Analysis and Modelling of Welding

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Lecture – 05
Heat removal

Hello. My name is Gandham Phanikumar. I am a faculty member with the Department of Metallurgical and Material Engineering - IIT, Madras.

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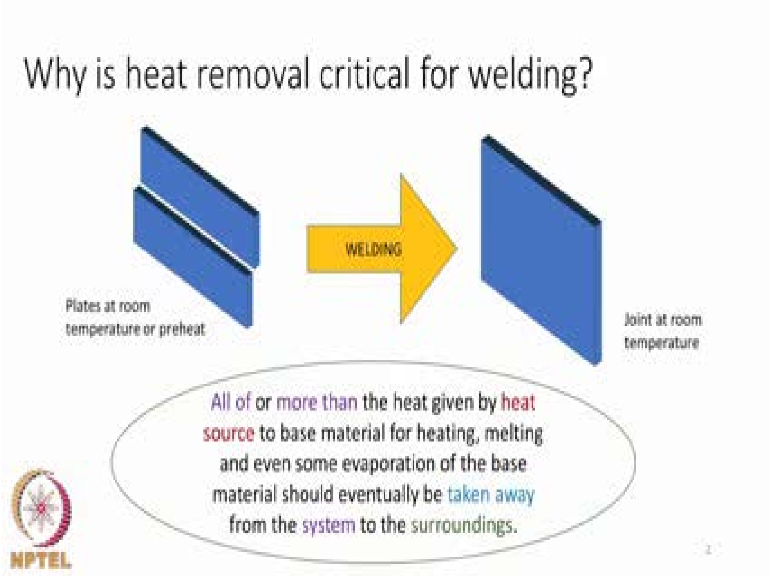

Why is heat removal critical for welding?

All of or more than the heat given by heat source to base material for heating, melting and even some evaporation of the base material should eventually be taken away from the system to the surroundings.

Today, we will be discussing about the topic heat removal, as part of the NPTEL online course on Analysis and Modelling of Welding. Why is heat removal very important in the topic of welding? The reason is as follows. The two parts that have to be joined will be usually at room temperature or maybe, sometimes at a higher temperature. And then, after the welding process is completed, then we want a single piece with the joint, which is again at room temperature so that it can be deployed in an application; which means that, we have to take away all the heat that we have given to the two parts, through the heat source, and sometimes more than that.

The reason why it is more than what we have given is, because sometimes we may have preheat. For example, in super alloy welding at elevated temperature kind of processes, we have situations, where the preheat can be quite significant, and all these heat must be taken away from the weldment, and which means that, we are going to take away this heat from the system into the surroundings.

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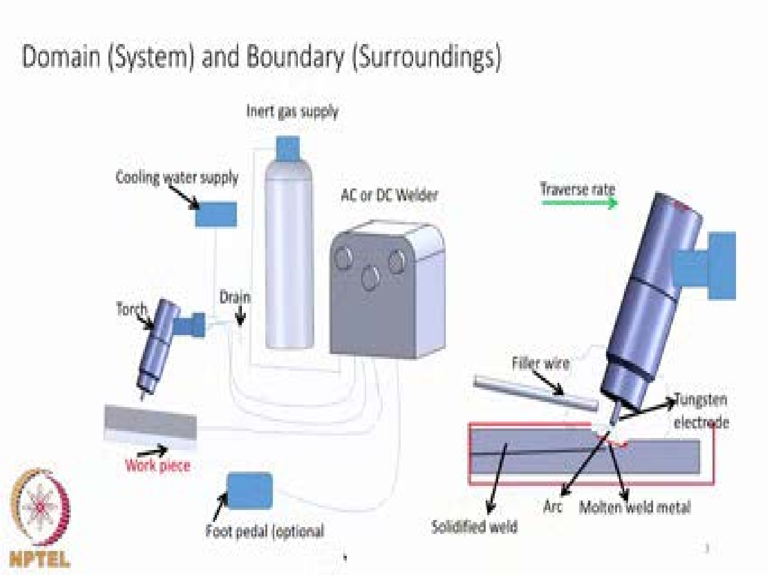

Domain (System) and Boundary (Surroundings)

So, we just define what is the system, and surroundings, now. The schematic there shows you a typical setup about a (Refer Time: 01:31) and we have various parts that are shown here. And, the ones which are in red are the ones which we refer to as the system; that is, basically the weldment. The plates that are being joined, they are our system, and everything else is in the surroundings. So, there may be a lot of aspects that, to be looked at in the power supply; may be also about the gas supply, or water cooling supply, etcetera; but, these do not constitute usually, what is known as welding research and we will be focusing on the weldment.

So, sometimes, there are alternative terminologies also, that are used. System is also referred to as domain, because that is the part which we are going to focus our attention to. And then, the boundary is also sometimes referred to, for the surroundings, because of the notation that boundary conditions are going to be applied about the domain.

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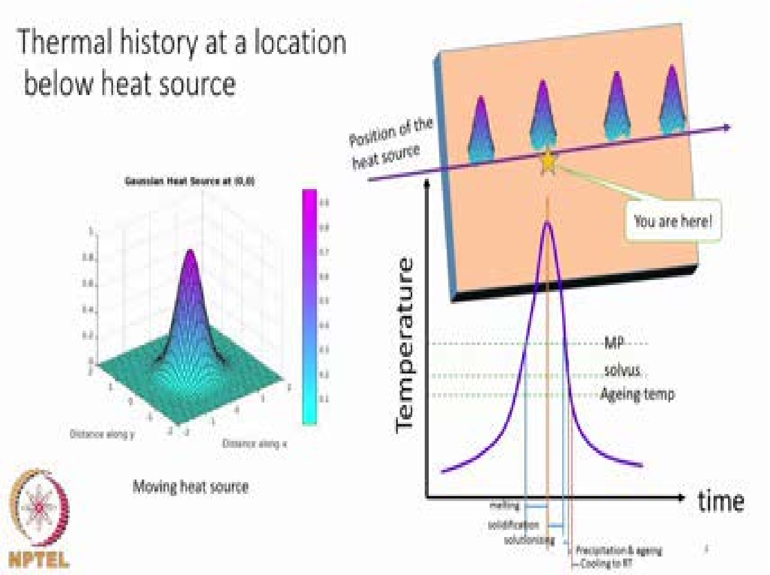

Thermal history at a location below heat source

So, the reason why we have to pay attention to the heat sources and heat removal is as follows. Let us have a look at the heat source, at a very popular one, something like a Gaussian which is shown here. And, this Gaussian heat source is going to be moving along a path to create the weld. So, I have shown you a schematic here, with a star indicating the location at which we are going to inspect, how the temperature would vary. And, as the heat source is going past this point, the temperature at that particular location will be increasing as the heat source is coming near, and it will be reaching a peak temperature, when the heat source is right at the location.

