Analysis and Modeling of Welding
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Lecture – 12
Fluid Flow Modeling – part 2

Welcome back to the part-2 of Fluid Flow Modeling. We will continue from where we left over in the part-1. And in the part-1, we have done the entire formulation along with initial and boundary conditions; up to a point, we have not looked at this specific boundary conditions or special terms that are applicable for the fusion welding; and the formation we gave was almost like for any liquid that would undergo fluid flow within the domain.

So, we will look at those special terms that are applicable for welding now.

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The first thing that comes to our mind when we looked at the driving forces for fluid flow that are happening in the weld pool is the thermal-buoyancy and that is basically the buoyancy effect due to the temperature differences within the domain.

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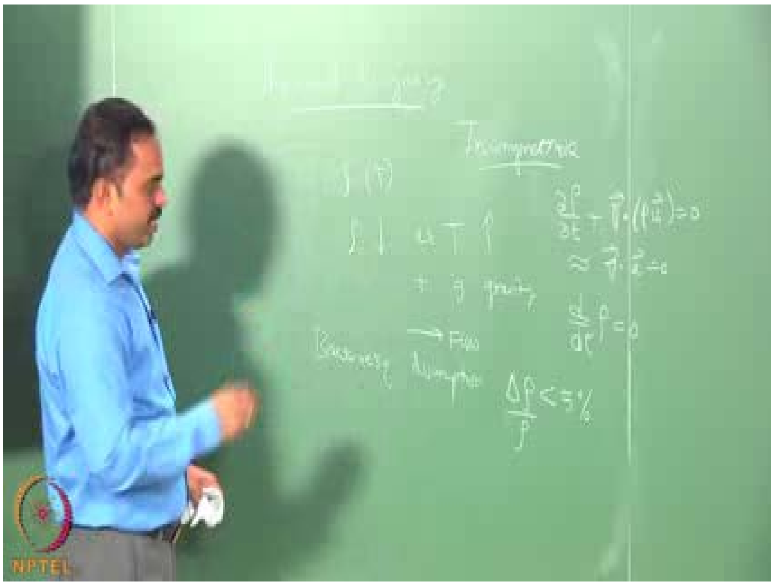

So, let us see what it look like. So, basically the driving force because of the thermal-buoyancy is coming from the density changes which are function of temperature. So, in other words, density is going down as the temperature is going up; and because of density changes, you would have combined with the gravity, you would have the resultant flow; and the flow is such that the liquid that is having lower density will go up as in away in the gravity direction opposite to the gravity, and the one which is heavy because of higher lower temperature that would be settling down. So, this is the kind of fluid flow that would be coming because of thermal-buoyancy.

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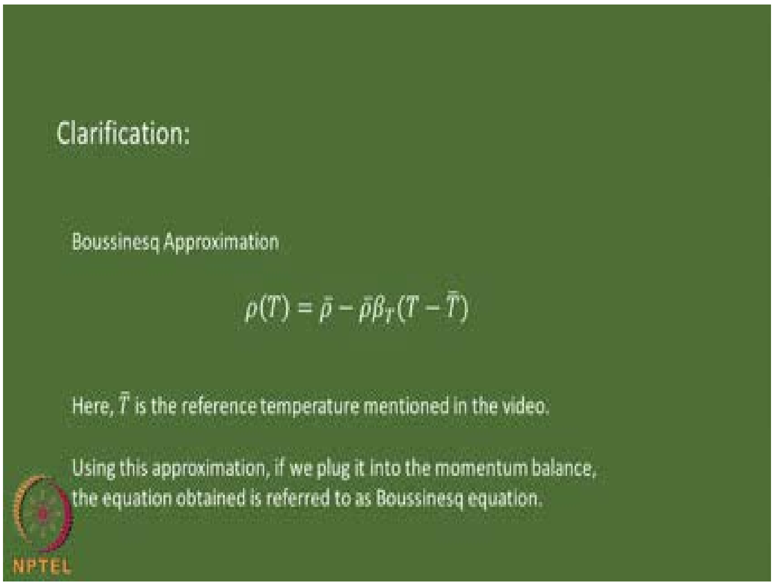

And the way it is modeled in the equations that we have written is as follows you basically have an assumption that is made. And I would just write the name for you here. The assumption is called Boussinesq assumption. The reason why mean it to make some assumption to combine the thermal-buoyancy with the fluid flow equation that we wrote is because of an apparent clash between two assumptions; first assumption, we made is incompressible. Incompressible, we made an assumption that 1 by rho by dou rho by dou t plus, so the continuity equation that we wrote we said that this can be changed as rate of dilation is 0.

So, in this process, what we have said is basically the material derivative of rho is 0 that is what we are saying basically. So, this implies that you should not have the density changing across the difference control volumes taking into account the advection term and that goes opposite in the phase of the density changing because of the temperature changes. And therefore, we must make an assumption that the density changes are only to lead to flow, but not to lead to the in compressible assumption been invalid, which means that this assumption is valid whenever the changes are less than 5 percent.

So, in such situations you can 5, may be about 10 percent, it is fine. So, for small changes in the density because of temperature variations, it is possible for you to make an assumption which goes by the name of Boussinesq assumption to say that incompressible fluid flow equations are still valid. So, under that constraint, we can just then use the thermal-buoyancy has a volumetric term.

