Heat Exchangers: Fundamentals and Design Analysis
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Lecture – 53
Fixed Bed Regenerator Analysis

Welcome to this lecture. In this lecture, we are going to talk about the Fixed Bed type Regenerator Analysis. And in the last class, we have talked about the different type of regenerators and in that one we have talked about the a bulb type or the fixed bed generator, and we also talked about the rotary type regenerator.

Here in this lecture, we are going to talk about the analysis of the fixed bed type regenerator; and in the context we just want to look into the actual system where this kind of regenerators are in use. And it will be easier for us to analyse it, if we look into the action or the operation of this particular type of exchanger. So, for that we have taken an example of a cryogenic application particularly it is called the pulse tube refrigerator where we find thin walled empty tube is first periodically pressurized and depressurized.

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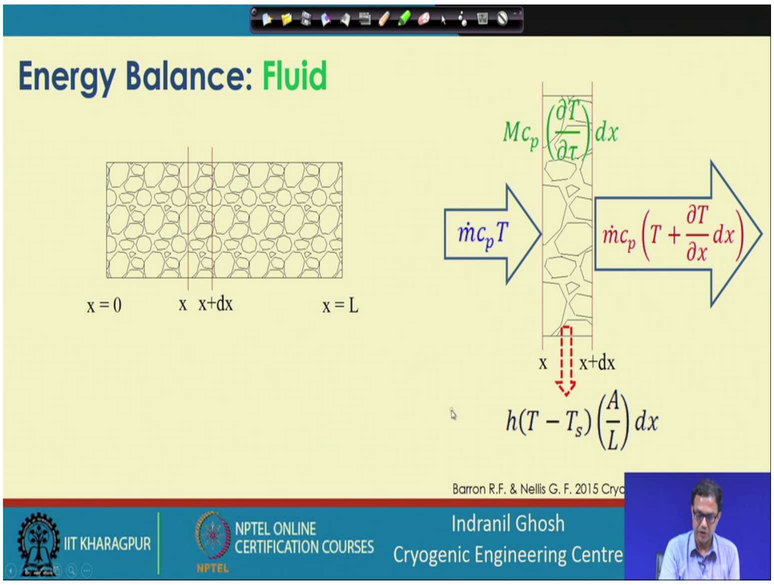

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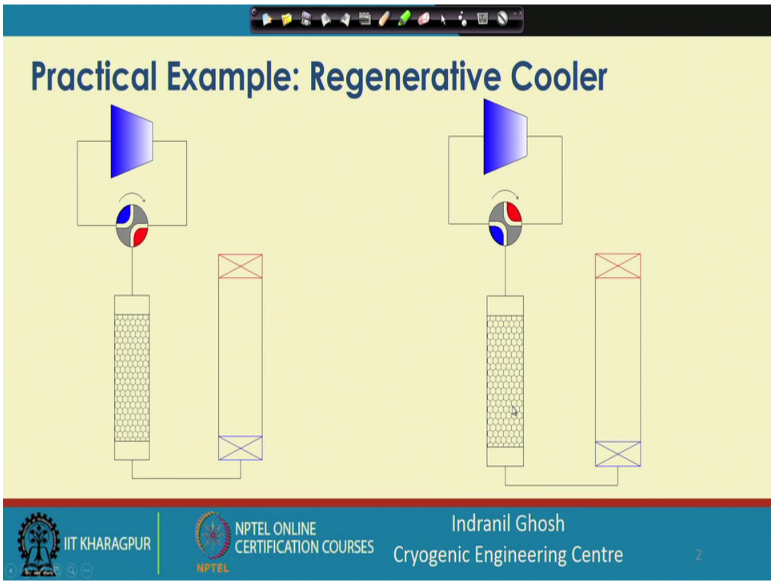

Here this is the positive where we have a thin walled empty tube; and on this side we have a hot end heat exchanger, and on the other side we have another cold end exchanger, this is the cold end exchanger. And this is periodically; this is periodically pressurized and depressurized with the gaseous helium. Now, if we are looking into this operation, you will find that there is a small valve and this valve we call it as a rotary valve. So, this rotary valve periodically sends high pressure gas into the system or after one cycle it will connect it to the suction side of the compressor.