And then, it will be falling down towards the ambient temperature, when the heat source is going to move away. So, this rise and fall in the temperature is going to be very important in understanding what changes will be happening in the base material. And, how fast the temperature will be rising, and how fast it can be brought back to ambient temperature, depends upon how quickly we are able to remove the heat. And, the slope of this upward and downward curves in the thermal profile, determined by the heat removal process, faster the heat removal, higher is the slope.

And, the slopes will then be translated to the amount of time that is spent in different regimes, at the particular locations. For example, we have seen some horizontal lines in this schematic. The time that is spent above the melting point is how much time the location is in liquid state.

And, longer the duration more is perhaps the mixing in the liquid zone. And, there is a temperature, indicated as solvus. Above this temperature, some precipitates, if it is applicable for the material we are looking at, will be dissolved; and the longer we spend time the more will be the dissolution of precipitates.

So, some of these things will be discussed in detail later on, once we have modelled the thermal processes completely, but it is very evident now that the slope of the thermal profile is important. It is going to play a role in the properties of the material, and it is determined by the heat removal process. So, we must now look at the heat removal processes little more closely.

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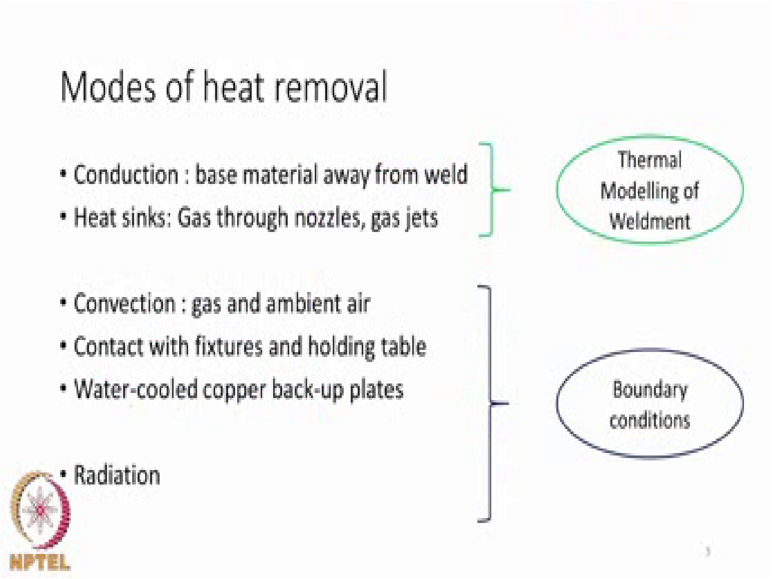

Modes of heat removal

- Conduction : base material away from weld
- Heat sinks: Gas through nozzles, gas jets

Thermal Modelling of Weldment

- Convection : gas and ambient air
- Contact with fixtures and holding table
- Water-cooled copper back-up plates
- Radiation

Boundary conditions

We do have heat removal process in the weldment, mainly by conduction process; that is, the rest of the material, away from the weldment, is going to act as a heat sink to remove the heat; and, that is done by the conduction process. So, that is going to be covered in the thermal modelling of the weldment. So, we will not be looking at it now, in this particular lecture. And, we also have heat removal through the gas nozzles, or gas jets, etcetera. So, these are basically heat sinks, and as we have discussed in the previous lecture, heat sinks will be regarded as heat sources, with just a negative sign for the amount of heat flux; and therefore, we will also not be taking up those things in this particular lecture.

So, what we are going to look at are, what will be covering as boundary conditions. So, basically, the convection boundary condition, when the heat is removed by either a gas, or an ambient air, that is flowing past the weldment. And then, these contact that the weldment will make with the table, and though, those contact points will be also responsible for heat removal.

And then, we also have sometimes a water cooled copper back up plate to remove heat more efficiently from the bottom of the weld plate. So, those things also come under the convective heat loss regime in the boundary conditions. And, obviously, on the surface of the weldment, where the temperatures are very high, heat is going to be lost also through radiation, and that is also going to come under the boundary conditions.

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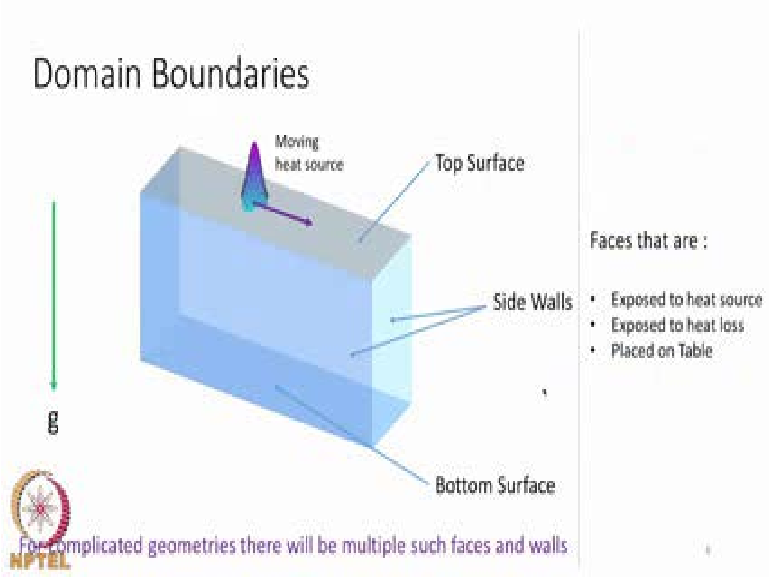

Domain Boundaries

Faces that are :

- Exposed to heat source
- Exposed to heat loss
- Placed on Table

For complicated geometries there will be multiple such faces and walls

So, here I am showing you a schematic, to just also indicate the separation of different planes that is used for our analysis. So, on the top surface, we have the heat source, that is moving in one direction; and usually, this will be in a situation where the welding is done in the flat position. The vertically going downwards arrow shows the gravity direction. And, we have in this particular schematic, sidewalls, which will be exposed to ambient air and we will be losing heat by convection.

And then, there is the bottom surface, which will be in contact with the table, on which the welding plate is going to be kept. And, there are geometries which are very complicated in the real industry, where we may have many many such planes, so that will be existing and multiple welds maybe performed simultaneously. So, we must pay attention to, basically different faces in the three categories. Those faces that are exposed to the heat source, the situation will be analogous to the top surface.

