Steel Making

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The Science Base of Iron and Steelmaking

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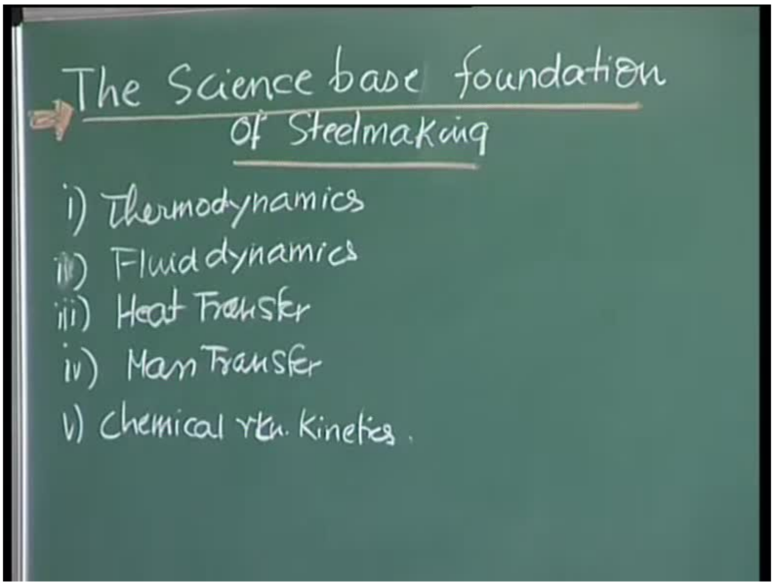

So, let us continue to talk about the science base foundation of steel making, and I have already briefly told you about the relevance of thermodynamics and try to introduce certain key concepts of thermodynamics. And as I have mentioned, as it is not possible to cover each and every topic, but at least in the context of prediction of feasibility of a reaction or equilibrium calculation, I have tried to make use of certain concepts and demonstrate to you that - yes, with the knowledge of equilibrium, knowledge of activity, composition, relationship, etcetera you will be able to formulate equations, use thermodynamic data, and then, make prediction about the state of equilibrium in terms of temperature pressure and composition.

Now, on thermodynamics there are various textbooks available, for example a nice UG text book that we follow at IIT Kanpur is the text book by Professor Gaskell. There are innumerable other metallurgical thermodynamics textbooks and I ask that you go through that text in order to get a comprehensive idea of the subject of thermodynamics. Following thermodynamics, now I would like to talk about fluid dynamics. Now, steelmaking parse from the stage of basic oxygen furnace to down to continuous casting at every stage, we have processing and transfer operations and these are controlled by fluid flow. In the sense, that melt flow or flow of steel in reactors like DOF, EAF, ladles tundish and mould will control the interfacial reaction weights, will control the mass transport within the fluid, will control refractive material interactions and refractive erosion rates. You name a process, which is occurring in the steel making reactor and you will find that the root of that problem, the fluid flow really plays a decisive role.

Now, we all know that for example, if we introduce stirring the mass transport and mixing is going to be very intense. For example, if you take a cup of tea, add a spoon of sugar and you do not stir it then the sugar does not dissolve. So, to get a homogeneous mixture of sugar in your tea, you have to stir it vigorously with a spoon and then only you get a mixture, and that is why in every stage of steel making as we see that we try to deliberately introduce stirring either by injecting in inert gas or a reacting gas or the metal of falling from a certain height and this creates enormous amount of convection current in the system and that convection current aids in controlling the rate of heat and mass transport and various other processes.

For example, you name it and the process is going to be, most of 99 percent of the cases, you will see that the rate of the process is really enhanced by in the fluid dynamics prevalent than the reactor. Now, intensity of flow is very important for us and the intensity of flow can be regulated or would or depends on the system geometry; it depends on the power, which is stirring power we say, which is being fed into the reactor and the level of intensity will eventually determine. For example, if you have added an allowing addition and you want the allowing addition to melt and dissolve in the bath, you invariably will conclude that greater is the stirring rate in the system greater at the movement of the fluid more will be the rate or faster will be the rate of melting and dissolution.

So, there is no ambiguity as far as the relevance of fluid dynamics in steel making. It is a very complex subject, you require very good knowledge of Maths and you require very good knowledge of vector and tensor in order to understand the subject. And it is the scope of the subject is enormous, you can run, rather you can be diverse topics, which are involved starting from you know, simple laws of fluid dynamics to complex flows turbulence and etcetera. And the scope is enormous and possibly it will be very difficult for me to introduce all the concepts, but I am going to try to highlight the role of fluid flow and how can you know, our objective is you know, to know the state of fluid motion in the reactor having you obtained information about fluid flow, how can you use that information to predict the rate of metallurgical processes or steelmaking processes is our essential objective. And I will hover around that central point that how to get some meaning full information about the state of fluid motion in steel making reactor.

