Solar Energy Technology
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Lecture - 16
Theory of Air Based Solar Flat Plate Collectors

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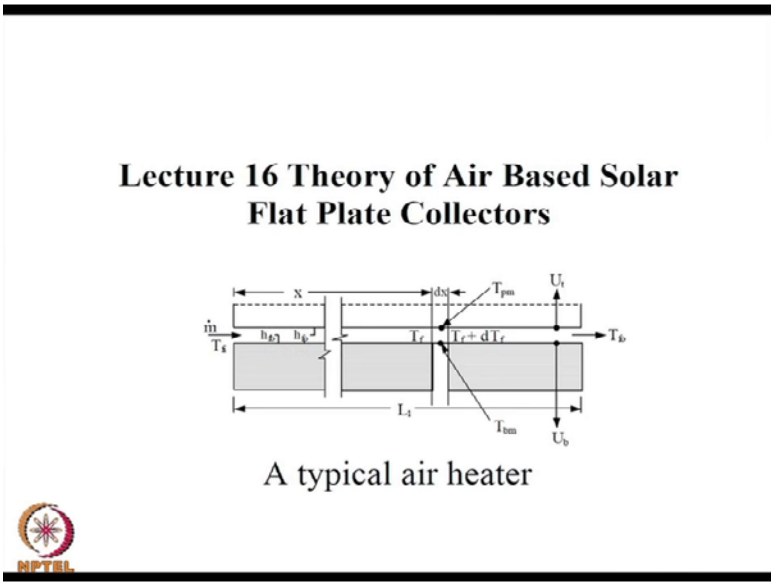

In the last few lectures, we considered liquid based solar collectors. In general, they are water heaters, though occasionally anti freeze of fluid, also is used, it may be used for heating other liquids also. Apart from that, solar collectors, in the category of flat plate collectors, are also in wide used, based upon air as the fluid. In general most of the time no other gas is used to heat through the solar collector.

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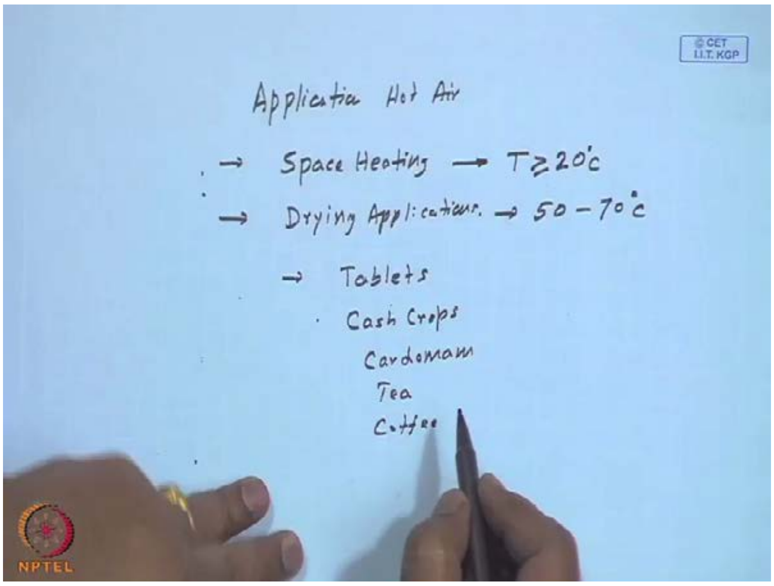

The importance of air based collectors comes in to the picture, because of a large number of applications, for hot air; it could be space heating in colder climates, various drying applications, and solar, in that sense, is ideally suited, because if you want space heating, it requires temperature, slightly greater than or equal to 20 degree c, to be maintained for comfort condition, under cold climatic conditions. Drying applications typically will be 50 to 70 degree c, and normally not at a very high temperature. Some of the things are, it could be tablets, medicine tablets, in the pharmaceutical industry, or it could be cash crops, like cardamom, tea, coffee etcetera.

We will talk about these things in detail little later part of our lecture series. The important point is, the temperature should not exceed, or is not used, because along with that the flavor and the oils, also get evaporated, which we do not want in any food product. So, air based solar collectors, derived their own strength for good number of applications, and solar flat plate collector, with a reasonable efficiency, at about 50 to 70 degree centigrade is operable, consequently this appeals to be a promising application, or promising device, for different applications. However, one deterrent appears to be larger pressure drop, through solar air collectors, compared to our liquid heaters, that we shall again consider and I am showing here a typical air heater.

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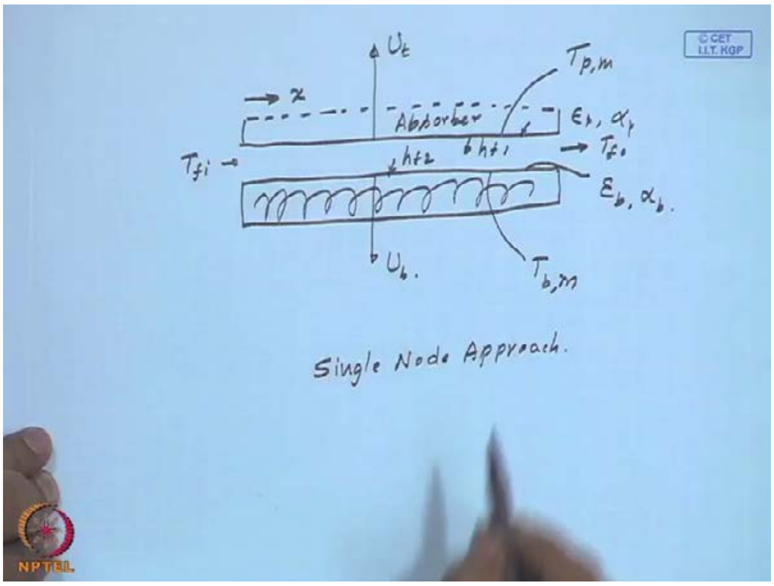

You have a duct, the top one is the absorber, the fluid flows entering at a temperature of T f i and leaving at a temperature of T f o. the bottom is insulated, and top will have one or two glass covers. So, this will be having a emissivity of epsilon p, and absorbity of alpha p. Similarly the bottom plate may be having an emissivity of epsilon b, though absorbity does not come into the picture, and this part is insulated. So, as the heat is absorbed, this is the direction of flow, and as the heat is absorbed transmitted through the glass cover, by the top cover, it is transferred to the fluid, with a heat transfer coefficient of h of one, and again another heat transfer coefficient to the bottom, with a h of two. This is typically at a temperature of T p m, as we have been doing, and the bottom is at T b m; that means, we follow a single node approach, the absorber is represented by one temperature. The bottom plate is represented by another temperature, and there is of course, a heat loss coefficient from the top U T, and a bottom heat loss coefficient of U b.

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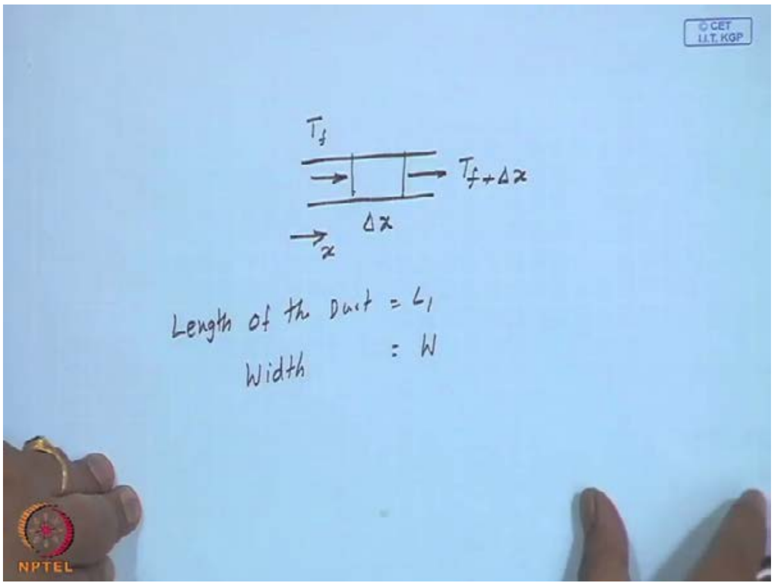

So, we shall try to analyze, and I shall show a small control element, the at any particular distance x, and an elemental length of delta x. The fluid enters at a temperature of T f, and leaves at a temperature of T f plus delta x, and the total length could be L 1 as we have seen, length of the duct, and let also width W, which is perpendicular to the plane of the paper.