And then, those faces where the heat loss in going to take place and that is analogous to the sidewalls, we are talking about. And then, those faces which are going to be in contact with some support system, and in our case, it is the bottom surfaces. So, by looking at these three situations, we will be able to understand, how to handle the boundary conditions in any given welding geometry.

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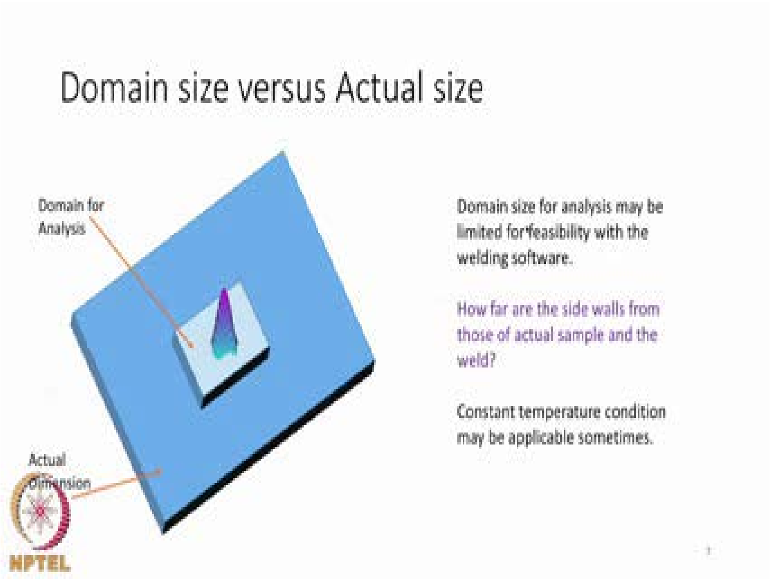

Domain size versus Actual size

Domain size for analysis may be limited for feasibility with the welding software.

How far are the side walls from those of actual sample and the weld?

Constant temperature condition may be applicable sometimes.

And sometimes, we may not take up the actual plates' dimensions for the welding analysis; the reason being that, the actual plate may be very large, whereas, for our analysis, we may want to limit it to only a small region around the weld pool. Very often, the temperature drop away from the weld pool is quite fast, which means that, as you go to about 3 or 4 times the width of the weld pool, then the temperature would have already reached the ambient temperature, and it would not have been heated much at all. So, this would mean that, we do not need to consider the entire actual plate for the analysis, and in such situations, we also need to understand, whether the boundary conditions require a change.

As you can understand, if we choose a domain size that is smaller than the actual size, then, the boundary conditions for the sidewalls need not be the heat transfer through convection mode, but it can be a very simple boundary condition, such as, a constant temperature at all the walls. And, this may be realistic for many situations, where the domain is much smaller than the actual size.

And, we also need to always verify before we apply such conditions, how far are the actual walls of the plate from the domain that we have chosen, and how far is the weld heat source from the actual wall, so that the wall effects are not playing a role.

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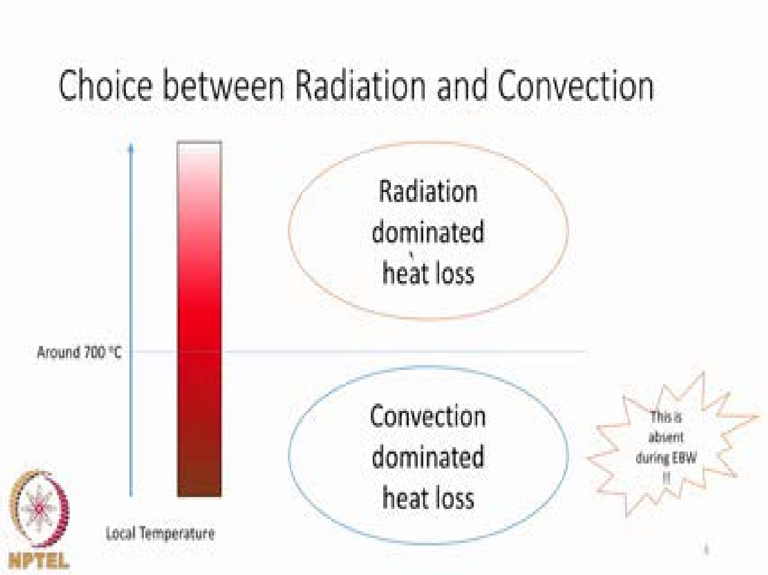

Choice between Radiation and Convection

Radiation dominated heat loss

Around 700 °C

Convection dominated heat loss

This is absent during EBW !!

Local Temperature

And, we may sometimes simplify the problem by analysing the weldment, looking at the heat loss mechanisms. Here, I have shown you a trend of the temperature rise at a given location. So, what normally is observed is that, around 700 degrees centigrade, we have a shift on the domination of which process will be removing the heat. So, radiation is seen to be dominating the heat removal process at temperature significantly above 700 degree centigrade.

At lower temperatures, it is the convection that plays a role in removal of the heat. That means, that we need to pay attention to the temperatures that are achieved in the actual weldment, looking at the actual materials that we are going to join, and then see, whether we can simply the process by neglecting one of the two heat removal processes, if applicable. We must also note that, in electron beam welding, we do not have any gas medium in the chamber, which means that, convection dominated heat loss is totally absent, and we have all the heat loss primarily by the radiation, even at lower temperatures, which will not be very effective.

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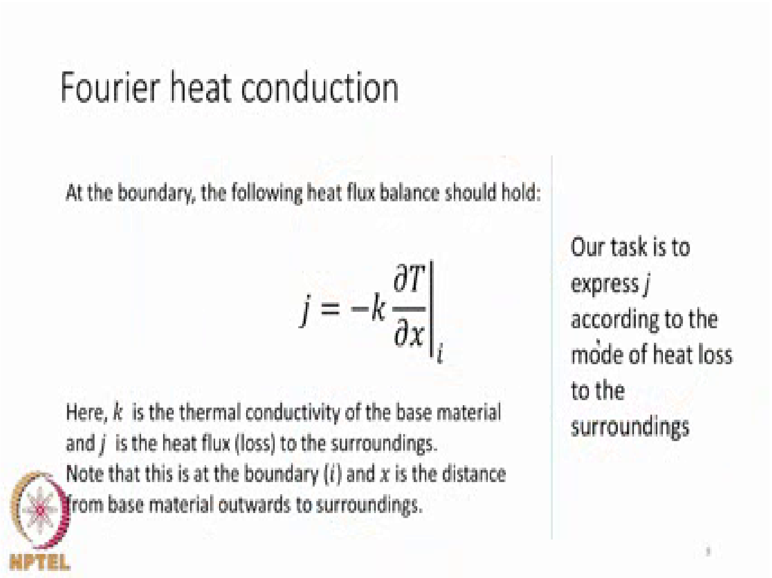

Fourier heat conduction

At the boundary, the following heat flux balance should hold:

$$j = -k \frac{\partial T}{\partial x}\bigg|_i$$

Here, k is the thermal conductivity of the base material and j is the heat flux (loss) to the surroundings.
Note that this is at the boundary (i) and x is the distance from base material outwards to surroundings.