And to be able to do that what information do you require at our end? Now, the intensity of flow in steelmaking reactor varies appreciably from one process to another process. So, we understand that the nature of fluid motion in steelmaking reactor is going to be different. By nature I am saying that if the intensity of the fluid motion is very small, maybe we can get a laminar or a transition flow.

On the other hand, if the intensity of motion is vigorous, in that case we can have turbulent motion in the system. Now, I have mentioned to you that, for example, in tundishes, we have a flow of the order of centimeters per second when you refine a stepping operation we may have flows of the order of few meters per second.

So, therefore, the state of fluid motions in reactors is different and invariably we will see that because the size of the reactor is large and that the kinematic viscosity of steel is very small. So, therefore, the Reynolds number of the flows is appreciable under steelmaking condition.

So, as a thumb rule, we can say that flows in steelmaking reactors are going to be invariably turbulent. What are the other characteristics of the flow? Other characteristics of the flow would be, is the flow one dimensional, two dimensional or three dimensional.

Because now, for example in a pipe flow problem, the fluid goes moves, comes at one end, leaves at other end; this we say there is a predominant direction of motion, but in steel making reactors these are all three dimensional reactors.

So, there is a x component of fluid flow; also there is y component of fluid flow; there is z component of fluid flow. So, all three components of motion are going to be prevalent. So, simplification and idealization in terms of dimensionality of the problem is not going to be very much advantageous in our case and we will find that the flows in majority of the cases are going to be three dimensional in nature. Pipe flow type problems or flow over a flat plate type problems, these classical flow problems will never be encountered under steelmaking situation.

Particularly, if you look at the processes starting from BOF to the continuous casting nowhere, approximation of two dimensional flow or one dimensional flow will be tandem.

Now, is the flow steady or unsteady, the next question that we ask? that Now, depending on the process, the flow can either be steady or unsteady, because we know that if flow becomes in the… when the process is just started, for example metal is sitting in the ladle and the moment I start to inject gas, from that moment onwards the velocity is going to change as a function of time at some point of time the velocity will become constant.

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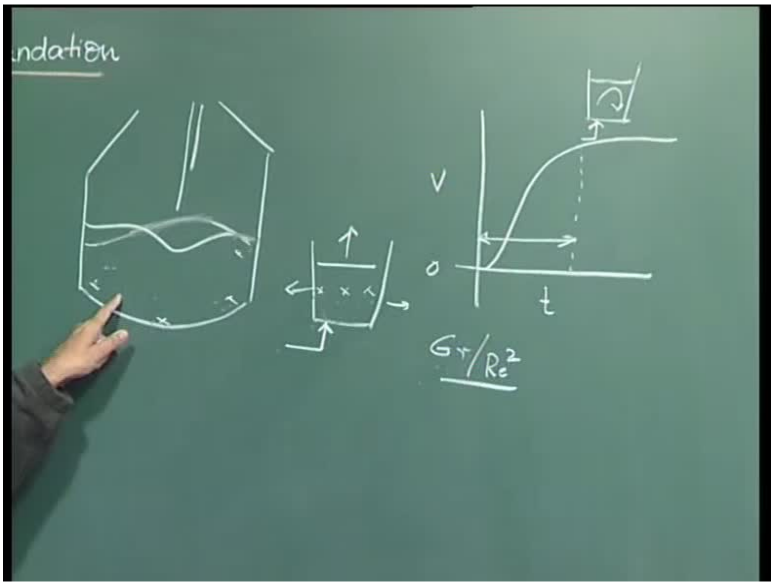

So that looks something like this. So, for example, if you plot velocity at a location versus time with gas injection in a ladle - small little figure I draw, so I introduce a gas here and then, the flow develops and you see the flow goes something like this.

So, this is basically the period, which is called the flow establishment period or the period of transience, that means, we have started to blow gas and then, for some time what happens is, we have buoyancy power which we input through the gas and it accelerates the fluid and at some point what happened is the energy supplied by the bubble is balanced by the losses you know, through various mechanisms and then we obtain a steady state process.