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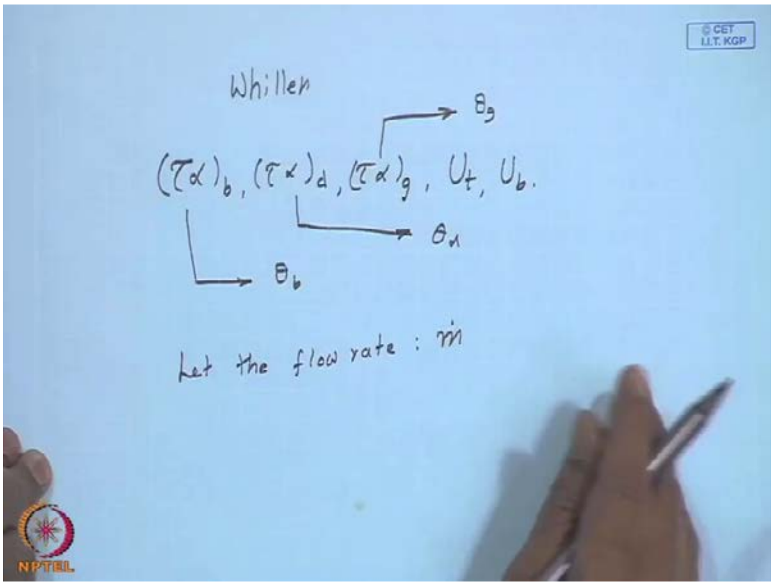

This analysis is due to Whillier, reference also is given. this is similar to the analyzes we followed for the liquid collectors, and we need to calculate transmittance absorbance product, for the direct radiation, and the transmittance of certain product for the sky diffused radiation, and the transmit absorbance product, for the ground reflected radiation, along with top loss coefficient U T, and the bottom loss coefficient U b. In other words, this is calculated at theta b, and this is calculated at theta d, and this is calculated at theta g. The correlations of which have been given by brand muro and beck man, and this is the angle of incidence for the direct radiation, at the given time under consider, let the flow rate m dot.

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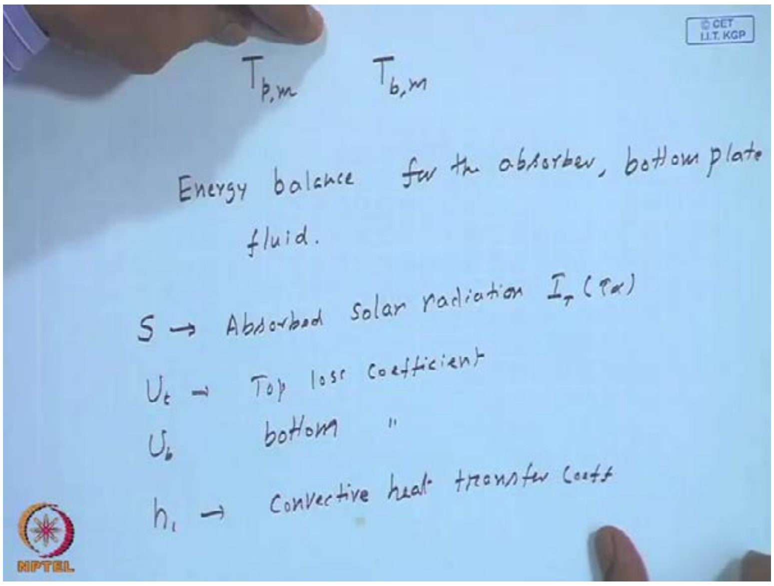

And the plate is at T p m, and the bottom is at T b m, which we have already identified as a single node approach. Now we will make an energy balance for the absorber, then the bottom plate, and the fluid, here is our notation S, is the absorbed solar radiation, which we know is I T times tau alpha, where I T is the solar radiation on the treated plane, and your tau alpha is the combination tau alpha b, tau alpha d, and tau alpha g. And U T of course, we have stated as a top loss coefficient, and U b the bottom loss coefficient.

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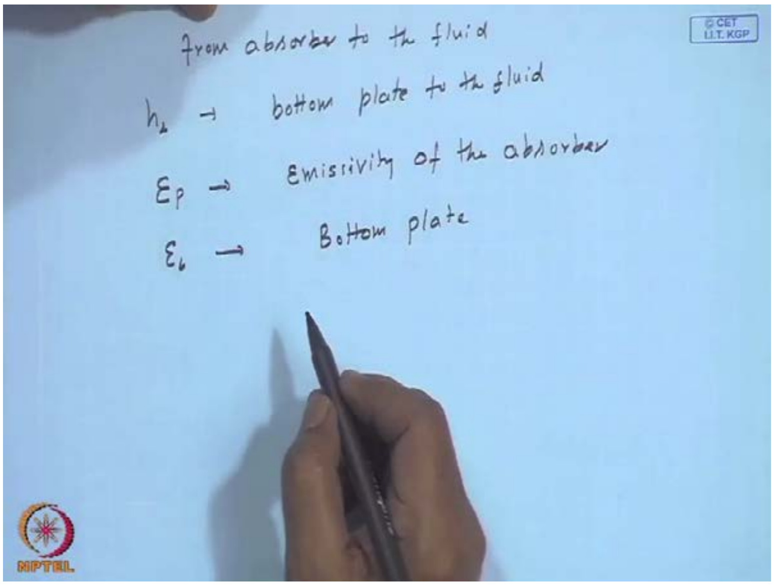

Then h 1 is the convective heat transfer coefficient, from the absorber to the fluid. Similarly, h 2 from the fluid bottom plate to the fluid or from the fluid to the bottom plate. The heat trans direction will depend upon the elective temperatures; epsilon p is the emissivity of the absorber, and epsilon b is that of the bottom plate.

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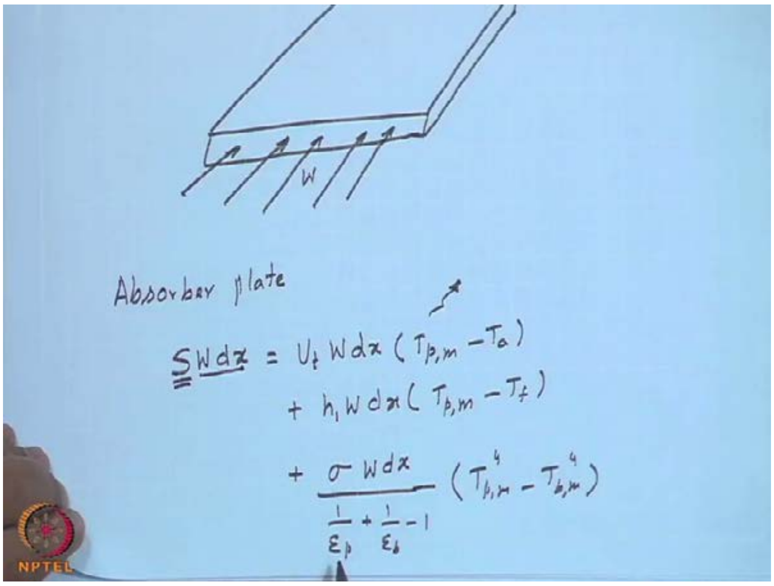

So, if you want to have a another view, of this air heater, you have a sort of rectangular duct, this is the width W that is not seen, and this is the length L we are talking about, and the flow is now through this rectangular passage. This entire thing is having a glass cover at the top and a bottom insulation. So, the energy balance on the absorber plate, if s is a absorbed energy, area will be W into d x; that should be equal to U top into W d x times T p m minus T a this is a loss plus h 1 W d x T p m minus T f plus sigma W d x by 1 upon epsilon p plus 1 upon epsilon b minus 1 times T p m to the power four minus T b m to the power 4. Let me explain the absorbed energy is s per unit area, and the elemental area we have considered area is W into d x. Of this absorbed energy, something is lost to the ambient through the loss coefficient top U T, and something is transferred to the fluid, with the heat transfer coefficient of h 1, and the temperature difference being T p m minus T f, and then also from T p m to T b m there is a radiative heat transfer parallel taking place, whose value is given by sigma, into the temperature difference 4 power, into area by the normalized emissivity, which is epsilon p plus 1 upon epsilon b minus 1.