Our task is to express j according to the mode of heat loss to the surroundings

And, let us just recall the Fourier heat conduction here, because, it is applicable for all the welding situations in the industrial environments. What happens at the boundary of the domain is that, there are, heat removal should be balanced across the interface; which means that, the heat loss into the weldment, through the conduction process must be balanced by the heat flux that is taken away from the interface, into the surroundings. And, we have an equation here, j equals minus k dou T by dou x, at the interface location, that is applicable at the boundaries.

And, this also means that, the moment we know what is the expression that we can use for the heat flux j, then, we can estimate how the temperature changes will be happening inside the body, and vice versa.

Here, the quantities that I have listed are as follows: j is the heat flux at the interface, which is given as watt per meter square; and then, k is the thermal conductivity; T is temperature; and x is the distance away from the interface into the base metal; and i is the interface location. We must note that, k here refers to the thermal conductivity of the base material, which is the solid, most of the time, at the interface. And, as long as we are able to find an expression for j, then we can say that our heat removal process is more or less understood at all the walls.

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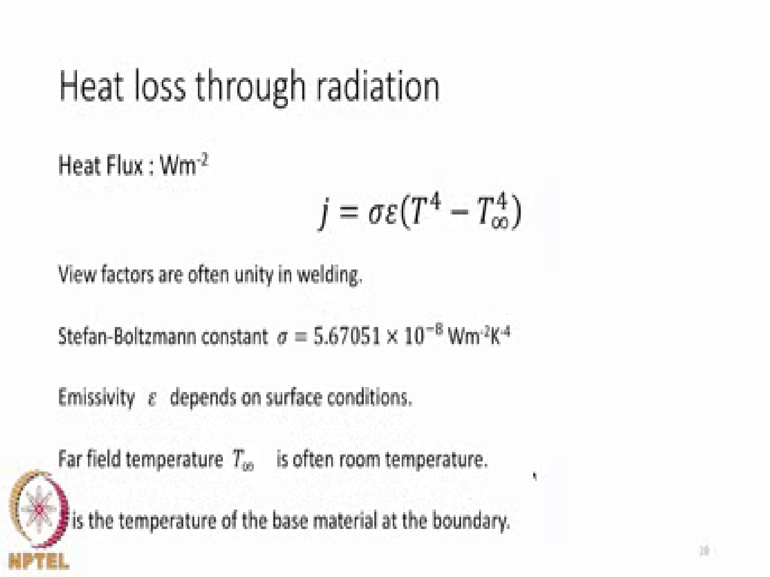

Heat loss through radiation

Heat Flux : Wm^{-2}

$$j = \sigma\varepsilon(T^4 - T_\infty^4)$$

View factors are often unity in welding.

Stefan-Boltzmann constant $\sigma = 5.67051 \times 10^{-8}\ Wm^{-2}K^{-4}$

Emissivity ε depends on surface conditions.

Far field temperature T_∞ is often room temperature.

is the temperature of the base material at the boundary.

So, there are two major mechanisms that we have looked at, radiation and convection. We will go through them one after other. So, the radiation heat loss is going to follow the expression that I have listed here; j equals sigma epsilon into T raised to the power of 4 minus T infinity raised to the power of 4. Here T is the temperature at the surface of the weld plate, which normally will not be very high on the sidewalls and at the bottom wall; but on the top wall, the peak temperatures in the weld pool may reach several hundreds of Kelvin above the melting point.

So, the T will be significantly higher than the ambient temperature. T infinity is the far field temperature. In the case of welding what happens is that, most of the space around the weldment is occupied by objects that can absorb the radiation, and they are all usually at the ambient temperature. So, T infinity is nothing but the room temperature, in most of the situations.

And here, we have neglected the view factor; the reason being that, again, in welding, most of the time, all the radiation that is coming out of the top surface of the weld pool will be absorbed by a material that is placed all around, and therefore, the view factor can be taken as unity.

The value of the Stefan-Boltzmann constant is given here. Emissivity is a constant, and usually it will be a small fraction, and it depends upon the surface condition. Though the surface condition can be modified by coatings, on the surface of the weld pool, normally these coatings will be disturbed and removed, because of the fluid flow in the weld pool and therefore, we may have to look up the emissivity value applicable for the temperatures the weld pool is going to experience, and then use that in the expression that I have given here. Again, here T is the temperature of the surface.

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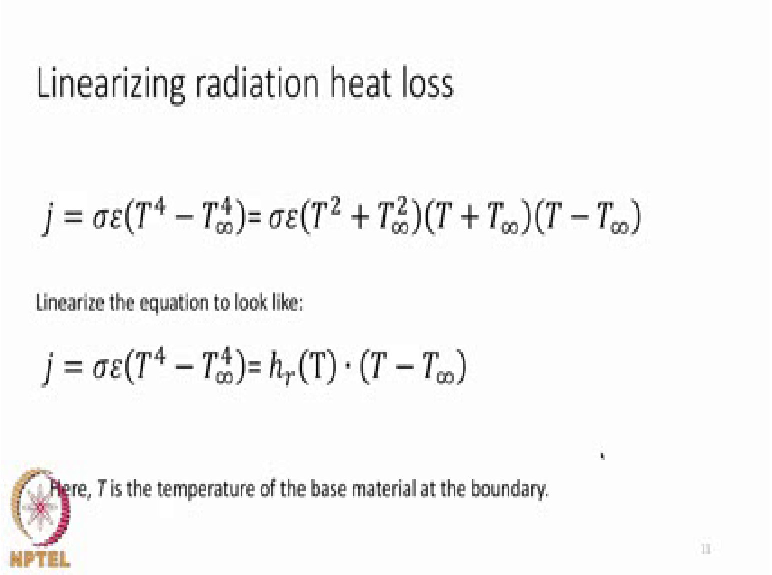

Linearizing radiation heat loss

$$j = \sigma\varepsilon(T^4 - T_\infty^4) = \sigma\varepsilon(T^2 + T_\infty^2)(T + T_\infty)(T - T_\infty)$$

Linearize the equation to look like:

$$j = \sigma\varepsilon(T^4 - T_\infty^4) = h_r(\mathrm{T}) \cdot (T - T_\infty)$$

Here, T is the temperature of the base material at the boundary.