Just like the way you take a kettle of water and you try to heat it. So, initially the temperature of water is going to be increased and at some point of time, the rate of heat input to the kettle will be exactly balanced by the rate of heat loss and then, you are going to heat a constant temperature that is the characteristics also exhibited in this particular case, from 0 the velocity is 0. So, the velocity starts to increase as we introduce gas and then, eventually the velocity becomes a steady state.

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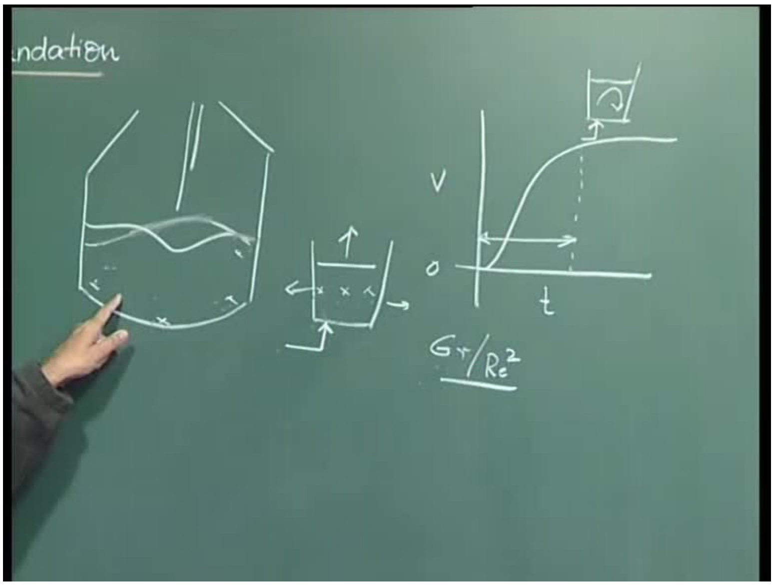

So, it depends on the process in which we are looking at. If you are looking at the initial period of gas injection, the flow is unsteady; if you are looking at a long duration of gas injection, in that case we can say that the flow is steady.

Furnace tapping compilation, continuously the bath is being filled up; the ladle is empty initially metal is coming from the furnace it is being poured into the ladle and as a result of which the bath get increases.

And as the bath depth increases, the distance between the lip of the mouth as well as the free surface or the surface of the liquid continuously decreases as this level increases. So, the distance between distance of separation between the furnace lip and the level of melt continuously decreases.

So, as a result of which the flow phenomenon in the system throughout the tapping operation remains unsteady. So, we will not be able to draw say always that the flow is steady or unsteady depending on the scenario, the flow can be steady or flow can be unsteady.

Now, having said so, we understand that our flows are going to be multidimensional, mostly three dimensional, flows are going to be unsteady flows have or steady depending on the process, depending on the duration at which we are concentrating flows are most likely going to be turbulent .

Now, we have non-isothermality also in steel making reactors, because I have been saying all along that we know that you have a furnace or a ladle and then, through the wall or through the mouth heat radiates. So, as a result of which we can expect that if we have a BOF convertor here, particularly when there is not much stirring, so I can say it is going like this. So, there is expected to be some gradient in temperature and this difference in temperature will depend on how good a stirring is there; this difference in temperature will be mini-mum, if the stirring in the bath is very good; if this difference in temperature could be pronounced, if the stirring in the bulk of the metal is not same.

So, there is difference in temperature that could be difference in temperature, in the system ladle which is being held at some you know, there is no gas injection nothing like that. So, the ladle contains molten metal and then, there is going to be heat loss through all the surfaces and as a result of heat loss, there is going to be difference in temperature between various locations.

So, this will have a higher temperature; this will have a lower temperature, because of heat loss and as a result of which we have differential temperature, which makes the process non-isothermal in nature.

So, we are not talking of isothermal process; so the fluid flow melt flow is going to take it under non-isothermal condition .And non-isothermality as you must know, from your basic transport phenomena may introduce some kind of thermal buoyancy into the system.

And what governs thermal buoyancy? With these are the force convection, free to force convection is the ratio, which you say Grashof's over Reynolds number. It is this term that will say for example, whether we have a strong free convection current or strong force convection current.

Grashof's number is a measure of the buoyancy. Reynolds number is the measure of inertial forces. So, calculating this ratio, we should be able find out that whether free convection is important or not.

So, therefore, I may have force convection when I am introducing a gas into the system or I may have some alternative form of studying electromagnetic stirring and also I may have free convection also and free convection particularly, because of thermal gradients or because of concentration gradients we may have free convection currents in the system.

So, whether free convection is important? So, there may be some situations in which there will be no force convection. For example, holding period in a ladle, where there is no gas is being injected into the ladle in that case, I will have no force convection, but if there is any flow at all, that flow is going to be attributed to free convection.