In one cycle, it connects it with the discharge side or the high pressure side; in one cycle in the alternative cycle, it will connect it to the suction or the discharge I am sorry, suction or the low pressure side of the compressor. So, alternatively it connects it to the high pressure and the low pressure and between the pulse tube or the empty tube and this compressor, we have one regenerator. So, this is the regenerator, this is of fixed bed type. And we find that this regenerator is basically, what it is doing is it is trying to connect, you see when the high pressure gas is coming from this end to this end, this will allow the gas to pass through this. If it is in this configuration, so the gas will be high pressure, gas will be coming from this end and it will pass through this regenerator and then it will come to this pulse tube.

So, now in one cycle what is happening, this high pressure gas is coming to this side and this is at say the hot T h temperature. And on the other side, when it is you know in the steady state operation, we will find that this is the cold side and this is also at the cold side. So, here we add the refrigeration Q c. So, now, in the in this cycle, so what is happening, the high pressure gas is coming and flowing through the regenerator, so this gas is at high temperature and by the time it is coming over here it is passing to T c.

So, while passing through this regenerator matrix, it will be heated up this matrix will be heated up and the gas in turn will cool down to T c. And at the end of this cycle, what we will find that this gas, you know it is coming over here and getting expanded in the other cycle. When it is connected to the suction side of the compressor, we find that this cold gas is coming to this side and it will be passing through this one. So, this gas is that T c or slightly lesser than T c and this gas is going back to the suction side of the compressor via this regenerator. When it is passing through the regenerator, it will pick up the heat, it has left earlier in the earlier cycle to this regenerator bed.

So, now we can understand that in one cycle the hot gas is coming, generally this gas is helium, gaseous helium, and this pressurized gaseous helium will be passing in the one cycle, you know through this configuration. And in the other cycle, when it is getting discharged to this low pressure helium or expanded helium will flow through this regenerator, and you know in this configuration it will pass through this one, and go to this one. So, this is how it works in both the cycle helium is the gas which is passing through this regenerator, this is of our concern at this moment.

So, in one cycle, we will find that pressurized gaseous helium flowing through this regenerator. In the other cycle, we will find that the low pressure helium expanded helium from T c, it will move to T h in the ideal condition. So, this is what is the configuration of a fixed bed regenerator or the principle of working in the pulse tube refrigerator operation this is the basic pulse tube configuration.

Now, if we move with this basic knowledge of this fixed bed regenerator, if we now move to the next I mean its analysis part, we understand that in one cycle the gaseous helium or the hot fluid stream is flowing from one direction to the other direction. And in the other cycle the cold stream is flowing from this end to the this end, from x equals to L to x equals to 0 this end. So, as you can understand that this hot steam and cold streams are alternatively flowing through this direction and the direction is reverse in nature I mean counter current in nature. That means, in one cycle they are flowing from the hot stream is flowing from the stream this end to this end. In the next cycle the cold stream is flowing from this end to this end. So, the configuration is basically counter current in nature.

So, now we have, if we look in detail about this is elemental you know area between x and x plus d x basically, it is an one-dimensional model. And here this is x equals to 0 we have x equals to L in between, we have taken some region bounded between x and x plus d x. Now, with that one we find that some you know, let us assume that the gas hot stream is flowing through this and you know it is when it is flowing through this medium it is moving out with an temperature of T plus del T del x into d x and it is the mass flow rate of the hot fluid stream maybe m dot.

Now, if you look into this one this configuration what we find that we have some solid particles and we have certain amount of void. So, this is the solid particle and this is solid particle and we have void in the last class we have talked about it. So, the void is you know it is given by e v that is the void fraction. So, now if we look again into this part we find that we have the some amount of heat transferred from the fluid to the solid part. So, if it is hot fluid, we find that the hot fluid is giving heat to the solid particles. And this is the amount of heat transfer, where h is the heat transfer coefficient, T is the temperature of the fluid stream, T s is basically the temperature of the solid particles or the matrix temperature.

And we have considered that for the length L, we have some area associated with it is L, A. And so in the length d x we have A by L into dx area associated with this region. So, h into A by L into d x is the area and this is the temperature difference, so that is the amount of heat that will be transferred on the hot fluid to the solid particle.