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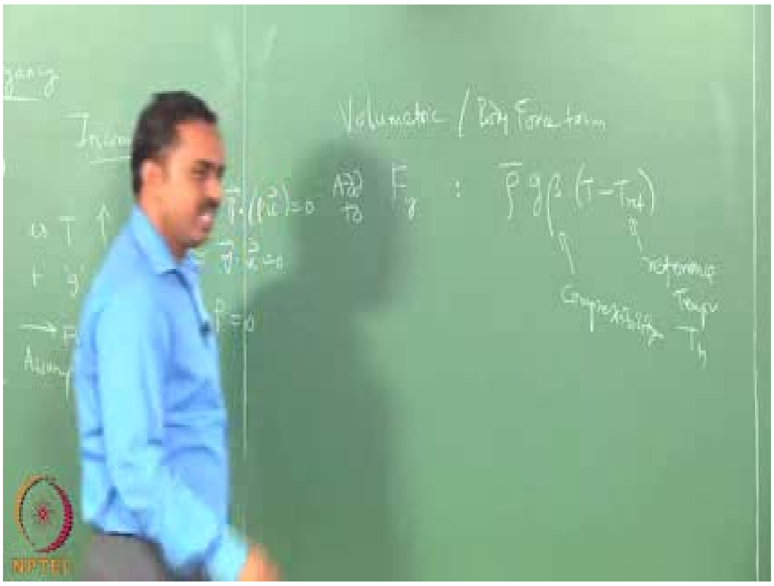

So, it is going as a volumetric term. Volumetric or the body force term, and which means that for the y component, assuming that the gravity vector is along the y-direction; for the y component, you could then add a term, which add a term which is going like this. With this is the term that would be added to the equations, so which means that we have F y minus p by dou y, so in that you can add one more term like this. This is basically the reference temperature, which would be usually the melting point itself, because the reference temperature above which you can take the differences and look at what would to be change in the temperature.

And this is the compressibility, it is property of the material; and this is the acceleration due to gravity; and this is the average density over the temperature ranges for which the melt flow is going to be experiencing the flow.

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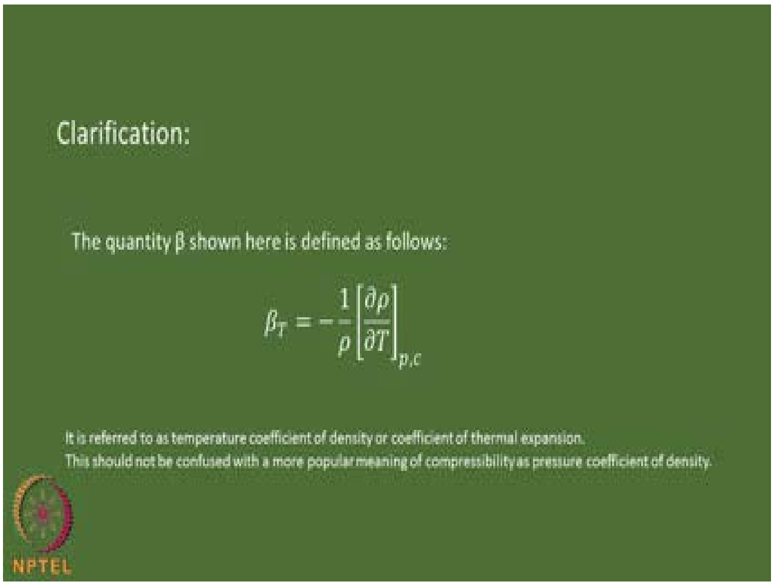

So, by adding this term, you basically have take into account how the density changes are happening. You can actually see that beta into T into rho bar is nothing but this is somewhat like something like that. So, it is basically take into account how the density changes are causing the fluid flow to come about. And thermal-buoyancy is essentially taking the density changes come may because of the temperature differences in this manner.

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So, we could actually then by analogy see also if a solutal-buoyancy can be looked at.

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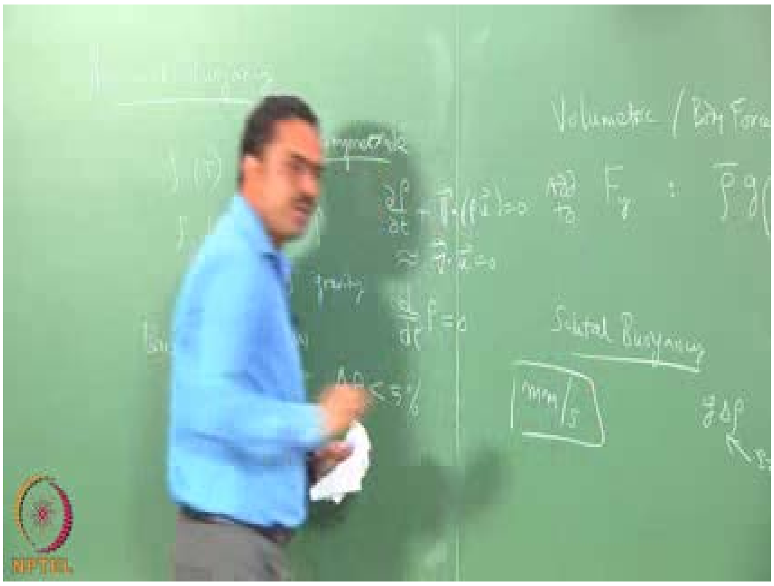