And, sometimes, in some software, or in your own programs, it may be possible that, the fourth power law may not be amenable for implementation, and in such situations, sometimes, people do linearize the radiation heat loss. It is not really the correct thing to do, but then it is at least possible to linearize it, and use it, when the temperature changes are not happening too fast.

So, I have here shown you, how to linearize that, and showing you that, we can, for example, imagine the radiative heat transfer also as analogous to the convective heat loss, except that the coefficient in front of T minus T infinity will be a very strong function of the temperature of the surface.

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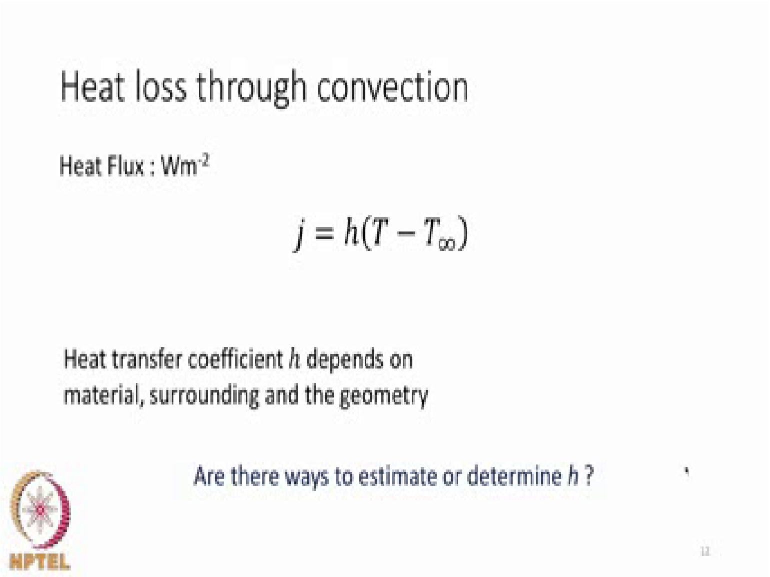

Heat loss through convection

Heat Flux : Wm^{-2}

$$j = h(T - T_\infty)$$

Heat transfer coefficient h depends on material, surrounding and the geometry

Are there ways to estimate or determine h ?

The convective heat transfer is going to follow the Newton’s law here, where you have written j is equal to h into T minus T infinity; and here, h is the heat transfer coefficient, and j is the heat flux that is taken away by the convective heat transfer. And, this h is what we need to determine, so that, we will be able to understand how the heat removal process is taking place.

Unfortunately, h is not just a material property, unlike k. So, thermal conductivity is a material property, but heat transfer coefficient h is not a material property. It depends upon both the material, as well as the medium that is removing the heat, the velocities at which it is being removed, the geometries, and so on; which means that, we need a method by which we can determine h, so that we can have a grip on the heat flux that is removed from the weldment.

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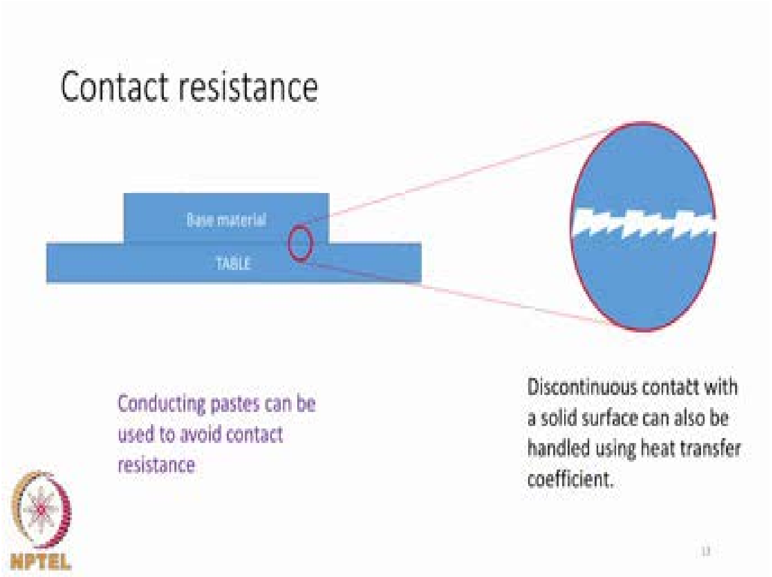

Contact resistance

Conducting pastes can be used to avoid contact resistance

Discontinuous contact with a solid surface can also be handled using heat transfer coefficient.

And, what are the ways to know more about h? We can come to that in a moment; I want also tell you that, the concept of heat transfer coefficient is also applicable for situations where you have a contact resistance. What I mean by contact resistance is as follows. We may place, for example, the materials to be joined on the surface of a table. However, every object, engineering object, will surely have roughness, and when you have two rough surfaces that are coming in contact, then as you can see in the inset zoomed out, the contact is not prefect all through; which means that, the conduction that is going from base material to the table is not happening at every location across the length; which means that, there is what is called as a contact resistance.

If you want to model this contact resistance, the best way to go about is to assign h, heat transfer coefficient value to the contact resistance also, and then, use it along with the rest of the walls. And, one can also estimate the contact resistance through the same methods that we are going to do for the heat transfer coefficient, in a moment.

We can actually avoid this kind of a contact resistance by applying conducting pastes that will make the base material join with the table very closely. These are sometimes applicable, when the objects are small, and the weld joint is very critical and at small thicknesses. However, in situations on engineering applications, such possibilities may not exist, and we must keep that in mind while analysing or modelling the welding at the bottom surfaces, where the contact is going to take place.

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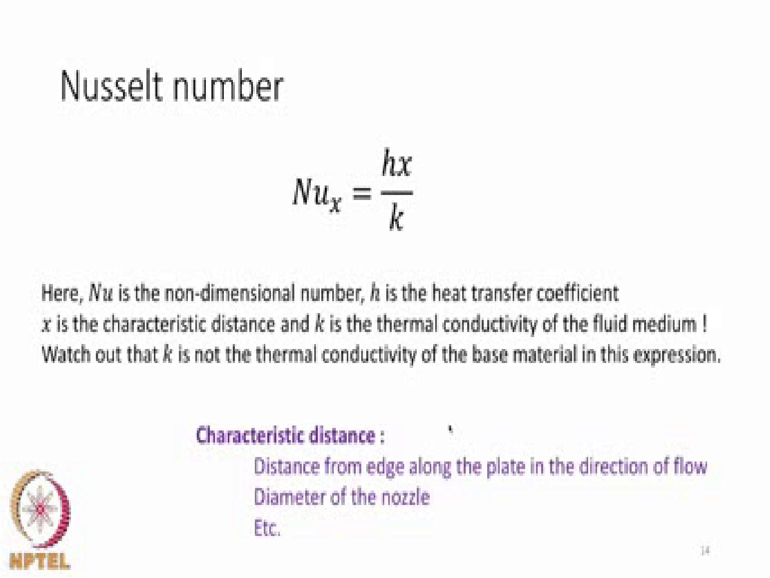

Nusselt number

$$Nu_x = \frac{hx}{k}$$

Here, Nu is the non-dimensional number, h is the heat transfer coefficient
x is the characteristic distance and k is the thermal conductivity of the fluid medium !
Watch out that k is not the thermal conductivity of the base material in this expression.