Now, in turn what will happen because of this change in of the, I mean as the hot fluid is giving the heat to this solid particles it is temperature is you know odd there is the change in the enthalpy of this gas. And in turn I mean as the gas is flowing through it is giving heat to the solid particles. And what if a gas which is there inside I mean some part will be you know the energy will be stored in this void fraction that is a we find that this is the amount of energy that will be stored within this one, within the gaseous volume.

What is the gas that M part that is you know that is equals to the void fraction I mean that void where we have the gaseous part and multiplied by the C p of that one that is sorry C p is the gaseous C p, and mass is the particularly that is equals to the rho of the gas and V of the gas, so that is the void volume multiplied by the actual or total volume of that system. So, we will come to that part to how to evaluate that part.

And so now we can understand that within this element we will have this much amount of gas associated with it and that is how the energy will be stored within that volume. And with this I mean knowledge this is the energy balance, we are talking about the fluid. And we find that the gas is moving from one end to the other end, it is giving some heat to the solid. And there is some change in the overall enthalpy of this fluid, and some amount of energy is getting stored inside the element of this gas. So, if we now write an energy balance, we would be able to make an energy balance for this one.

And next is the how do we write that one how do we write the equation. So, this is what is entering, so it is m dot C p into T. And this is moving out, so it is m dot C p then you have T plus del T del x into d x. Then this part is also moving out, so it is h into T minus T s, then we have A by L into d x and that is exactly what is it is getting stored in it. So, it is M into c p and this is del T by del tau that is equals to the time within this time tau this is the energy that has been stored in this element, so that is multiplied by d x and that is exactly the energy balance for the fluid stream.

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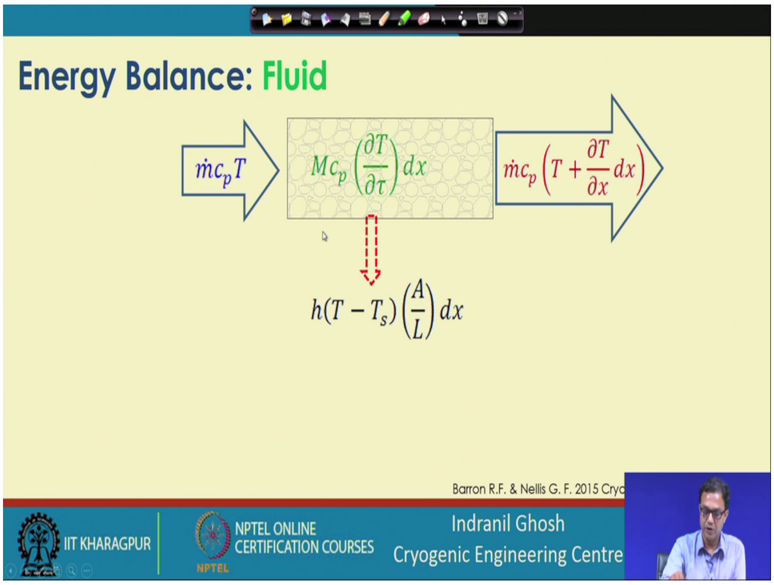

Now, the same thing we can try to you know look into I mean for the this is, for the energy balance I mean as we have just a noted in the previous slide that that was the energy balance we have a written.

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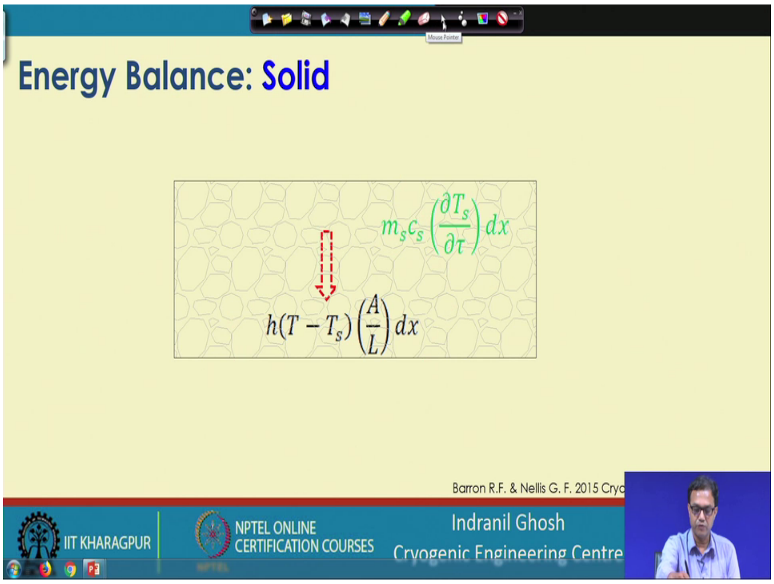