And solutal-buoyancy is quite straightforward. This term, it should be modified in the following manner. The density changes are because of solute or concentration differences and not the temperature differences is what distinguishes solutal buoyancy from thermal-buoyancy, because other than that there is no other difference. And what does it mean it means that this is going to be this to be expressed as due to concentration differences that is how. So, if you express delta rho as temperature differences then you get the beta term there is coming up, and the rho bar, but if you want you can express the change in the density due to the concentration differences in the location within the melt pool and concentration differences are coming because concentration is function of location within the melt pool that is actually the situation when you have dissimilar welding or a weld pool in which you are adding a fire wire that is of different density in such situations that is valid.

So, solutal-buoyancy and thermal buoyancy are both together as categories of buoyancy convection which means that they are basically caused by the density differences within the melt pool acted upon by the gravity to lead to the flow. And how would the average magnitude look like, it would be for typical weld pool shapes about in the order of millimeters per second which means that is a very weak convection you are talking about.

So, there is a reason why many of the models are usually ignoring the buoyancy, because very weak. We will see what is the strong term, shortly, but millimeter per second also is the kind of magnitude you will get. How did we arrive at that kind of a magnitude that is scaling analysis, we will do look at it in a small exercise as a part of the tutorials later on in this course.

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And, the other driving force that would be playing a role in the case of welding for the melt pool conversion is a thermal Marangoni.

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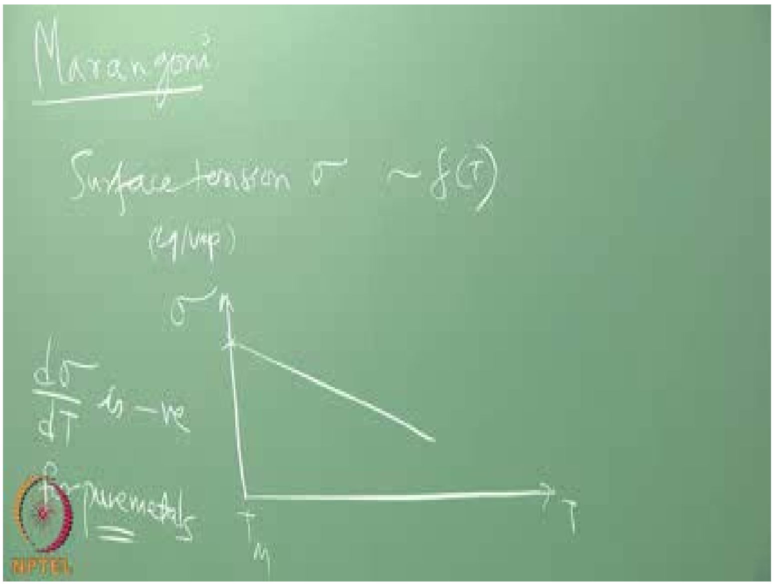

So, I will just call it as Marangoni convection. Marangoni convection is basically caused by the surface tension differences as a function of the distance and that can be understood by the small following steps. So, step-by-step we can understand how it comes above. So, first thing that we must appreciate is that the surface tension forwardly this is the surface tension from the liquid to the vapor. So, liquid vapor you can say. The surface tension is a function of a temperature, which is very well know because at boiling temperature the surface tension is not acting all the atoms are escaping into the vapor readily. So, there is no surface tension acting because surface tension is nothing but forces that are keeping the atoms in the liquid together bound to the rest of the bulk.

So, therefore, you can imagine that the surface tension must be a function of temperature. So, how does it vary, usually it looks like that. You normally start the plot of a surface tension in the liquid domain with x-axis going from melting point because below the melting point it is not liquid. So, it starts from the melting point. And the way surface tension is going to change is from a high value, it keeps going down. So, in other words, the temperature coefficient of the materials, surface tension temperature coefficient is negative for pure metals, so that at temperatures close to the boiling point surface tension is negligible it has gone to 0.

And it melting point is very high, because that is when the bounds are most active in keep in the liquid atoms bound to the rest of the bulk. So, this is the variation that we already know. How does this variation cause, the fluid flow to take place the weld pool is a question and that will be illustrated now by drawing is small schematic on showing which part of the volume element of the surface is going to go in which direction.