On the other hand, when I am going to have a gas injection into the ladle, I will have both forced convection and free convection, because free convection will be there because of temperature differential in the system, thermal stratification in the system and force convection flow, which is going to be there, because of that introduction of the gas itself.

Now, whether, free convection effect is important or not. As I have mentioned, this will be dictated by this particular number. Now, on the coming back to the issue of non-isothermality. So, therefore, in some systems, where we have no strong force convection current in that case, the non-isothermality can affect our fluid flow, because we know that difference in temperature will cause difference in density; so heavier density fluid will go down, lighter density fluid will go up and that creates a natural convection current under the influence of gravity and that is called natural convection or thermal buoyancy.

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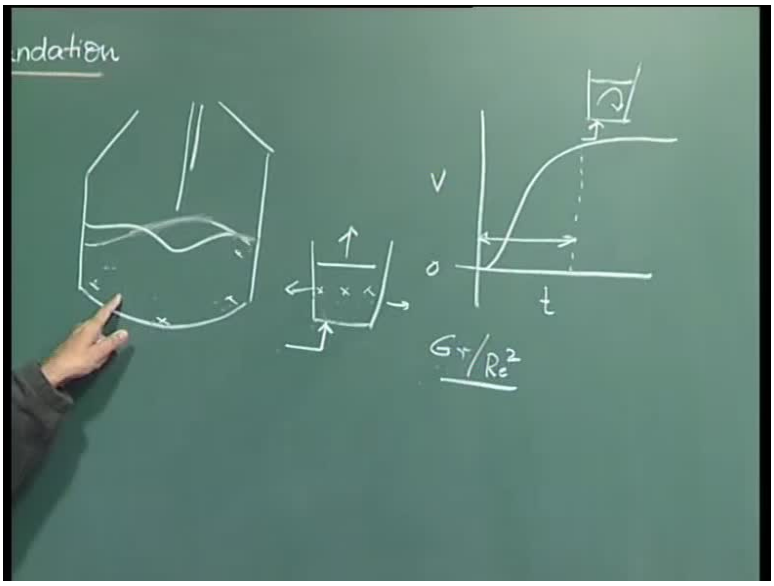

And so, therefore, any isothermality may also affect the fluid flow condition in the system that can precipitate into fluid flow in the system naturally because of thermal gradient. Similarly, if you have concentration gradient, that concentration gradient, for example at some point you have little amount of carbon, at somewhere you have bigger amount of carbon; so more carbon means less density; less carbon means higher density in steel. So, therefore, you are going to have a differential motion and as a result of which you have buoyancy, which is not thermal buoyancy, but which is we will call as solutal buoyancy.

So, in steelmaking systems, while we have concentration gradients in the system, while we have temperature gradients in the system, we will see that the fluid flow in the system or melt flow in the system could be a result of the combined effect of thermosolutal convection also in addition to free forced convection. For example, particularly if you look at the continuous casting, suppose you are considering a bloom casting and you know that there is a metallurgical length and this bloom casting we go towards the lower part of the metallurgical length, where we have little bit core of liquid and rest everything is solidified and there virtually you do not see the impact on the SCN, because the SCN is located much high metallurgical length we are talking about 10 meters or 8t meters therefore I am talking about distance of 7 meters down the meniscus where we may know some weak motion and that weak motion it is now well known is as a result of thermosolutal convection.

So, within the mould region in continuous casting, the flow is going to be primarily given by force convection, because of the incoming jet of molten steel. On the other hand, towards the lower part of the strand, where we have still some molten metal and there if you see any noticeable motion and that noticeable motion is going to be as a result of thermosolutal buoyancy, that means, there is a difference in temperature; there is a difference in concentration and both these difference in concentration and difference in pressure, difference in temperature have precipitated to flow.

So, non-isothermality can be a big factor in our fluid flow - in our melt flow analysis- concentration differences also can play an important role in our fluid flow understanding. Most importantly, however that is in a steelmaking reactor bit little primary steel making converter BOF or EAF you have multiphase interaction.