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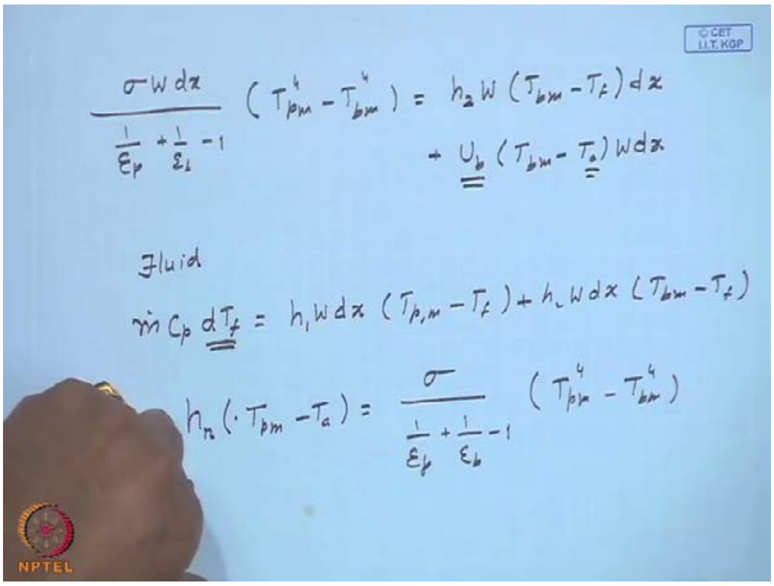

Now for the bottom plate, what it receives is, sigma W d x by radiation from the top plate. This should be equal to h 2 times W into T b m minus T f plus U b into T b m minus T a times W d x, there should be a d x here also. So, this is what it receives by radiation, and this is what it transfers to the fluid, assuming T b m is more than T f, and this is the again loss from the bottom, with the bottom loss coefficient of U b, and to the ambient temperature T a. The energy balance on the fluid m dot c p into temperature race, should be equal to what it receives h 1 W d x into T p m minus T f plus h 2 into W d x times T b m minus T f. As long as we are consistently writing this, the sign of T b m minus T f will take care of, whether it is an addition or a subtraction, in making d T f, for the air flow of mass flow rate m dot. So, we can define a radiative heat transfer coefficient, like we have done earlier, based upon T p m minus T a, which is equal to sigma 1 upon epsilon p plus 1 upon epsilon b minus 1 times T p m to the power 4 minus T b m to the power 4 this is nothing, but expressing the radiative transfer, in terms of a heat transfer coefficient h r, and we solve, and h r will be equal to again will be written as, T p m square minus T b m square into T p m minus T b m or an approximation can be made, if T p m minus T b m is small.

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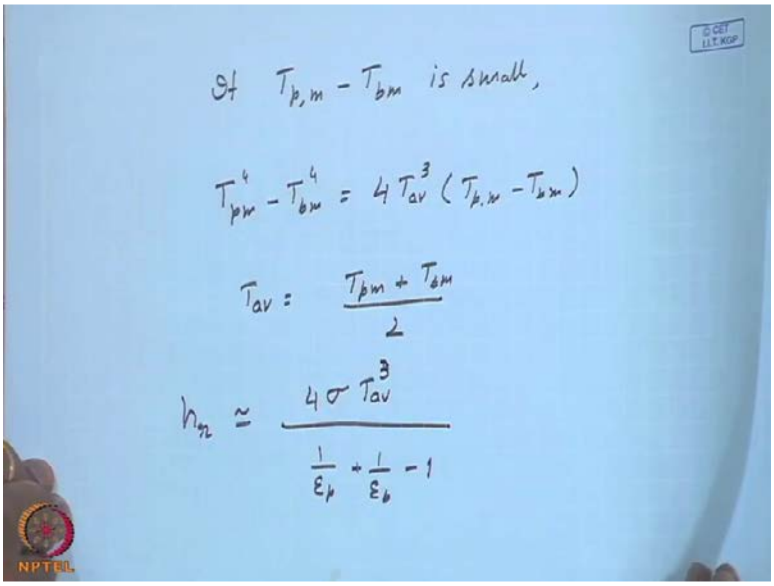

So, this forth degree difference can be written as, 4 times T average cube times T p m minus T b m, where this T average, is T p m plus T b m arithmetic mean of two temperatures. So, h r now is approximately 4 sigma T average to the power 3 by 1 upon epsilon p plus epsilon b minus 1. So, now we have written the energy balance equations on the absorber, the bottom plate, and the fluid, and the radiative heat transfer coefficient has been expressed, in terms of an average temperature, little approximately compared to the exact equation.

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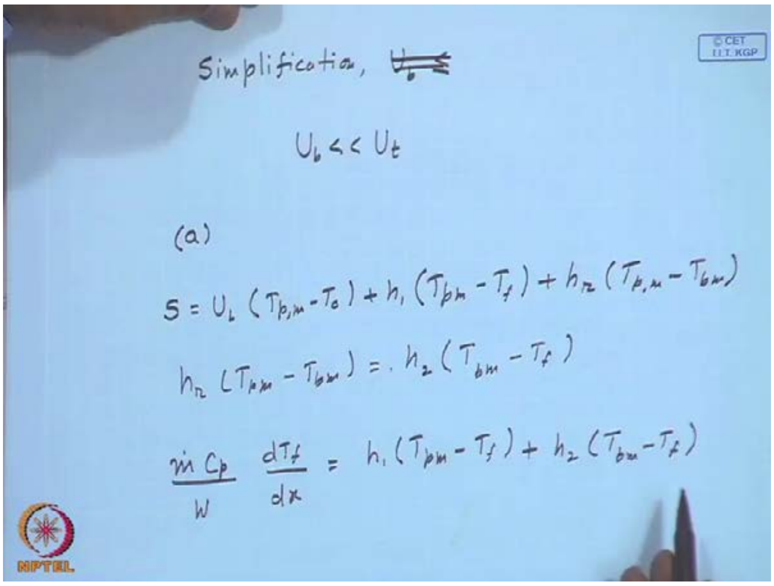

Another simplification, though it is not that, we cannot do the analysis, we can do this; U b is assumed to be much smaller than top loss coefficient, what we are saying is, if the bottom plate temperature is low, the losses from the bottom are might smaller, than the radiative and convective losses from the top glass. So, with this simplification, I will call them some numbers, a equation this absorber in the from the first equation follows U L into T p m minus T a plus h 1 into T p m minus T f plus h r times T p m minus T b m. Now W d x in the equation first we have written, is common throughout, so that is cancelled, and you have the absorber energy equal, to whatever is the loss plus, whatever is gain by the fluid, and whatever is transferred to the bottom plate, and h r T p m minus T b m, simply equal to h 2 times T b m minus T f, whatever is transferred by radiation should be converted to the fluid. On the fluid, this is a equation we will call it b and then m dot C p by W d T f upon d x equal to h 1 times T p m minus T f plus h 2 into T b m minus T f. The rate of increase of the fluid temperature in the x direction is equal to whatever it is gained from the absorber plate, plus whatever it is gaining from the bottom plate.