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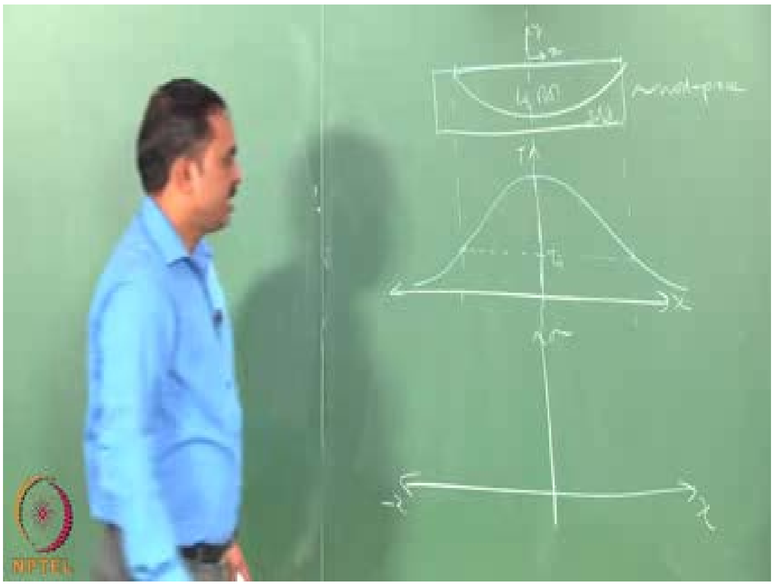

So, let us consider a schematic of the liquid pool, and look at elements and see how the surface tension variation would be affected. So, let us look at this pool as follows. This is the liquid pool; and rest of it is all solid and together this is the work piece. And in this, let us look at a plot and we would then look at how the different plots are to be approximated. So, at the function of the distance, let us first plot the temperature. So, how would the temperature look like when you go from the center of the pool away is something that we can plot and that means, I am actually now looking at the top most layer in this region.

So, how does a temperature distribution look like, it looks like this; here is a melting point so I am putting points here because that is what is defining the fusion zone end and that the center of the pool you would have the temperature very high. So, you would have a peak temperature like this. So, you would have a temperature profile like that. So, that that is the width of the fusion zone as I can be seen also on the top.

Now this is how the temperature profile is going to look like hot at the center; and as you go away, the temperature is falling; and where it reaches the melting point that is melt pool width. And then further away, it goes to even the ambient temperature, which is of the temperature of the solid far away from the center of the melt pool.

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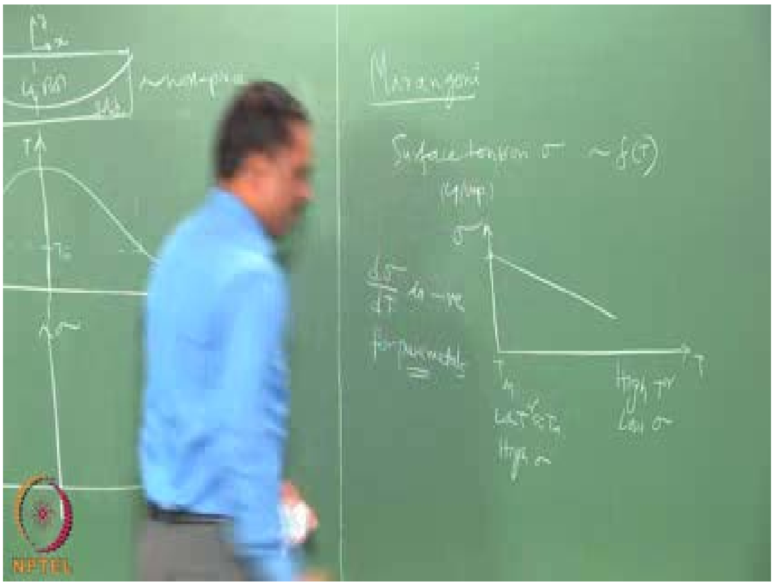

And if this is how the temperature variation is need, then how would the surface tension variation look like is something we can plot. You can see that as a function of distance, you can see that at the highest temperature that is at high temperature, you would have low sigma; and at low temperatures - close to melting point, we have high sigma right. So, from that what we can do is that at high temperatures, we have a small value; and at low temperatures, we have a large value, which means that surface tension is going to look something that kind.

Some small value, it goes to high values away from here, so which means that on the liquid melt pool how does this kind of a surface tension difference is going to be play a role in the flow is something that we can illustrate.

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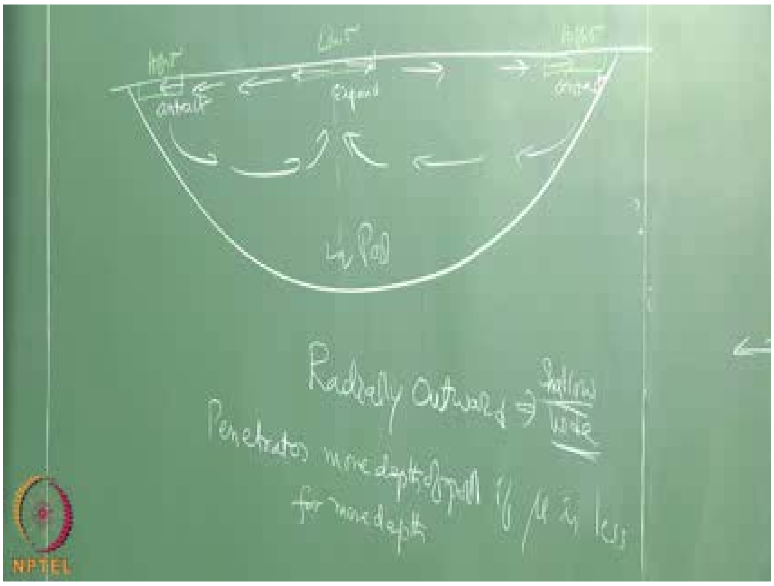

And for that, I would just draw the pool much bigger and then show you. Consider the elements like this at the center; and element here and an element here. Here you see that because a temperature is high the surface session is low, so here it is low sigma; this is high sigma then here also a high sigma. And the reason why the liquid in the melt pool is going to convect, because of surface tension gradients is essentially to minimize the surface energy contribution from the whole surface.