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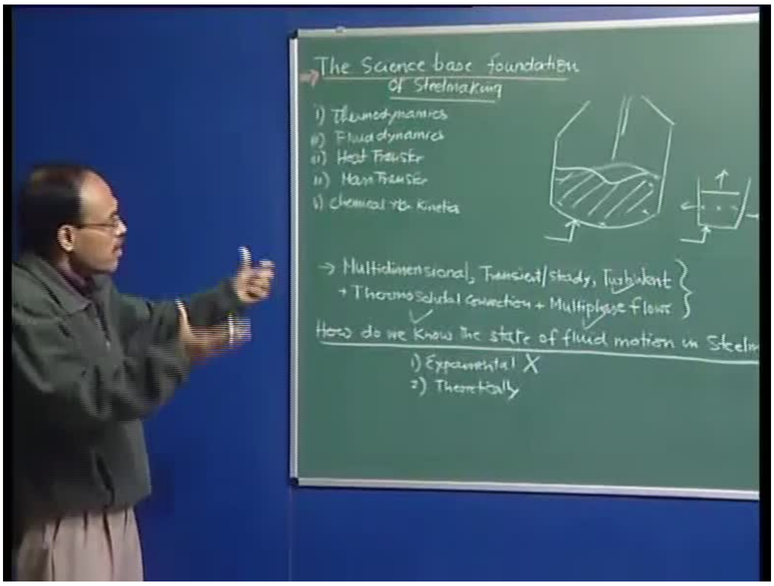

It is not just flow of one fluid, we have gas is flowing; we have liquid is flowing; we have slag is flowing; we have added solid, the solid may be moving in the system; so it is a multiphase system. So, therefore, to summarize the nature of steelmaking flows, I could say that steelmaking flows are multidimensional.

Steelmaking flows could be transient or steady, they are invariantly turbulent, three convection of I will say thermosolutal convection thermosolutal convection is important. So, multidimensional, transient or steady, turbulent, thermosolutal convection plus multiphase flows. You name a complexity, you will find it in steelmaking and also for example, in some cases what we see that on top of this flow, the domain either shrinks or expands, because of solidification and melting phenomena, which is the consequence of heat transfer itself.

So, the fluid flow or the flow of melt is not as parse is a unique phenomenon; it is actually interrelated to so many other things, which is going to influence flow. It is not just like a simple flow of a pipe, flow or a homogeneous fluid moving in a tank no it is not that kind of a flow. You name a phenomena, solidification, multiphase, thermosolutal convection all these features characteristics are going to influence the flow. Therefore, we have to understand, all these things in great detail in order to address the fluid flow or fluid dynamics in steel making reactor.

So, the subject at hand is an extremely complex and the scope is going to be enormous as you see so many types of concepts are, they are particularly subjects of turbulence, the subjects of multiphase flows, the subjects of thermosolutal convection, these are in the free convection these themselves are you know, a huge topic with enormous scope and you know on each of this subject may be more than one semester course can be run and you can imagine therefore, that the effort and time that will be needed in order to master the subject of fluid dynamics and then, apply the theory and our understanding to the reactor in order to see how the fluid flow does really influences the process. Then as I said in the beginning that our objective is, we have to know about the state of fluid motions somehow in the system.

So, this is you know, cut throat statement. The theory says in its place you know the text book are their place, but as a steelmaker my objective is to know the flow and why I know wish to know the flow, because I want to calculate melting rates; I want to calculate desulphurization rates; I want to calculate refractive erosion; all these things are my basic aim, but the background I see that these are intricately related to fluid dynamics in the reactor.

So, therefore, I have no option, but to study the subject of fluid dynamics in great detail so that I can really address the rate of the metallurgical processes that are been taking place in the steel making reacts.

Now, how can you predict or know the state of fluid motion? I am not going to discuss; the theory is enormous so it is not possible for me to discuss the theory. So, I am addressing it that from the end point objective that how do you know the fluid flow, how can you calculate the fluid flow, what are the resources that we need? We have of course many types text books, which you can follow, understand the fundamentals and assuming that we have the fundamentals proper fundamentals. The question that I pose before you is how do we know the state of fluid motion? This is the basic or the essential problem. Concepts like parallel flow, Newton laws of viscosity, Navier Strokes equation irrotational flows then simple parabolic flows creeping flows, these are very essential in order to develop a comprehensive framework of for our understanding, but assuming that we know you know our fundamentals are ready; we are ready in terms of our fundamentals. The question is now, how do you know the state of fluid motion in steelmaking reactors?

Now, in any system we can get information about a given phenomena either by carrying out experiments or by carrying out calculations. We can develop a simple mathematical model, for example and then, we can find out that what is the state of fluid motion or we can use a probe or a sensor and then, find out that what is the state of fluid motion. So, we have two different stand points. Now, one is experimentally we can obtain the fluid flow information about the flow and number two is theoretically, provided an adequate theoretical background exists in many of the cases. Because of the complexity of the flow, we are going to see that in adequate mathematical description, adequate means near perfect mathematical descriptions still does not exist and therefore, as I have mentioned or as you might be knowing that if the mathematical description in the theoretical background is not right, if the mathematical model is not correct in that case, we will not be able to predict the process correctly.