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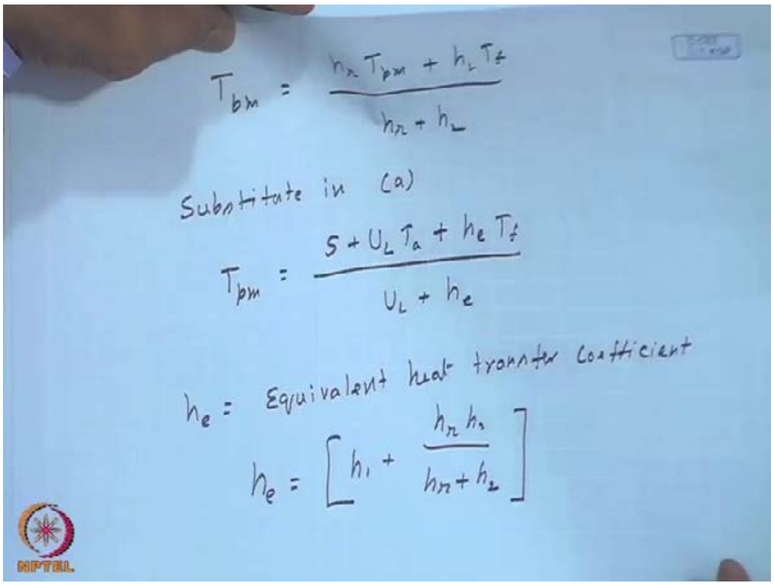

And from this T b mean, is h r T p m plus h 2 T f upon h r plus h 2. So, substitute in a, let mean temperature will be, s plus U L times T a plus h e into T f by U L plus h e, where h e is a equivalent heat transfer coefficient. So, this is nothing but a simplification the notation. In other words, instead of a long expression h one plus h r h 2 upon h r plus h 2, we simply write it as h e. So, it can be called an effective heat transfer coefficient between the absorber plate, and the air stream, because it compresses of convention from the absorber plate, and again convention from the bottom plate.

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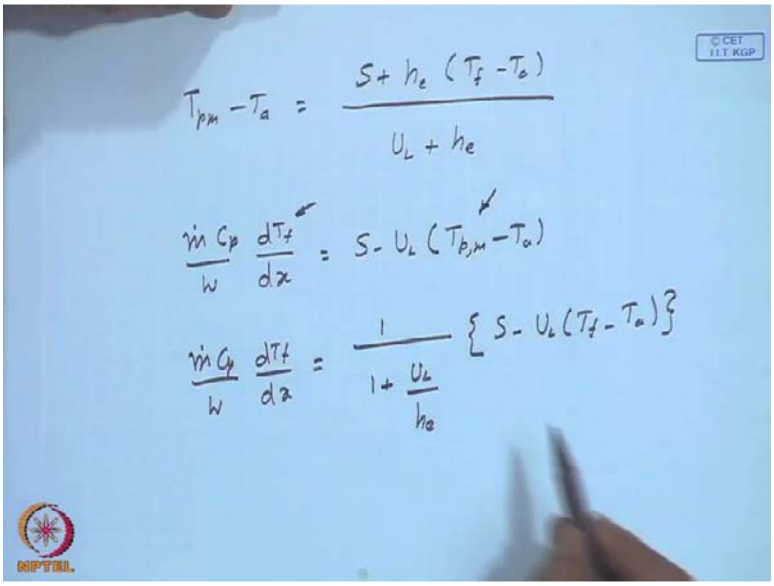

So, from this, you can now express T p m minus T a equal to s plus h e into T f minus T a by U L plus h e. So, from c equation m dot C p by W d T f by d x equal to S minus U L times T p m minus T a. You may realize that this analysis is exactly similar to, what we have done for the liquid base collectors, but since there is no fin effect involved in the absorber, that is a simple equation, and the rate of change of in the direction of the flow, we are having exactly similar to what we had for the liquid heaters. So, this can be rewritten m dot C p by W into d T f by d x is 1 upon 1 plus U L upon h e times s minus U L into T f minus T a.

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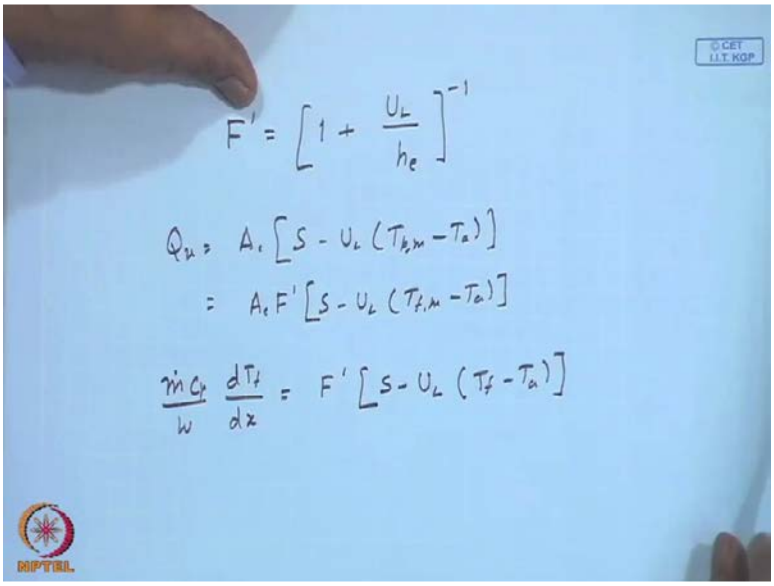

So, this is in terms of the mean plate temperature, and this is in terms of a mean fluid temperature. Consequently, if you recall this is f dash now is given by 1 plus U L upon h e to the power minus 1, because how did we first define, useful energy gain Q u is a c times S minus U L into T p m minus T a, which is the same as A c into collector efficiency factor F dashed times s minus U L into T f m minus T a. So, the other two equations; one is in terms of T p m, and the other is in terms of T f, and with a multiplication factor of 1 plus U L by h e to the power minus 1, which hence will be equated or called the collector efficiency factor. So, now the equation for the fluid m dot C p by W d T f by d x will become equal to f dashed times s minus U L into T f minus T a.

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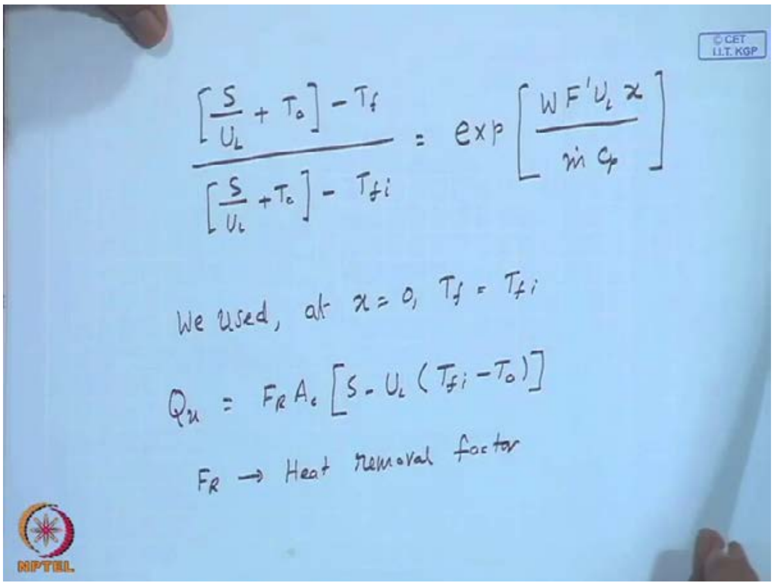

So, one can integrate this, this is a first order equation; S by U L plus T a minus T f by S by U L plus T a minus T f i should be equal to exponential W f dashed U L into x by m dot C p. So, we used the condition at x is equal to 0 T f is equal to T f i. So, if I express useful energy gain, in the conventional manner F R into A C times S minus U L times T f i minus T a. Now F R is your heat removal factor.