And the way it can minimize is by having more area, which is having low surface tension, or high area more area high area with low surface tension, or smaller area with high surface tension, both ways the multiplication of surface tension with area can be minimized, which means that the way this should move is that if this can expand, this layer can expand, and if this can contract, so then you achieve the surface tension contribution to the energy at the surface coming down. And this means that the direction of the flow is such that it goes like that radially outward.

And the surface tension variation is only at the very surface of the liquid pool, and it does not have an effect on the entire pool. So, which means that this recirculation to close the loop to satisfy the continuity equation is going to happen inside, and it could be like this. And it could penetrate to the entire depth or only of the surface depending upon the following situation. So, this convection penetrates more depth of pool, if the viscosity is less for more depth. And you know already the viscosity is actually function of temperature, which means that if that temperature variation of viscosity is not strong, if it is weak function of temperature then what happens is that at high temperature is viscosity is less, and which means that you could have the pool entire convection in the depth of the pool.

And in the case the viscosity is the strong function of temperature, it means that at high temperature, it is less viscous; at low temperature, it is more viscous, which means the viscosity gradient up and; that means, at this liquid the bottom is very viscous, it cannot be moved easily. So, then these surface convection will be limited to the top layer; either way it is basically radially outward. And what is it mean by saying radially outward, it means that it would actually make the pool shallow and wide, so that is the reason why that is how it will be affected. So, marangoni convection essentially leads to a melt pool which is shallow and wide.

And the magnitude of the surface tension driven flow, we can estimate it using a small scaling analysis which I would discuss in a tutorial session later on, and that would come out to be a unit meter per second, so magnitude.

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So in other words, surface tension driven flow will be the strongest component of the velocity in a liquid pool, and it will be on the order of the minutes per second which should be actually slightly higher than the traverse rate of the torch. Because traverse rate of the torch is generally about couple of hundred mm per minute or you know of that order and that means that is a very, very strong convection.

The reason why it such a strong convection is because of the strong change in the surface tension as a function of temperature; and temperature is also changing very dramatically with respect to the distance. So, couple to that we will have this as the strong driving force. Now, there is a small modification in the way the fluid flow will take place, when there is a solutal effect on this, and that is where you actually bring the idea of solutal Marangoni. In what way it changes, I will try to redraw on this itself, to show you the difference.

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So, what we mean by Solutal Marangoni is effect of solutal elements on the Marangoni convection.

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So, that the surface tension is not a function of only temperature, it is a function of composition also; and composition also are a function of distances in a particular manner, so let us see what should be the effect - solute effects. And particularly we let us take the effect of some surfactant elements such as oxygen or sulfur in steels. So, what these elements do is basically the following.

These elements tend to go to the surface and segregate there, so that they can reduce a surface tension. So, such elements which migrate to the surfaces readily are basically the surfactant elements, some solutal elements like for example, nickel in liquid iron, for example, they do not behave like that. They will be in the substitutional positions wherever iron is there, and they will not segregate selective to one boundary; however, let us say boron, sulfur, oxygen etcetera, they will tend to migrate to the boundary and then segregate their change the composition locally, so that the surface tension is lowered. So, such elements if they are present, they are going to change the surface tension behavior of that particular liquid metal.

And how does it change in what way, so that is given by this relationship. I will show here this for an alloy, for example, what happens is very close to the melting point, the effect of the surfactant elements is very high which means that there will reduce the surface tension significantly, but the reduction of surface tension is not effective as you increase the temperature.

So, as you go further and further at higher temperatures, amount of reduction is not significant; and after some temperature, it is not at all present. So, in other words, the plot would look like that goes up and down. So, in other words, whenever there are surfactant elements, the surface tension at low temperatures close to the melting point, goes up; and then at a peak value, after that it just keeps coming down.

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So, we could then say that the plot is going to look like that; some T naught beyond which it goes. So, which means that surface tension coefficient of temperature is not negative always, it is actually positive at low temperatures here I say; and in this region, negative at very high temperatures. So, in other words, the sign of the surface tension coefficient is going to change. And if that changes then our argument that we have discussing here is going to also change; and there is because the temperature is actually changing; which means that this plot is going to be modified.