Now, if we go to the solid part, we find that the solid is receiving some amount of heat from the hot fluid and that is given by this amount. So, this is basically h into T minus T s A by L into d x that is what we have learnt that this fluid stream is giving this amount of heat to the solid. When the solid is receiving some amount of heat, what happens to the solid temperature, its temperature is going to rise. So, if we say that the solid is having a temperature T s we know that del T del tau it will be I mean the temperature rising rise.

And if we now look into the energy associated with it is del T s del tau as I told you and multiplied by the m s and c s. So, if the mass of this element is m s and c s is the mass associated with it then we have d x, you know the elementary length associated with it. Then we can write it you know we can equate it with this, this term and this term and we can find the energy balance equation for the solid.

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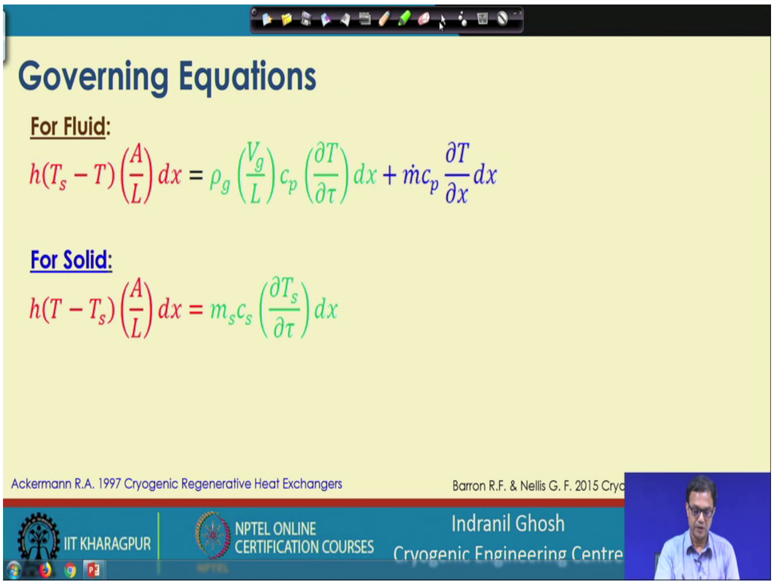

And in that case we will have, if we write both the equations, we find the governing equation for the fluid stream, if we rearrange them together we find something like this. So, this is the particularly the amount of heat that has you know we have talked about the hot fluid in the cold cycle I mean when the cold fluid stream is flowing through the regenerator. So, this is the amount of heat either received by, I mean given by the hot fluid or the received by the cold fluid, so either way and this is the amount of you know the stored energy in it and this is the change in the enthalpy, so that is how what is for the fluid.

Now, if we look into the for the solid part, we have this is the equation written for the solid part. And so these two equations are the governing equation and when we write any differential equation particularly involving the time and space we have to use some kind of boundary conditions or the initial conditions to solve this equation.

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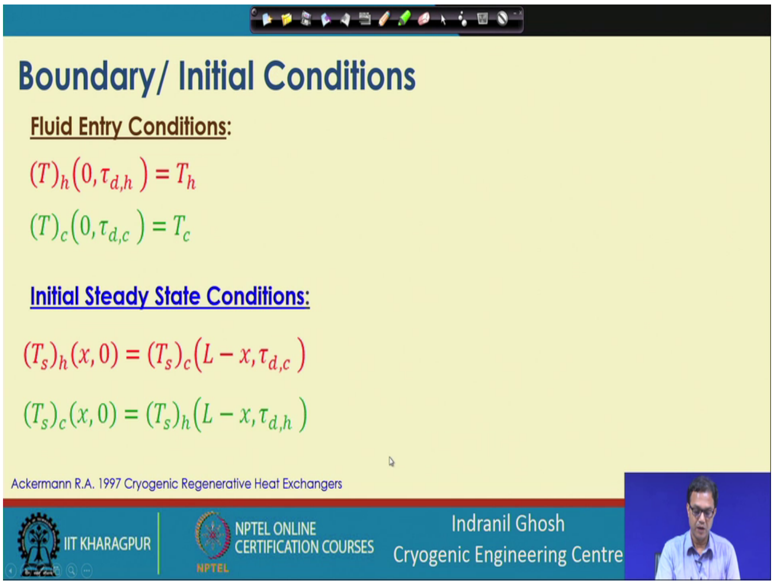

So, these are the boundary conditions as we have written in the or the entry fluid entry condition as we have written it here as part the Ackermann's cryogenic regenerative heat exchanger book and here what it is telling is that when it is entering the regenerator.