Characteristic distance :

Distance from edge along the plate in the direction of flow
Diameter of the nozzle
Etc.

And, heat transfer coefficient is generally not available as a raw parameter. It is converted to a non-dimensional number, and then, made available as a correlation. So, here is how I am showing you, the way it is converted to a non-dimensional number. The number goes by the name Nusselt number; Nu is the symbol that is used for the non-dimensional number. The quantity on the right hand side, h x by k converts the units of h into the non-dimensional method, by going to Nu, and x is the characteristic distance, and this can be, for example, the length of the plate in the direction of the flow of the gas which is removing the heat through convective mode.

It can be, for example, the diameter of the tube through which the gas is flowing, etcetera. And, k here, again, please pay attention, it is the thermal conductivity of the gas, and it is not thermal conductivity of the base material; the reason being that, we are non-dimensionalizing heat transfer coefficient applicable for the gas, and therefore, k must be of the fluid. And, the quantities that are appearing on the right hand side of this expression may be similar to Biot number also, but Biot number is not what we are looking at; we are looking at Nusselt number.

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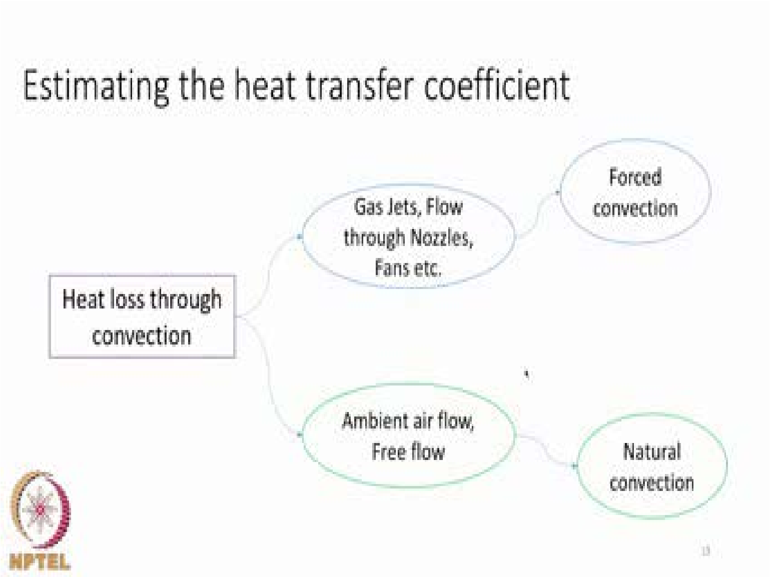

Estimating the heat transfer coefficient

Heat loss through convection

Gas Jets, Flow through Nozzles, Fans etc.

Forced convection

Ambient air flow, Free flow

Natural convection

And, there are two ways of writing a correlation of Nusselt number, depending upon the situation that is active in the actual convective heat transfer, and I have shown you here. Take the example when we have the heat removal through gas jets, the flow through nozzles and fans that are driving the air, or the gas, on the top of the weldment to remove the heat. So, in these situations, the velocity of the gas medium which is removing the heat is induced by us, and very often, we can even set that value at a particular number.

So, this is basically what is covered as forced convection. And then, there are also situations where we are not applying any external flow, but the heat removal is taking place by an ambient air flow, which is happening naturally. So, what happens when you have a flat plate that is just welded; you can place your hand slightly above the weldment, and you can feel the hot air approaching your hand; and this shows you basically that, as the air comes in contact with the hot weldment, it becomes hotter, and the density of the air will then go down, and you can see that, it would then, the air will move up by the action of gravity, because lighter stuff will go up.

And, in this manner, some amount of convection will be taking place above the weldment, and it will also aid in removal of heat. All of this is happening naturally. And, this will be happening in different geometries, the way we place the weldment in the geometrical arrangement. So, this kind of a removal of heat, where we are not applying any force convection, but we are allowing the convective heat loss to take place in a natural manner is called as a natural convection; sometimes, it is also referred to as a free convection.

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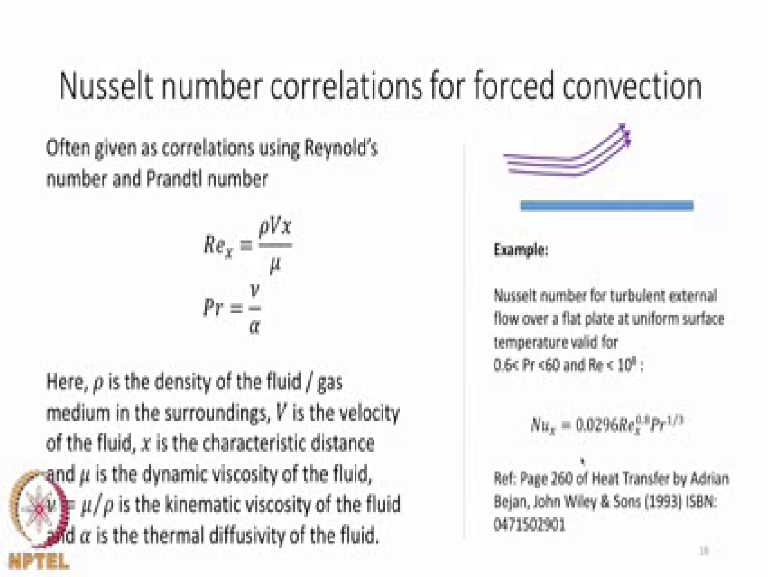

Nusselt number correlations for forced convection

Often given as correlations using Reynold's number and Prandtl number

$$Re_x = \frac{\rho V x}{\mu}$$

$$Pr = \frac{\nu}{\alpha}$$

Here, ρ is the density of the fluid / gas medium in the surroundings, V is the velocity of the fluid, x is the characteristic distance and μ is the dynamic viscosity of the fluid, $\nu = \mu/\rho$ is the kinematic viscosity of the fluid and α is the thermal diffusivity of the fluid.