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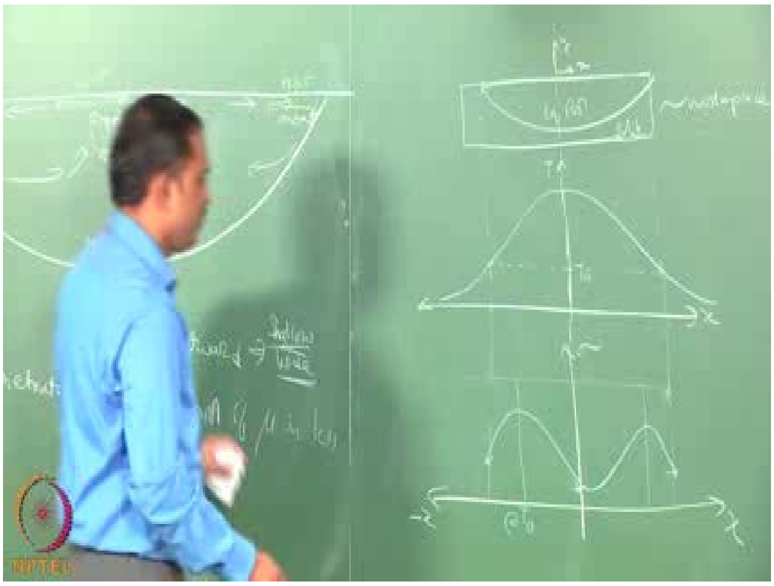

And you can see that at high temperatures, it is still low; and at low temperature, again it is low, but it is going to be. So, you have got at T naught, the distance correspond to the T naught is where the surface tension is maximum and so on. So, this kind of a variation would immediately change the way the fluid flow will happening for the same logic. What would do is just follows, it would change in the following manner.

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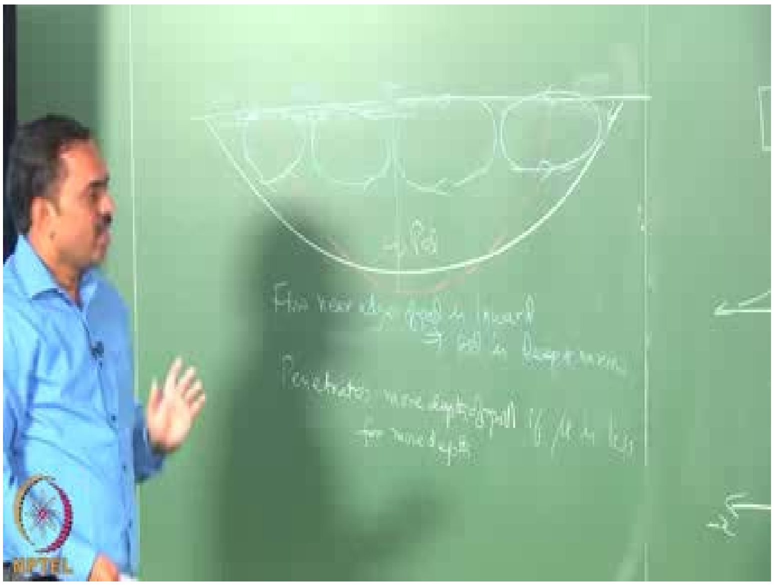

So, you would see that at the peak temperature, at very high temperature, it is low; and it very low temperature, again it is low; and here it is high. So, you have a situation, where you want to expand, but this wants to this also wants expand, and here wants to contract. So, in other words, you now see that you have two loops; and if you want to rotate it around then you would have, so you have radially away, and this is radially inward. So, you would see that at the center, it is away; but in the ends, it is inward.

So, this inward flow at the ends, this way inward flow if the ends, it is going to basically make the pool not very wide, but set in narrow, some which means that the flow is going to be like this. Flow near edges of pool is inward which implies that the pool is deep and narrow. So, in other words, if I want to super pose that kind of a change over this pool shape when you would look more like this, because of the heat going inwards of the pool must be narrower.

And it is also experimentally observed that in steels that contain a surfactant elements sulfur and oxygen, the same GTAW with everything all the parameters same for the weld pool, the weld pool is known to be slightly deeper and narrow compare to when it is not having those kind of an elements. So, this is how a surface tension is going to change the weld pool shape. And we can rationalize that from this surface tension variation.

And solutal effects are not playing a role only from the surfactant elements, it is playing role also from the normal alloying elements, because the alloying elements also can for example, change the surface tension in the case of dissimilar metals. So, one has to always pay attention to how the surface tension is changing as a function of composition, if composition changing as a function of distance, so that ultimately you have to inspect whether surface tension is changing as a function of distance. The moment it changes as a function of distance then immediately you start seeing the flow coming because of that variation. So, this is how the Solutal Marangoni convection is going to play a role.