So, this is entering at temperature of T h. So, this is this tau d h basically this tells about that tau d is the dwelling time for the hot fluid. This entire duration I mean when it is entering this I mean regenerator that means, we have if you remember that we were talking about the regenerator, it is the hot fluid was entering through this regenerator. And this is at x, if we say that this is equals to x equals to 0, at x equals to 0 it is entering and it is entering at a temperature T h we have said that that end is at T h the other end is at T c. So, the other condition for the cold you know fluid stream when it is flowing in the other directions. So, this is at it should be I mean either at x equals to, it should be x l or I mean if we consider for this direction also you know if we change it to x equals to this is should be x equals to L.

So, for this entire dwelling time T tau T c, we have a temperature it is entering at T c. So, now, the initial or the steady state condition is the basically what we mean is that what is the temperature of this is the bed, how it is behaving I mean or the temperature of this matrix basically we wanted to calculate. So, here we have for this is a earlier we talked about at x equals to L, but now we were talking about L minus x. So, here you see at x at a location x for this hot fluid stream, it is at any distance x that is equals to that is same as what it was there in the previous cycle at the same location.

So, I mean if the gas was flowing and this is a it was entering a T h by the end of this cycle, so it will leave the bed at a particular temperature, so that is what is the initial condition for the other fluid like when the cold fluid stream is moving through this one, so that finds that the bed is at that particular temperature at different location, so that is what is the initial steady state condition for the cold fluid.

Similarly, when the cold fluid is flowing in this direction at the end of the cycle, it will leave the regenerator bed or the matrix at a particular temperature, so that temperature profile that fluid the hot fluid when it has to come in the next cycle, it will find that the bed is preparing of the bed is having that temperature profile at the end of that cycle or at the beginning of that cycle. But it has what it has been left by the earlier cycle or the fluid it has left in, in that condition, so that is how is the I mean the boundary or the initial conditions. But as we as it can be understood that it gives a, I mean quiet I mean makes the analysis or the solving these equations is bit complicated, but we will not look into that details of that solution.

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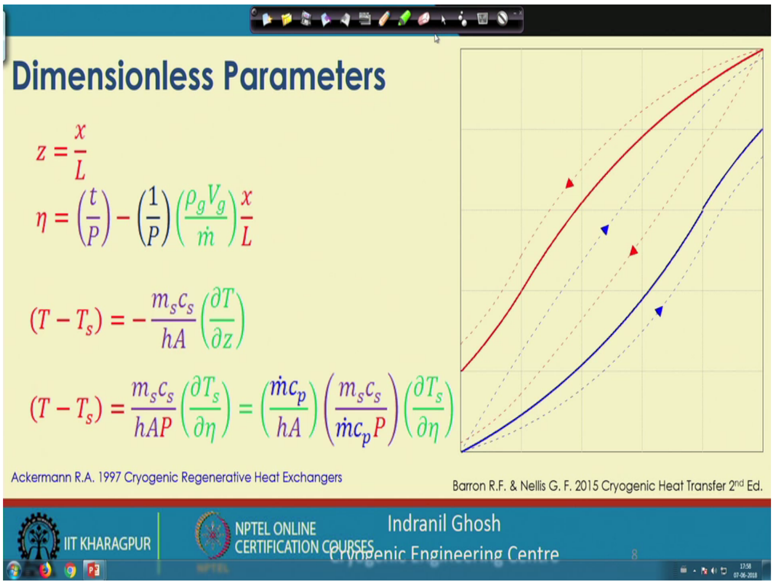

But before just you know we will just have a look into this slightly more in details, so we basically define two dimensionless parameter s, one is the dimensionless distance and the dimensionless time, one is z equals to x by L and then eta that is equals to dimensionless time. So, this makes you know with this transformation with this change in variable or dimensionless parameters, we can write the governing equations to this form, and the other equation will take this step.