Example:

Nusselt number for turbulent external flow over a flat plate at uniform surface temperature valid for
$0.6 < Pr < 60$ and $Re < 10^8$:

$$Nu_x = 0.0296 Re_x^{0.8} Pr^{1/3}$$

Ref: Page 260 of Heat Transfer by Adrian Bejan, John Wiley & Sons (1993) ISBN: 0471502901

The correlations for Nusselt number will be different for these two regimes. We will take the forced convection. The forced convection correlations for Nusselt number are given by two different non-dimensional numbers; one non-dimensional number is Reynolds number, where we have, for example, non-dimensionalised the velocity of the air, or the gas medium; and we have seen the way we have non-dimensionalised. We are using the density, the viscosity, dynamic viscosity, and the length scale, to convert the velocity into a non-dimensional number.

The other quantity which is used for the correlation is what is called as a Prandtl number. Prandtl number is nothing, but a non-dimensionalised property of the material. It does not depend upon anything else. It is a ratio of basically, the kinematic viscosity of the particular fluid, or the gas, to the thermal diffusivity of the gas. And, this number will be fixed for a given gas medium, at a given temperature, and composition.

And, the Nusselt number correlations are available as function of these two parameters, and we can look them up in various handbooks and textbooks. As an example, I am just showing you here, let us take, for example, a plate that is held horizontally, and is hot; and air that is flowing on top of it is going to remove the heat; and, we are going to set the velocity of the air to be at a particular value. So, in such situations, we can calculate what would be the Reynolds number; and we know what is the gas that is actually flowing. So, we can also estimate, from property handbooks, what would be the Prandtl number.

And, we can substitute these two into the correlation that I have given you here; Nu x is equal to 0.0296; Reynolds number raised to the power of 0.8, and Prandtl number raised to the power of 1 by 3, and substituting that, we get the Nusselt number. And, from Nusselt number, we can then obtain the heat transfer coefficient. So, this is how one would normally go about estimating the heat transfer coefficient for plate geometry, or similar geometries, under forced convection regimes. And, these correlations are available generally in most textbooks on convecting heat transfer, and in handbooks.

We will be going through a set of such correlations in a tutorial later on, which I will be uploading into the course website, and we will also see, how we can convert those expressions into the heat transfer coefficients through some illustrations. And, please pay attention to the range of the property, parameter, such as Prandtl number and Reynolds number, for which these correlations are valid. We should not use them blindly in a regime, where the validity is not there. If we do that, then, we get erroneous values of the heat transfer coefficient.

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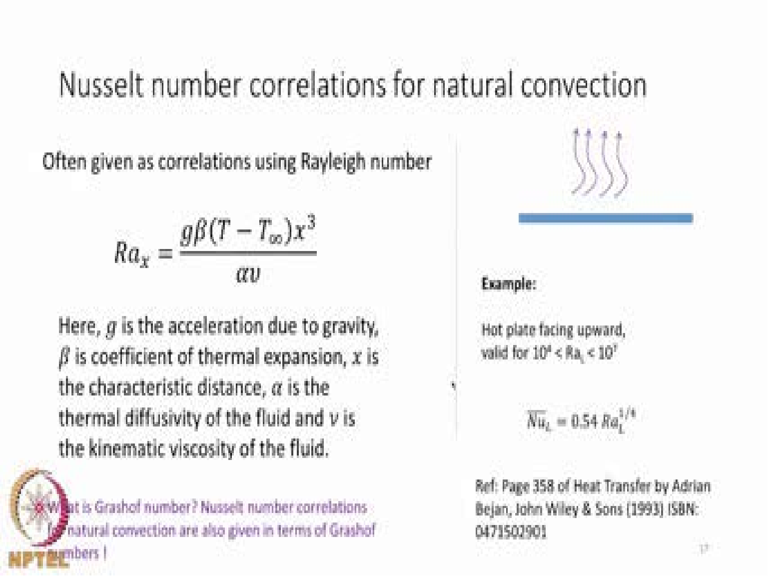

Nusselt number correlations for natural convection

Often given as correlations using Rayleigh number

$$Ra_x = \frac{g\beta(T - T_\infty)x^3}{\alpha\nu}$$

Here, g is the acceleration due to gravity, β is coefficient of thermal expansion, x is the characteristic distance, α is the thermal diffusivity of the fluid and ν is the kinematic viscosity of the fluid.

What is Grashof number? Nusselt number correlations for natural convection are also given in terms of Grashof numbers !

Example:

Hot plate facing upward, valid for $10^4 < Ra_L < 10^7$

$$\overline{Nu}_L = 0.54\, Ra_L^{1/4}$$

Ref: Page 358 of Heat Transfer by Adrian Bejan, John Wiley & Sons (1993) ISBN: 0471502901

The Nusselt number correlations for natural convection are available as a correlation with Rayleigh number. And, the Rayleigh number expression is given to you here. It has in the numerator g beta, T minus T infinity into x cube, and in the denominator alpha and nu; alpha and nu are the same parameters that we have seen earlier, namely, thermal diffusivity and kinematic viscosity of the gas medium.

Kinematic viscosity is nothing but the ratio of the dynamic viscosity mu, what normally we refer to as viscosity, and the density of the particular medium. So, all these parameters are supposed to be taken for the fluid, and not for the base material. And, g is the acceleration due to gravity; beta is the thermal expansion coefficient; T is the temperature of the surface; T infinity is the ambient air temperature, that is far away; and, x is the characteristic length scale.

In the case of a plate, it would be the distance along the plate, and in the case of a diameter of a cylinder, you would take b and so on. And, I am giving you an illustration here, how it could be used. If you take a hot plate, and it is held in such a way that the heat is removed in the vertically upwards direction, then, you can see, the hot air is going to go upwards, and such a situation would have the Nusselt number expression averaged over the entire length of the plate L, given by Nu L bar, is equal to 0.54 into Ra raised to the power of 0.25.

And, these are all basically averaged values for the entire length, and then, we can substitute the values for the g beta, T and T infinity, and then, the length L cube, and alpha and nu for the air medium, and then, obtain what is the value of the Nusselt number. And then, from the Nusselt number, we can obtain the value of the heat transfer coefficient; and then, that will tell us what is the efficiency with which the heat removal is happening; namely, the free convection or natural convection.

Now, it is possible that, the hot plate which is containing the weldment may not be in the same geometry always. So, whether the hot surface is exposed to the top, or to the bottom, or side, will definitely change the way heat is removed; and therefore, this correlations also will be different. So, you must pay attention to the geometry, apart from the range of these numbers for which the Nusselt number expressions are given, and, accordingly choose the expressions. If you do not pay attention to that, you may obtain erroneous results for the heat transfer coefficient.