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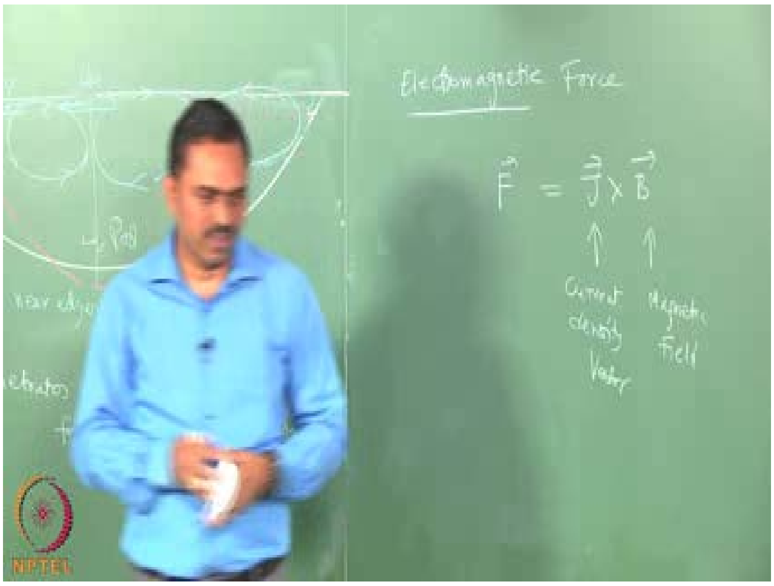

And let me just erase it, so that we can come to the end of this lecture with some more body force effects. So, the other body force that is going to play role in the convection is the electromagnetic force - Lorentz force. So, electromagnetic force is going to be given as, so the current density vector J, and the magnetic field induced by the current itself.

And this can be calculated, and you can see that this is basically a force which is going into the Navier-Stokes equation in the body force terms.

So, simply you can add this into the body force term, and you need calculate the current density vector in the entire domain separately, find out what is the force that is added upon the liquid and add that force to the respective body force terms. And that is also basically play role in the convection of the pool. And you can see that convection of pool is depending upon the current density vector; and current can be going inward or outward depending upon the polarity. So, change in the polarity also means that we are going to change the way the convection is going to happening in the melt pool because of the Lorentz force that is acting. So, this is a body force term.

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So, let us then look at a map of all the terms that we have done till now. And for which process which of the special terms are going to be effective. Let us do that as a map by making a tabular fashion, which we did in the beginning of this session.

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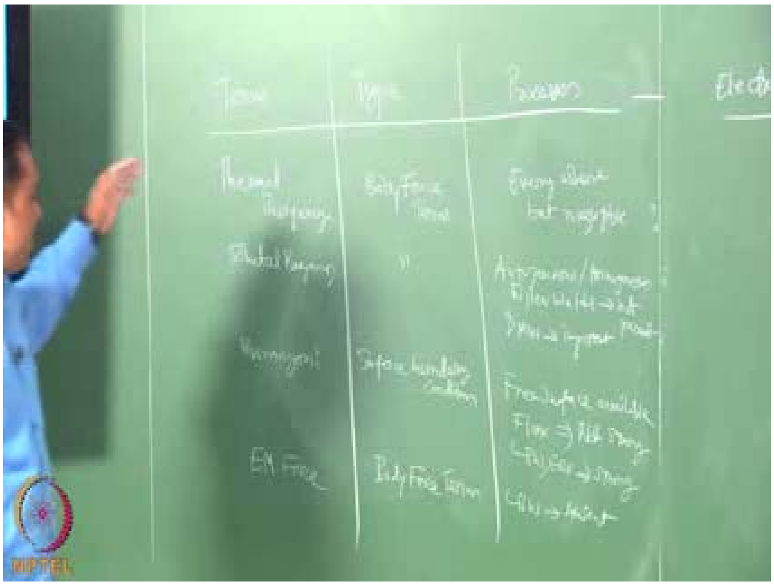

So, the first term is the buoyancy term. So, let us take the thermal-buoyancy. Thermal-buoyancy is going to be given as a body force term, which means that it is going to come into the equation itself as an additional term. So, which means that if we were to look at a formulation of the fluid flow modeling in any paper then you can look at the equation that they are solving, and you should be able to see the body force there. And if it is there that means, they are taking into account the thermal-buoyancy. And what processes is relevant, actually any process that is happening on earth where the acceleration due to gravity is present then this term should be valid; it must be present everywhere.

But we must play attention that most of the times the welding is then in a flat geometry. So, that the highest temperature is on the top and the gravity is actually downwards. So, in other words, when you change the geometry from flat geometry to over head the buoyancy convection is going to playing a role. So, it is not acting in the same direction. So, pay attention to the geometry, but otherwise, it is everywhere effective, but everywhere effective, but negligible in the sense, negligible compared to the Marangoni convection, but it is present everywhere, and it is strongly affected by the geometry.

Solutal-buoyancy is also a body force term, but it is only to be taking to account when there is a solute change that is present, which means that concentration changes are to be there, which means that in the case of let us autogenous or homogeneous filler welds not present. So, that is if you do not have any filler, and if are going to weld the material using autogenous welding, then there is no concentration differences that are happening, and therefore, there is no solutal buoyancy.

And if you are also doing to do a welding with filler, but the filler is actually homogeneous filler which means the same material as the base material, then again there is no concentration change, and therefore, there is no solutal buoyancy. In the dissimilar welding, it is very strongly present, because it is strong component change across the melt pool. And in the situation where the filler is added which is different from the base material, again it is present. So, it is not present in autogenous and homogeneous; and it is present in rest other situations. And in the dissimilar welding, I would say dissimilar welding, it is important.

Now, what about Marangoni, Marangoni term as you can see is because of the surface tension change and that means, there must be a surface that is available, and surface is available normally and this is actually a surface boundary condition. Unlike the remaining terms, it is not appearing in the equation, it is appearing as a boundary condition.