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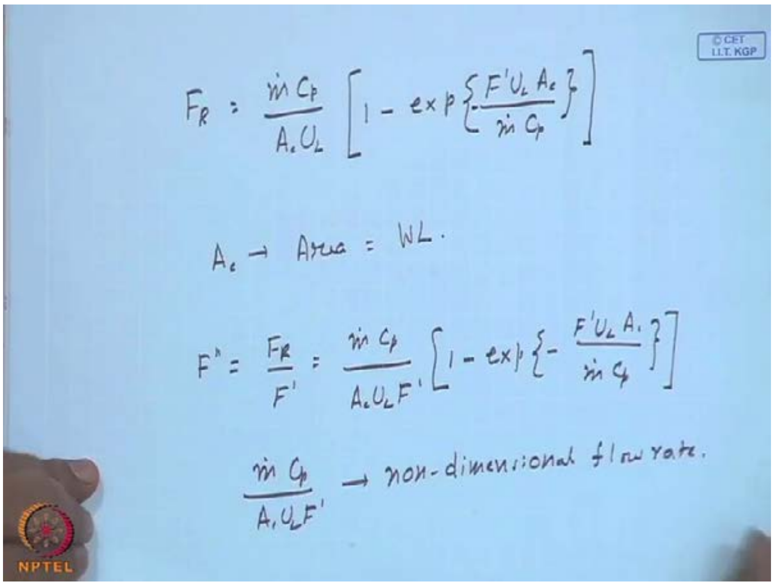

So exactly similar to, what we have done for liquid collectors, m dot c p by a c U L times 1 minus exponential F dashed U L A c by m dot C p, this is with a negative sign. So, A c is the area W into L if. So, now this is exactly whatever we had, in the case of our liquid collectors. One can also again define a flow factor F double prime equal to F R by F dashed equal to m dot C p by A c U L F dashed times 1 minus exponential minus F dashed U L A c by m dot C p. As we had noted earlier, the expression for F dashed may be different or F may be different, but this flow factor expression, is in terms of one non dimensional number, which is m dot C p by A c U L F dashed, we call it the non dimensional flow rate. For lack of a better word, we will call it the non dimensional flow rate.

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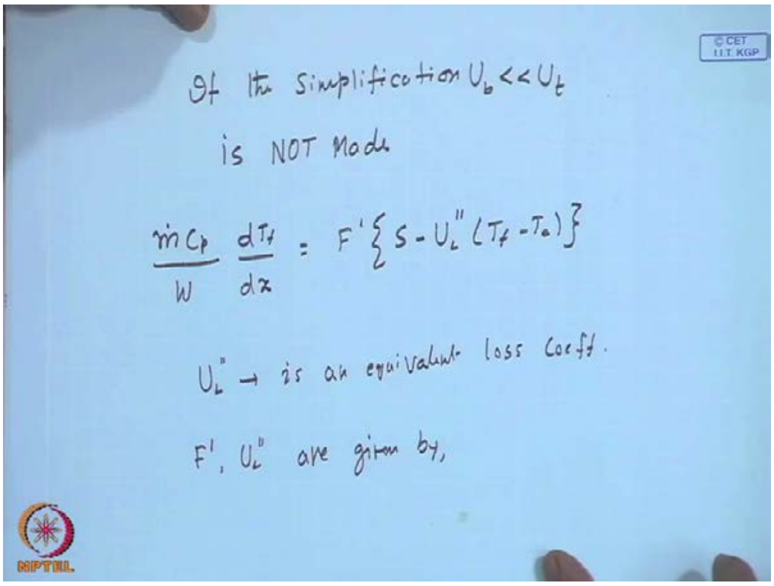

If the simplification, U b is far less than U T, is not made, the differential equation would be, you can work out straight forward m dot C p by W d T f upon d x equal to F dashed times s minus some U L double prime times T f minus T a. So, this U L double prime is equivalent loss coefficient.

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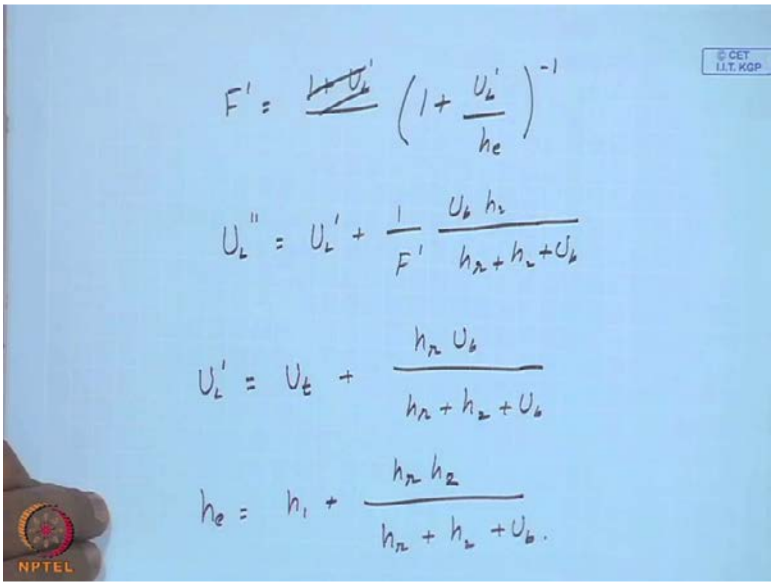

So now, F dashed and U L double prime, are given by, as usual to the power minus 1, and this U L double prime will be U L dashed plus 1 upon F dashed U b h 2 by h r plus h 2 plus U b. So, this overall effective loss coefficient will be a function or the collector efficiency factor also. And again U L dashed, you may be surprised that this is a new. Thing is nothing, but our original U T plus h r U b upon h r plus h 2 plus U b. So, you will have that U L dashed, will be U T plus this one if F dashed is equal to 1 U L dashed will be is equal to 1 U L double prime. And of course, h e is h 1 plus h r h 2 by h r h 2 plus U b. Now you may be wondering, too many equations are being written. So, what I would suggest is, you go back and starting with the three equations that we have setup, with the simplification that U b is far less than U double prime or U L, and top loss coefficient U T and, then simplification followed. You do not make that assumption, then re derive exactly along the lines that we have done, this equivalence will follow.

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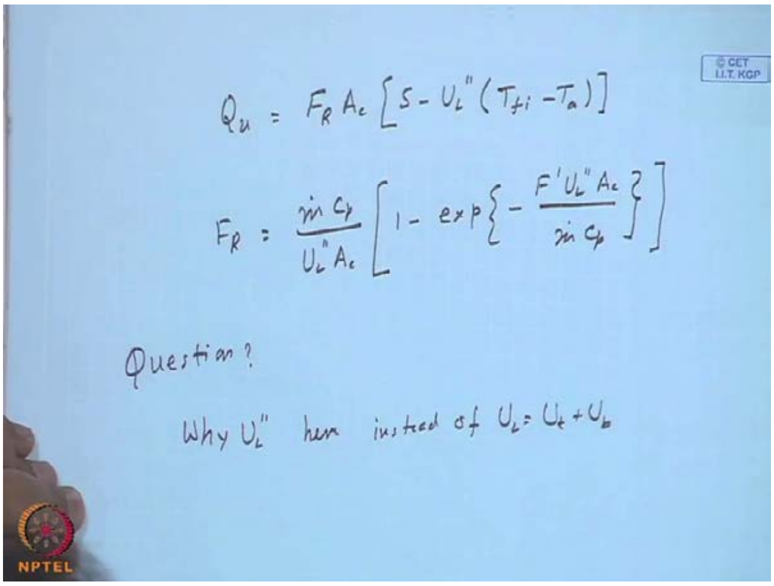

So, Q u F R A c s minus U L double prime by T f I minus T a, and again of course, this F R will be in terms of m dot C p U L double prime A c times 1 minus exponential T power minus F dashed U L double prime A c by m dot c p. Now, question, why U L double prime, here instead of U L equal to U T plus U b, you will notice U double prime is U L dash plus something, and where U L dash is U T plus something. In the case of liquid heaters that your U L is nothing, but U T plus U b, and here there is no direct heat transfer loss from the working fluid, or is there. Now, sometime back we pointed out U L may not be equal to U T plus U b, if the working fluid is in direct contact with a heat losing surface. Here what is happening is, the heat is being transferred to the fluid from the top absorber plate by convection, and by radiation it is transferred to the bottom plate, and inter the bottom plate is also transferring heat to the fluid, or loosing heat from the fluid. Consequently you may consider that this is a case of fluid coming in contact with the surface loosing heat.