Now, coming back to this point, experimentally it is perhaps extremely cumbersome; it would be extremely cumbersome to determine or map the velocity filled in a BOF reactor. We may not have probes; because we require probes which you have to immerse steel is opaque, so we cannot see what is going on and that we may not have probes which can work on a sustain basis under such a larger environment of 1600 degree centigrade and in a huge reactor size.

So, perhaps we can say that experimental determination- rigorous experimental determination - or mapping of flow filled in steel making reactor as of now is not possible; it is going to be enormously time consuming; it is going to be very difficult; it is going to be very expensive; so we can rule out the possibility. So, only possibility is that we can calculate possibly the melt flow phenomena from experimental background.

Steel as we all know is a Newtonian fluid. So, the theory of Newtonian fluids can be applied and although molten steel would exhibit most of the time incompressible flows, but if you are injecting gases to the bottom, in that case the gas density can change enormously, because of the difference in temperature and some compressibility effect can come as far as the motion of the gases is concerned; while the flow of liquid is concerned, the compressibility may not have direct relevance, of course the motion of gas would influence the motion of the liquid react. So, if the gas compressibility influences the motion of the steel motion of the gas, in that case there is going to be an indirect influence of gas compressibility on the movement of liquid steel.

Now, how does when you inject gas, how does the liquid moves? The liquid moves because of the application or drag forces, the bubbles move or the gas steam moves, it drags along with it fluid and therefore, there is going to be momentum exchanges between the gas and the liquid; there will be various surface forces through, which the gas and the liquid are going to interact and they interchange momentum through their surfaces and as a result of which the bubbles or the gas as it rises, it imparts momentum to the liquid and then it recirculates.

That concept perhaps, you know from your elementary transport. So, we have to stick for the theoretical background. Now, we can first say that well look when you are talking of a theoretical background and we want to know the velocity and this velocity comes from basically expression comes from a Newton’s law of motion.

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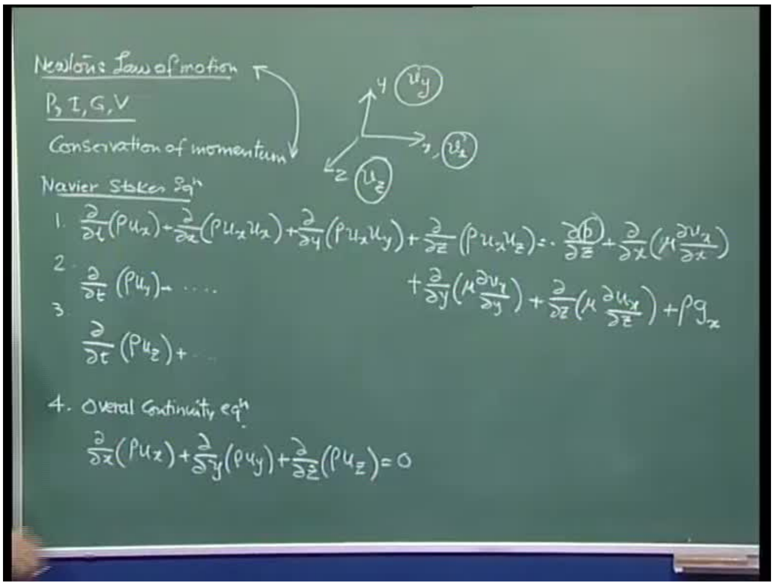

So, the theoretical background is formulated on the basis of Newton's law of motion and where we say that the net acceleration produced this is equal to the algebraic sum of the forces and what are the forces that are acting in the fluid one may take into account.

And when we consider that pressure, inertial, gravitational and viscous forces are the only relevant forces, which are acting in the fluid element and then, if we carry out a counter volume based analysis or derivation, then we can derive what is known as the conservation of momentum.

We can carry out a conservation of momentum or which is essentially this gives rise to what is known as the Navier Stokes equation. So, the basic framework based on which the velocity fields within steel melt is going to be calculated is the Navier Stokes equation. And we all know that in the Navier Stokes equation, we have other expressions like stokes, flow, etcetera, which are incorporated. So, this also statement is not unfamiliar to you; you know this statement of Navier Stokes or the Navier Stokes equation from your knowledge of transport phenomena.

