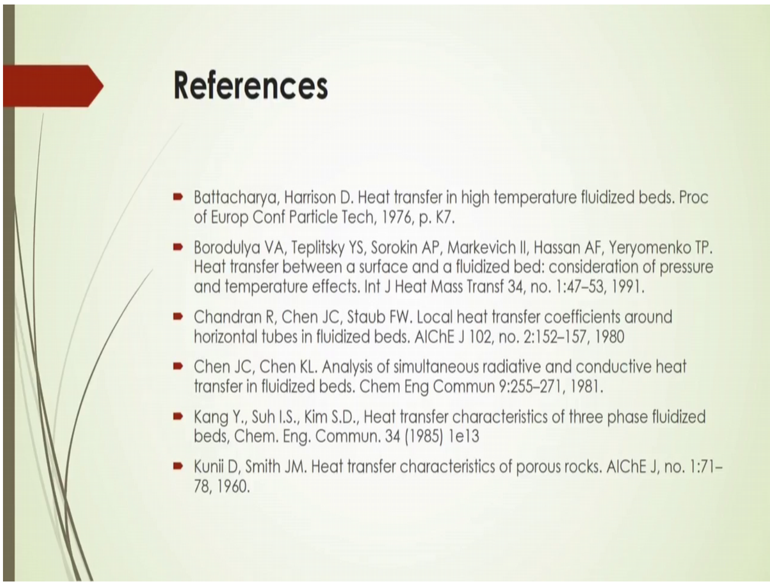

So, thanks for your attention for this lecture.

Thank you.