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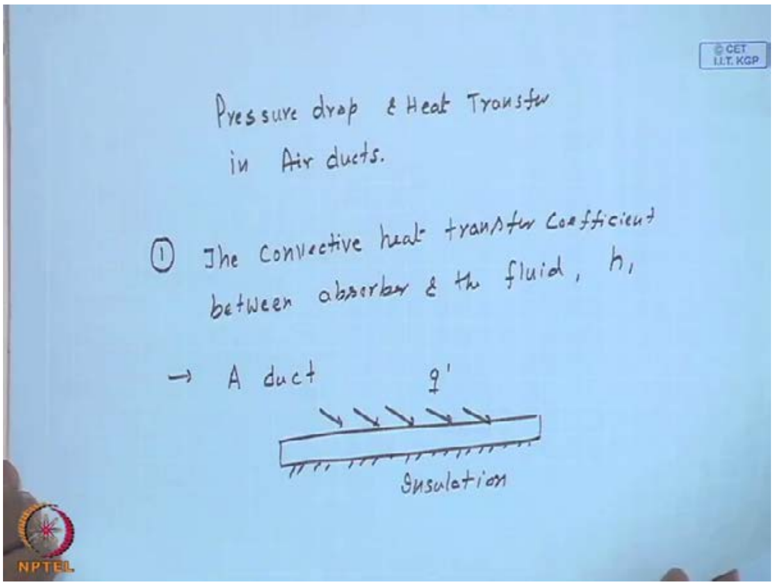

So, we shall continue, with the theory of air based solar flat plate collectors. One of the concerns what we said was, the pressure drop, and heat transfer, in air ducts alright. First the convective heat transfer coefficient, between absorber and the fluid; that is our h 1, and this is a case of a duct, subjected to some flux, some q dashed, and bottom being insulated. Some of few are familiar little bit of advanced convective heat transfer, there are basic four types of boundary conditions; one is insulated, the other is constant temperature, or the insulated and constant heat flux, so on and so forth. So, this is one of those basic boundary conditions.

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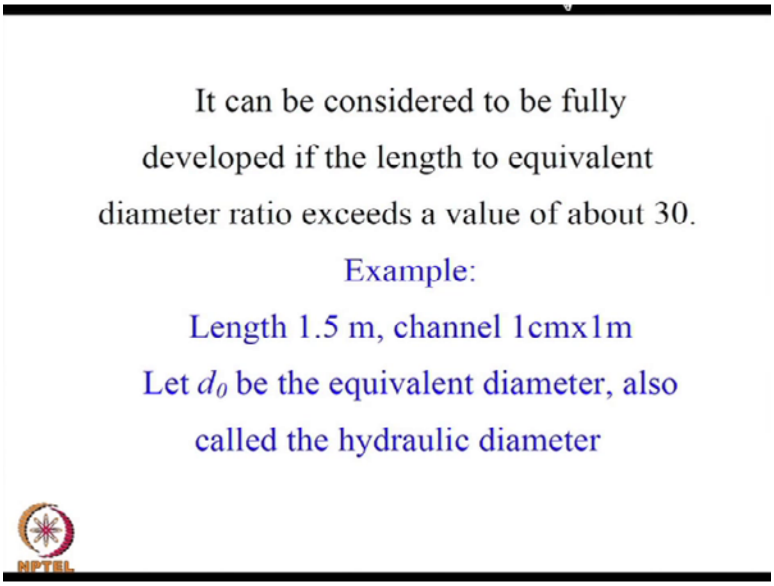

Now there is what is called, a fully developed condition. This we can call it for, fully developed flow, or temperature field or both.

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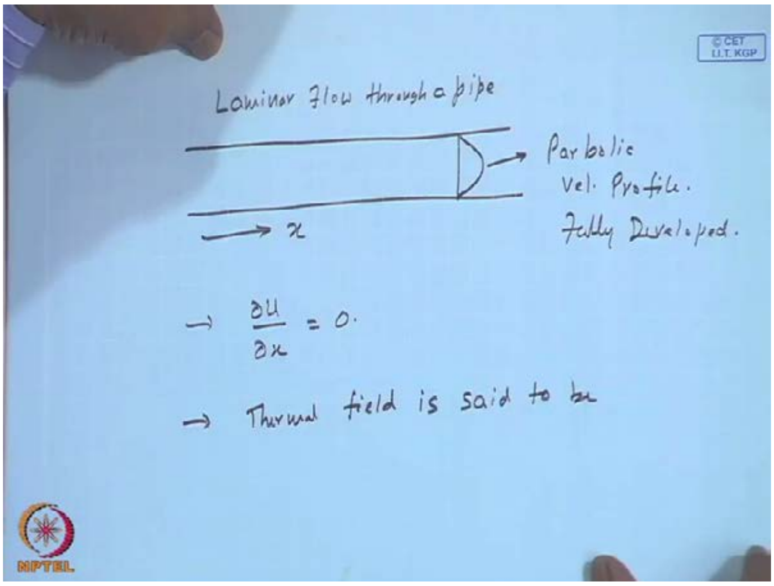

So, if you consider the classical thing, that you may be aware of; a pipe flow, and let us say laminar flow, the standard velocity profile is parabolic, fully developed. So, this condition generally we state it as; d U d x, this is the direction of x equal to 0. So, there is no more change in the velocity, in the axiom direction, with respect to x. It still is a function of radius, but not that of x. But again in the beginning the both U will be changing with respect to x, consequently the normal component of velocity also is not equal to 0.

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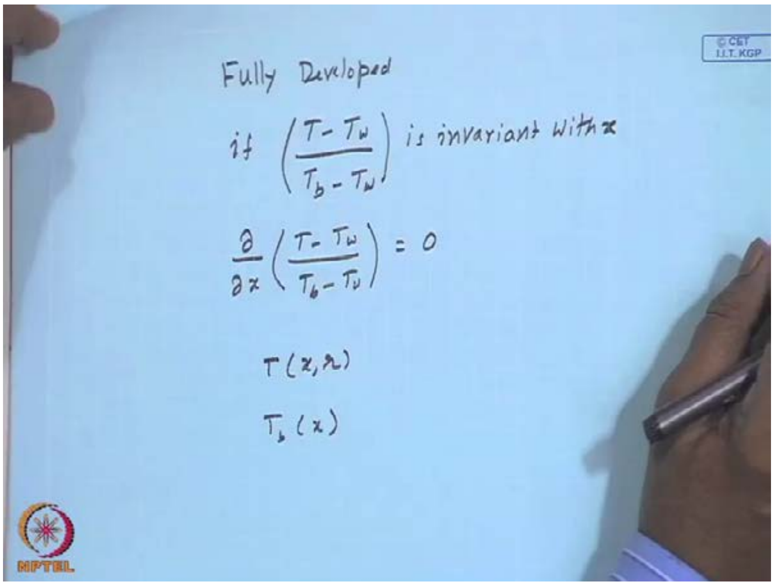

And the corresponding thermal field is said to be fully developed if T minus T W by T b minus T W is invariant with x or d by d x of T minus T W by T b minus T W equal to 0. In other words, there exist a non dimensional temperature, defined by T as a function of x and r and T b a function of x only, because it is the integrated average temperature at a section, that does not change with respect to x, under fully developed temperature field. This is satisfied by constant temperature, and constantly heat flux boundary conditions. Of course, we shall not go deep, whether the flow is developed, or thermal field is developed, which one develops faster, that is not in the part of this particular course.