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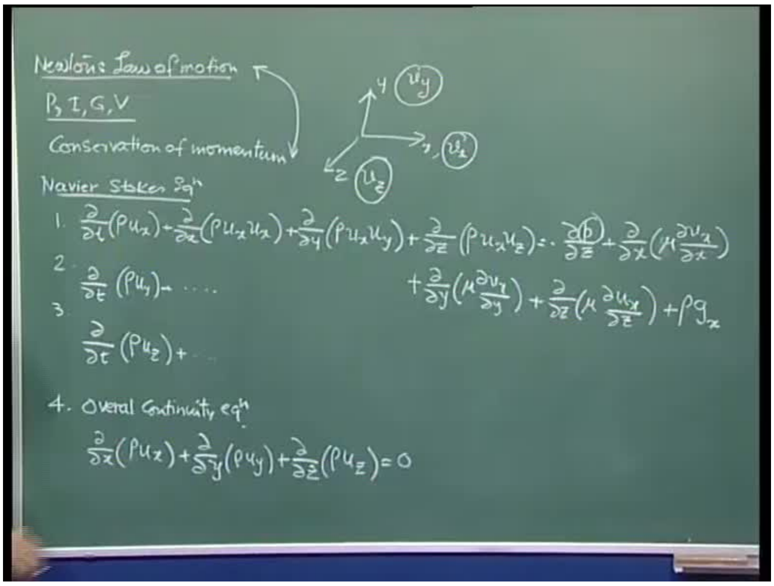

So, we have an overall continuity equation and the three equation s of balances. So, because we are talking of multidimensional flow, that means, we are going to have three different components of flow; we have x, y and z. So, we have v x component of flow; we have v y component of flow; we have v z component of flow. So, there is a v x conservation of momentum; there is a v y conservation of momentum; there is a v z conservation of momentum or we can say there is an x component of motion equation. For x component of motion, which is essentially the Newton's law forced balance equation applied along the x direction.

Then we can say there is equation of motion along the z direction, which is a momentum conservation equation along the z direction and then, we can say similarly, that there is a conservation of momentum or equation of motion along the y direction. So, we have three different equations therefore, when we talk of a multidimensional or a three dimensional scenario.

And this three equations as we will see, for example, if I write down the unsteady state equation, for example one such equation I can show that I write it in a conservative form three dimensional. So, this is the x component of motion that I am writing actually and so these are the viscous terms. Now, that I am writing this is the pressure force or pressure gradient term and this is the viscous term along the x direction; this is the viscous term along the y direction and this is the viscous term along the z direction.

And note that, I have considered that well the system under consideration can be described by… So, we are selected; we assumed that the system under consideration can be written or expressed in terms of a cartesian coordinate system.

So, we can have the Navier Stokes equation in cylindrical polar coordinate system; we have in spherical coordinate system and then, we have rho g x. And obviously, if you are saying that it is a gravitational component, the component of g x along the x direction is g x and that is in this particular case, if gravity is the force is actually is equal to 0.

Now, if we have x u x component , x component of equation, then we similarly we will have a term y component and similarly, we have third equation as z and note that this equations I have written in terms of in the unsteady state mode, because I have a net rate of accumulation term, this derivative term becomes equal to 0.

So, conversation of momentum - if it is a three dimensional flow, we get three such equations and on because in this three such equations, we have unknowns are what, unknowns are u x, u z, u y there are three unknowns but on top of that we see that there is another unknown pressure which is to be calculated as a part of the solution. So, the fourth equation, which is needed, is the overall continuity equation and if I say that the flow is incompressible then I can write that well, this equation goes like this. Note that I have written this equation for an incompressible flow.

I have written this equation for a Newtonian fluid, because of the viscous term, stress is taken to be directly proportional to the strain rates and now I have 1 2 3 4 equations and I have 1 2 3 and 4 unknowns. So, these are my four unknowns, this is 1; this is 2; this is 3; these are the 4 unknowns and I have 4 equations. So, therefore if I can solve these equations with the correct number, of course these are partial differential equations. I will require boundary conditions or initial conditions to be expressed appropriate number assuring that we have the correct number of boundary conditions; we should be able to solve this equation.

Note that this equation, it is valid for multidimensional flow; it is valid for transient flow; it is valid for Newtonian fluid; it is valid for incompressible flow and it is valid equally for both laminar and turbulent flow. No restrictions have been made, but if we try to solve this equation, I will come back to this issue a little bit in more detail.

If you try to solve this equation for turbulent flow, we are going to have some problem, but we will talk about it a little later; right now we see that we have four equations and four unknowns so that means it is a well-defined problem assuming that we have the right number of boundary conditions.