So, finally, if we apply those boundary conditions, and if we try to solve this one, I will suggest the readers or the students to if someone is interested about this one they can look into the Ackermann's cryogenic regenerative heat exchanger book or I mean for the detailed analysis of this. But, if we look at this is the solution of a ideal regenerator, we find that that I mean at the beginning the at the end of this one, how the cold fluid or the matrix is I mean how would be the temperature and the distance I mean relation.

So, here we have the temperature or the reduced temperature on this side we have the dimensionless distance so longitudinal distance. And this is how the cold fluid is entering to this heat exchanger. And we find that this is how it is, you know it has when it was started this is the temperature of the gas cold gas flowing through the regenerator. And by the time the end of the cycle, it will be coming to this temperature and this is the matrix temperature or this would be the at the end of the cycle this would be the temperature of the matrix.

So, on the other way or the other I mean end, we find that the cold stream initially it is you know flowing from this end at the beginning of the cycle, it is like this. And as time passes by the end of the cycle, it will be coming to this condition, whereas the matrix will be in this region. So, this is what is happening in the regenerator. And this is of course, the balanced condition and ideal regenerative action where we do not have any actual conduction losses and etcetera we have not considered.

But, if someone is solving that equation and with the boundary conditions applied as we have said one can solve and get this kind of I mean temperature profiles in the fluid as well as in the matrix of the fluid stream I mean in the regenerator. So, we are not going into that details of calculating the temperature profile or the matrix temperature profile in this lecture.

But rather we will be interested more interested to design or simulate a particular type of heat regenerator for cryogenic applications or any other application, where our job is basically to look for, I mean to simulate the regenerator under a particular application or to try to design the regenerator for a given condition. So, for that we will look into the analysis or the suggestions given by the researchers, and we will look into particularly for the cryogenic applications where I mean relevant to for this regenerator set cryogenic condition.

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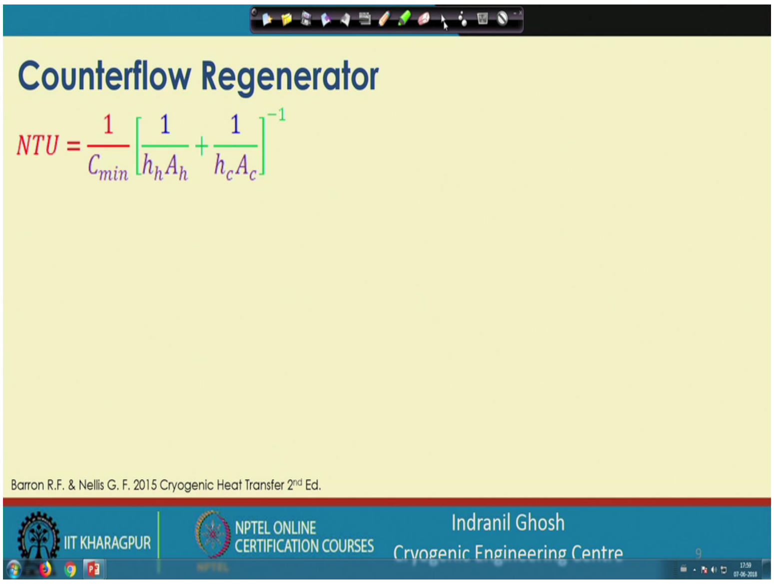

So, let us look into the design part. So, for a counterflow regenerator which is very common in, in case of cryogenic applications, we define the NTU and it is given as 1 by C min; C min again we have already learned about this C min that is the mass flow rate multiplied by the appropriate I mean appropriate specific heat. And along with that we have the hot fluid and the cold fluid this is 1 by h A h, and this is associated the heat transfer coefficient of the hot side and this is associated with the I mean area associated with the hot side.

And in general if it is a fixed bed most of the time this A h and A c are of the same area. And here this h c is the heat transfer coefficient associated with the cold flow. So, this is and this is whole to the power minus 1. So, this is how we define the NTU for this counter current, regenerator. So, with this basic definition now we will continue in the next lecture about the design or the simulation of the regenerator.

Thank you for your attention.