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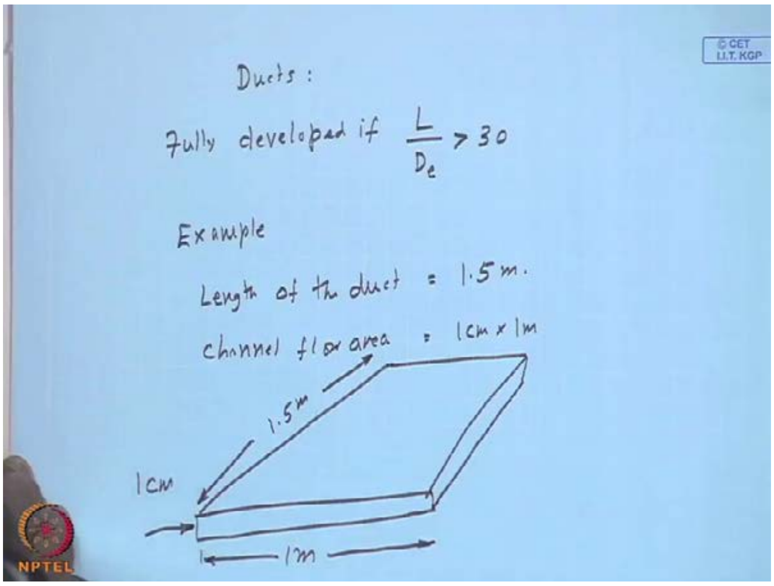

And generally it is considered for ducts, fully developed, if length by some d T is greater than about 30. So, if we take an example, small example, let the length duct be 1.5 meters, and let the channel be, rather flow area, be equal to 1 centimeter by 1 meter. This is in other words, is something like this; this is 1 c m, this is 1 meter, and this is 1.5 meters. These are quite typical air flow collector dimensions one can consider to be.

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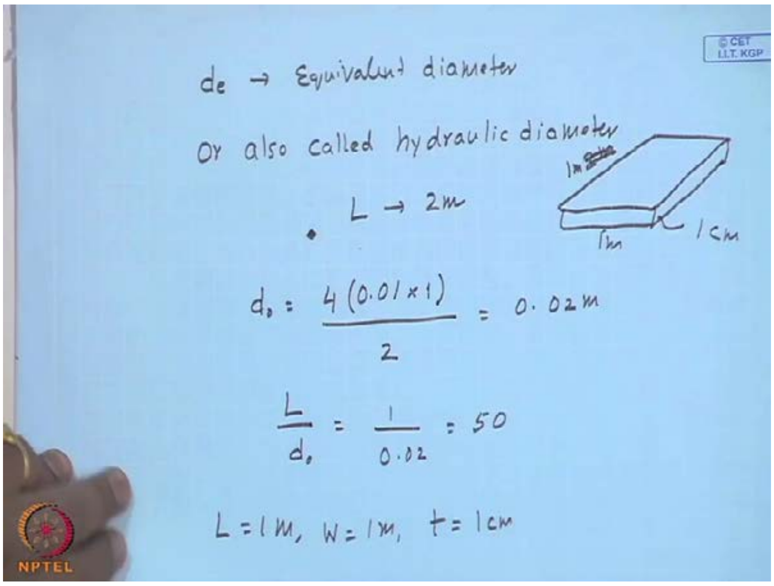

So, we define that d e, is the equivalent diameter, or also called hydraulic diameter, and. So, this d naught will be I will write down the formula a bit later, 4 times 0.01 into 1 divided by 2 equal to 0.02 meters. So, this is I think, the length is L is taken as 2 meters; that is, just for easily calculation. So, this L upon d naught, will be, how much it will be, four times area, this is, it is alright, one point does not matter L by d naught will be 1 by 0.02 equal to 50. Just one second, L is 1 meter, it is also 1 meter.

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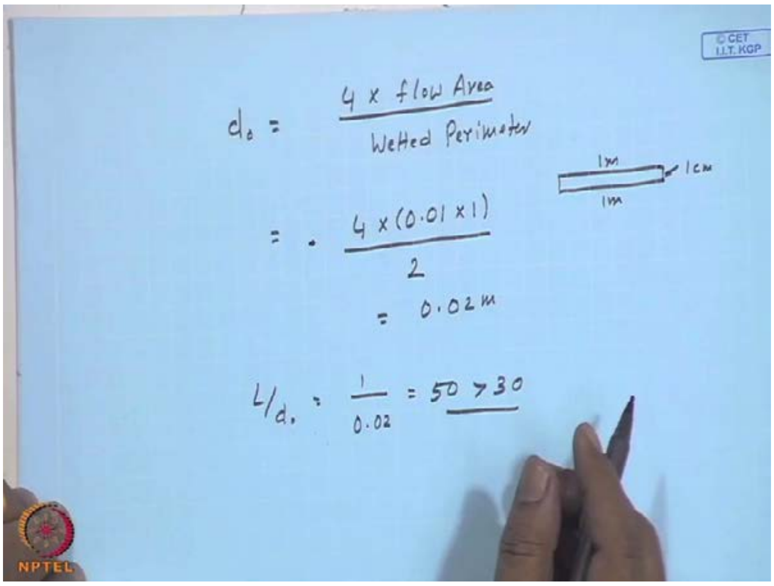

So finally, L is equal to 1 meter, W is equal to 1 meter, and that thickness is 1 centimeter. This hydraulic diameter is four times the flow area, by wetted perimeter; that is why we have written four into flow area is a 0.01 meters; that is 1 centimeter multiplied by W is 1 meter. By wetted perimeter is, this is 1 meter 1 meter 1 centimeter. If we neglect this 1 centimeter, it is 1 meter plus 1 meter which is 2. So, that is we get it as 0.02 meters, and now L by d naught gives 1 upon 0.02, which is equal to 50, which is greater than 30. So, a 1 meter by a meter duct with 1 centimeter, passage with, can be considered as fully developed conditions.

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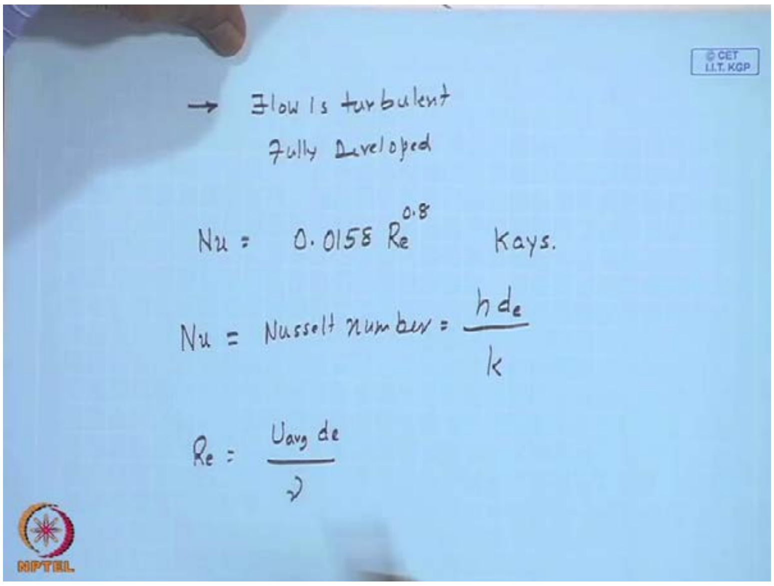

What we have here is the correlations for the Nusselt number. First of all the flow is turbulent, fully developed, and N mu is 0.0158 r e to the power 0.8, this is a result due to kays. Now I have to define, N mu, some of you are not very familiar with heat transfer, is the Nusselt number, equal to heat transfer coefficient times this d equivalent by thermal conductivity of the fluid k. Then R e also U average times d e by kinematic viscosity.