And it is present in every situation, where there is a free surface available. Are the situations where there is no free surface, for example, let us sake you know arc welding the when there is a flux, so the surface of the liquid metal is covered by flux; it is not exposed to the vapor directly. So, therefore, the surfaces tension that is relevant is the surface tension between liquid metal and liquid flux and that surface tension is not a strong function of temperature.

So, which means that whenever the liquid melt pool is covered by a flux completely, and there is no free surface of the liquid metal exposed then you can say that the Marangoni convection is very much, very suppressed and not very strongly present and which means that if you have flux implies not strong. And it is very strong for example, in materials which are being welded where the temperature changes are drastically changing from the center to the edge of the pool. For example, laser welding and electron beam welding, the peak temperature is very high.

And as you go in a small distance, in a small melt pool, the temperature drastically comes to the fusion zone temperature, which is the melting point temperature; which means that you basically have these effects very strong in LBW or EBW simply because the gradient is strong. And what about the electromagnetic force, that is also body force term. And naturally the electromagnetic force term should not be present, when there is no electromagnetic force in due to the process itself that is if it is an arch weld, you will have that force, but it is a laser weight is not there.

So, you can say that in laser being welding, it is absent; and in every arc welding, it is present. And it is depends from polarity also. So, as you can see that the different driving forces are to be kept in mind; and depending upon the welding process, you must choose which have these are active and you may see that some are boundary conditions, some are body force terms, which come in the equation. And then some can be neglected in some conditions and some cannot be etcetera, so that way you can actually see that not or all used in every situation. And one must be attend to the process conditions to pick the right kind of a term for the fluid flow. So, with this, we basically summarize by also telling what we did not look at.

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So, let us next scribble those words what we did not look at. So, these are only for the research interest mainly because some of you may want to further go into the research of these subjects. So, what is this? that we did not look at rippling; so surface ripples are known in welds; normally a good weld what is called the good weld appeal is going to look like that. And each of this is basically arc shaped surface undulations, which are supposed to be very uniformly spaced for a good weld.

And this surface rippling is basically due to the free surface deformation and that is not considered till now. And there are ways to model it; you will come to it, if there is a adequate interest among the participants. And there are other things that we have not considered for example, vaporization. Vaporization, we would look at it briefly when we discuss the conduction mode to the key whole mode; and otherwise we are not looking at so called Knudson layer vaporization and the related effects.

We have also not looked at the effect due to the nozzles on the flow that is the gas flow coming from the nozzles to protect the layer is going to affect the liquid pool flow. We did not consider. It can be dumped into the surface boundary if necessary, but otherwise you have not considered. So, like this, there are some effects that we need to keep an eye on to know whether they are important in the process; otherwise we need to consider.

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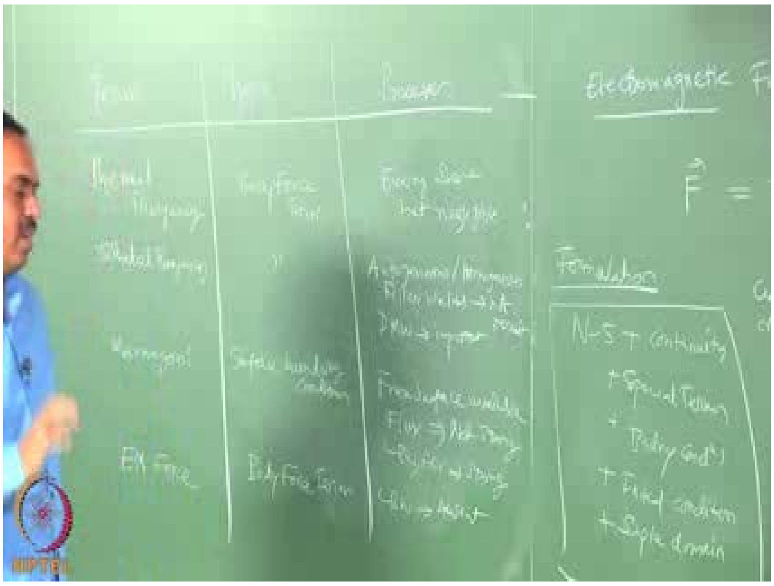

So, with that I would summarize by closure in the formulation. And the formulation can be closed as saying that Navier-Stokes equation plus we can say like this the formulation is close like this Navier-Stokes equation plus continuity plus special terms which are like this coming plus the boundary conditions. Which are basically in the case of Marangoni, you have got a special boundary condition; otherwise, no flow condition or rigid body condition or no slip condition etcetera, they can be the boundary condition and then you have the initial conditions which are simple because initially everything is at zero.

And you have got special terms also to take into account single domain approach, the terms that are require to make it is single domain. So, this entire thing now is enough for us to go ahead solve the problem for a fluid flow in a melt pool.

So, I will briefly discuss later on, how to go about solving or what kind of software are able to solve this for you etcetera. And we need to always keep an eye on what all goes in and how much can then be expected to come out. So, with this, we close the fluid flow modeling lesson, and we would discuss further on the solutions in a later lesson.

Thank you.