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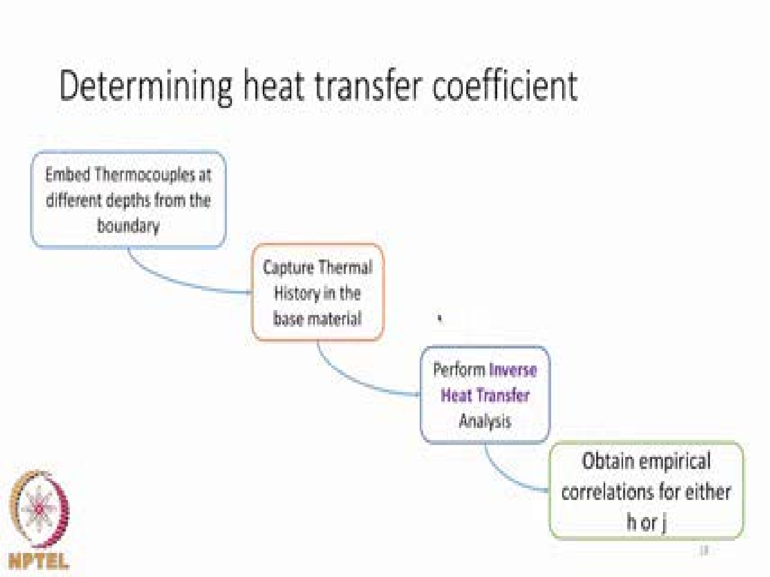

Determining heat transfer coefficient

Embed Thermocouples at different depths from the boundary

Capture Thermal History in the base material

Perform **Inverse Heat Transfer** Analysis

Obtain empirical correlations for either h or j

And, the way to determine them experimentally, or empirically, is also possible. So, the way that we go about to determine the heat transfer coefficient is as follows. What we do is, first, we embed the thermocouples at different depths at the interface, and estimate what would be the thermal history at each of those locations, using a data acquisition system. And, once we have the thermal history at different depths, then we perform what is called as the inverse heat transfer analysis.

What we mean by inverse heat transfer, is to ask a question, or for what kind of heat transfer coefficient do we expect these kind of a thermal profile. Naturally, you may assume that, this being an inverse problem, there may be multiple values of heat transfer coefficient which may give the same answer for the thermal history. But then, there are ways to find out what would be the reasonable range of the heat transfer coefficient, or the heat fluxes, and then, obtain the parameters using the inverse heat transfer analysis, which is a subject by itself. So, we will not be going to the depth in that particular topic, but we would say that, yes, there are methods to determine the heat transfer coefficient empirically, in a given experimental situation.

And therefore, we can say that, we have ability to get either h, or j, experimentally, or through estimates using the correlations. And, please remember, those correlations are also made from other experiments that people have done. So, we have the values of h, implies that, we know how the heat loss is happening in the weldment.

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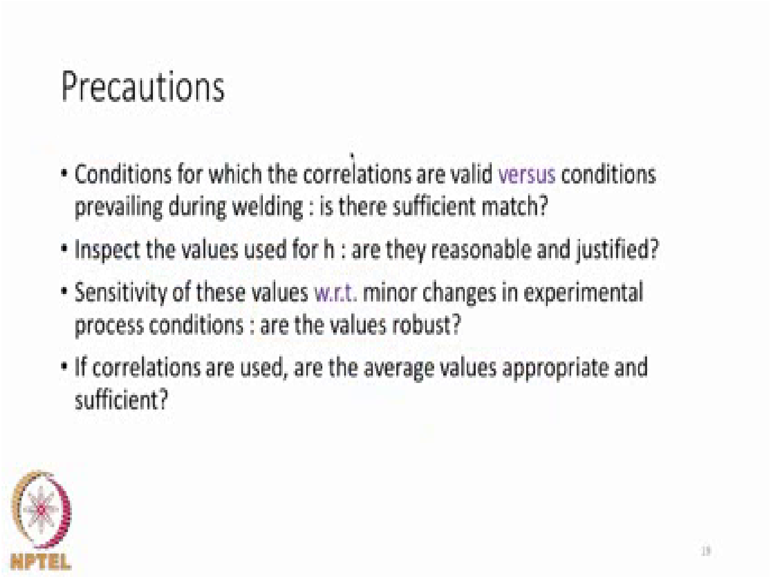

Precautions

- Conditions for which the correlations are valid versus conditions prevailing during welding : is there sufficient match?
- Inspect the values used for h : are they reasonable and justified?
- Sensitivity of these values w.r.t. minor changes in experimental process conditions : are the values robust?
- If correlations are used, are the average values appropriate and sufficient?

So, some precautions that we must take, before I wind up, I want to alert to you. We must always pay attention to the correlations, and see, for what kind of situations the correlations are actually estimated. And, we also look at the welding, to see what kind of situations the welding process is experiencing. And, unless there is a sufficient match between the two situations, these correlations may not be applicable. So, we must pay attention to the expressions, and the origins, from where those expressions have come, and then only use them in the welding literature.

And, once we have done all the exercise, and obtained the values of h, then, we must inspect them. We must see that, the numbers are not odd. So, when they are reasonable and justified only, we can use them. For example, whenever we convert a conduction problem into a heat transfer coefficient kind of an expression, we will get several 100s or 1000s of SA units of h, which may be reasonable; and however, a pure convection, using free convection, may give you heat transfer in SA units of about 5 to 20. So, there are values such as these are estimated by researchers, and validated, and we must have a look at the values we got, and then, compare and see whether we have the reasonable ones.

And, once we have these values, we must also see that, minor changes in the experimental situation should not change these parameters drastically. For example, let us say, we increase the flow rate of the gas by 10 percent, and the heat transfer coefficient jumps up by, say 200 percent. So, such a thing is generally not possible; well, one may claim that in nanofluids, but normally, those are not used in welding. And therefore, we must see that, small changes in the experimental parameters should give very reliable and robust expressions, without any drastic changes; and, such smoothness should be also conformed to the analytical expressions that govern such variations.

And, whenever we use these correlations, we must also see that, the average values are also appropriate and sufficient. So, once we have a grip on the heat transfer coefficient, or the radiative heat loss, then we can say that, we have a grip on the entire heat transfer process, to remove the heat from the weldment, from all the walls. And then, we are ready to go into the thermal modelling of the weldment itself, where we will be looking at a generalised Fourier heat conduction equation, its solutions, numerical, analytical etcetera; that we will be covering in the next session.

With that, we come to the end of this lesson on the heat removal process.