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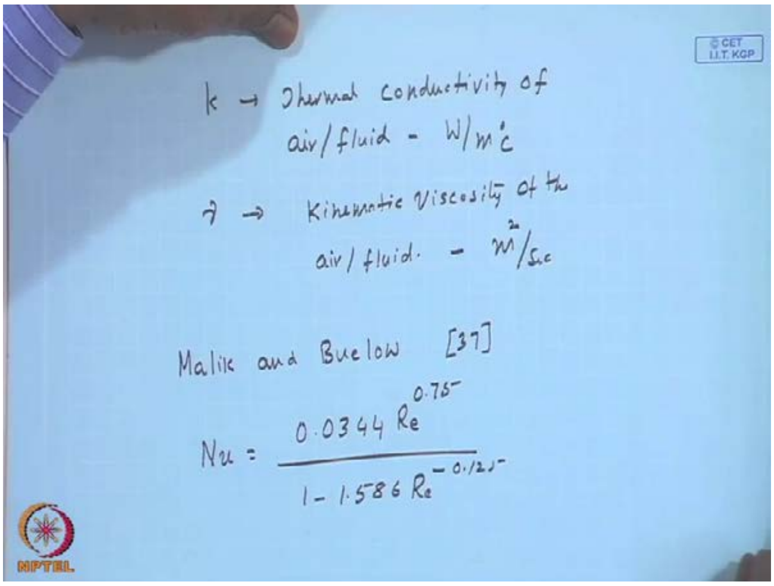

So, k is a thermal conductivity, of air or fluid, and kinematic viscosity. This has got the units of meter square per second, and this has watts per meter degree centigrade. Another correlation is due to, Malik and Buelow, which is again given in your reference in the notes 37. Again nusselt number is related to 0.0344 R e to the power 0.75 by 1 minus 1.586 R e 3 power minus 0.125.

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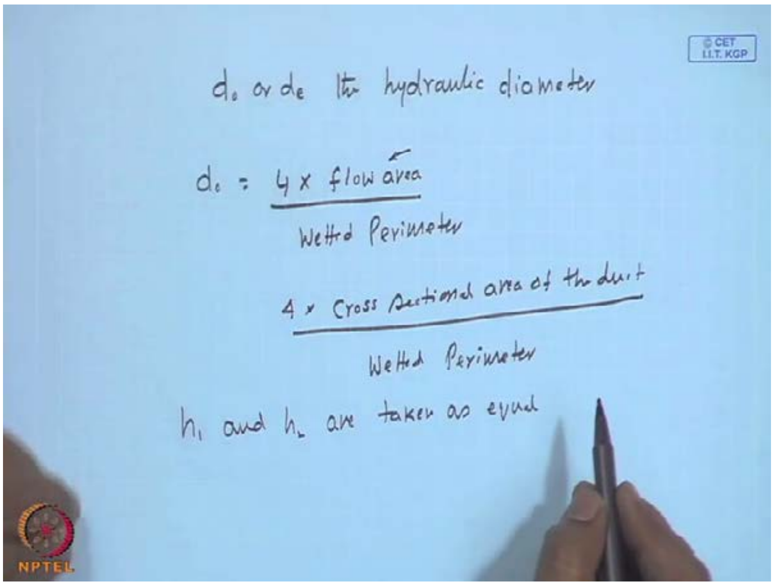

So, as we have, already explained d naught or d e d naught or d e, the hydraulic diameter, is 4 times flow area, or sometimes it is also written by. Just one second, wetted perimeter, or 4 times cross sectional area, area of the duct by wetted perimeter. Though one easily understands that this two are equivalent, at times it could be bit confusing, when you talk about cross sectional area of the duct, in the strictly drawing terminology, it may be the area of the pipe material when it’s cut a cross. So, it is desirable that we use the word flow area; that means, it is the area through which the flow is taking place, and most of the time h 1 and h 2 are taken as equal. This is certainly needs investigation, subject to some questioning. However, in the solar, in view of other uncertainties, and the flow is turbulent or laminar, that h 1 and h 2 are taken as equal.

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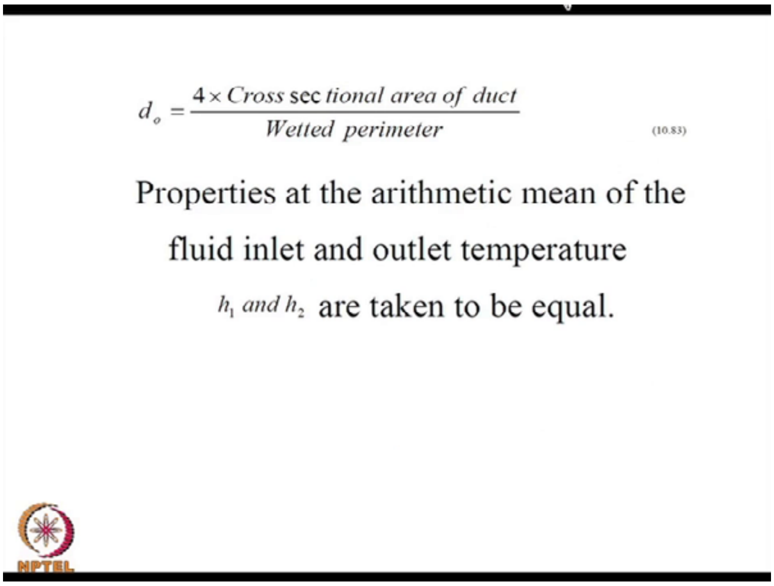

So, we know for air collectors, the governing equations have been obtained, by making an energy balance, on the absorbed plate, and bottom plate and the fluid, with a certain simplifying assumption, that U b is much smaller than the top lost coefficient, we obtain relatively simpler expression.

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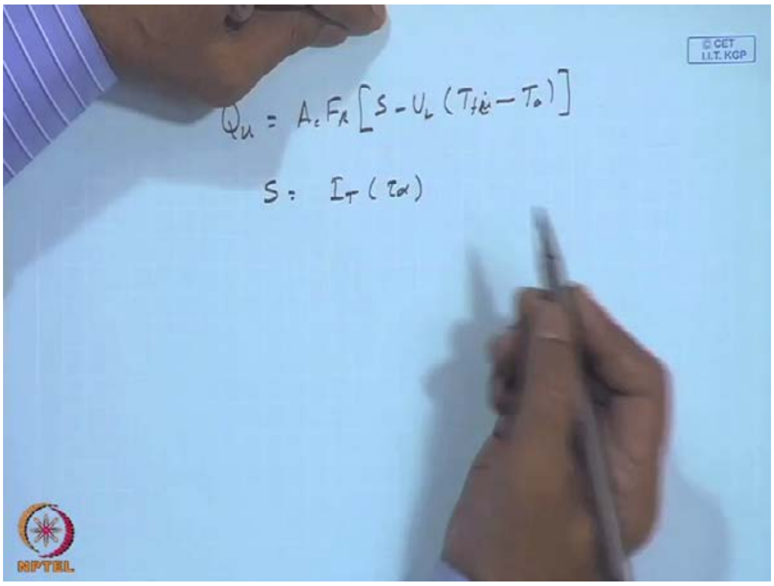

And this can be re cost exactly in the form, that we do for the liquid collectors A c into F R times S minus U L into T f m sorry T f i minus T a. Though, your definition of U L in terms of U b and U T will be different, and the heat transfer coefficient equivalent, has to be defined in terms of h 1, h 2 and h r. The radiative transfer coefficient between the top plate and the bottom plate, and the convective heat transfer coefficients from the top plate and the bottom plate, and top lost coefficient U T and the bottom lost coefficient U b. S is of course, the conventional absorbed energy, given by I T times tau.

Thank you.