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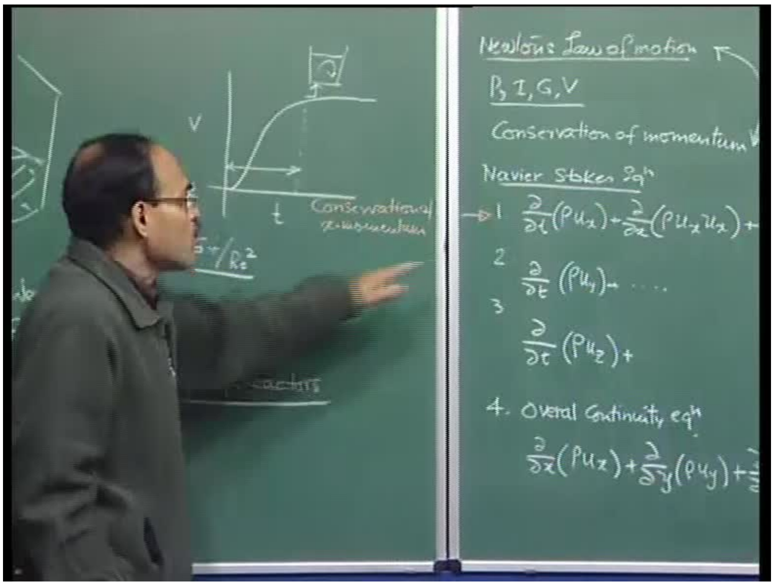

Now, this differential equations as you can see here are non-linear differential equations, because you see that you have product of the velocity terms, the second order term and also these equations are interrelated. For example, this is a this equation as I have mentioned, this is a balance or conservation of momentum along conservation of x momentum. So that is this particular equation.

Second equation is conservation of y momentum; third equation is conservation of z momentum. So, if you look at this equations, they are essentially multidimensional and you can see that they are non-linear and also in this equation, it is x momentum conservation equation, but you see the y velocity component and then z velocity component appears.

So, therefore, this equation and this equation are mutually coupled; both x velocity components depend on y, and y velocity component depends on x, and same is to for the z component process.

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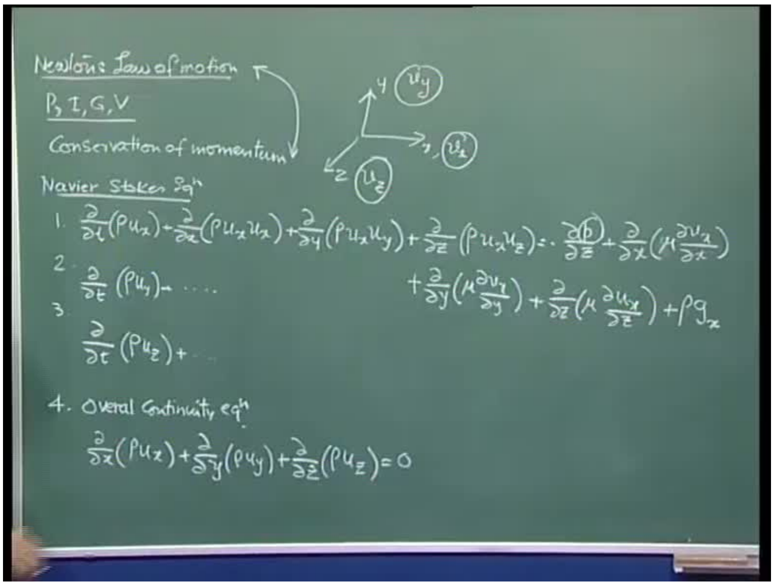

So, there therefore, you cannot solve these equations independently; they are mutually coupled equation. All the four equations have to be solved simultaneously and you therefore, you cannot solve them by hand; you have to take care of what is known as a numerical method in order to solve this equation.

And this is itself, the numerical solution of such complex differential itself is a very interesting important subject in this particular context, which we call as a computational fluid dynamics or CFD.

So, it is an entire subject on its own and this is also an area beyond when you talk of, we need some expertise in fluid dynamics, we have to know fluid dynamics. we In the context of metallurgical problems, we not only stop at the analytical work, we have to look at the possibilities of numerical solutions; understand the numerical solutions well and therefore, when we say that we have to have some expertise in fluid dynamics, we will have to know the subject of CFD also or computational fluid dynamics also when we work.

Now, you can have just four equations for example; on top of this as I have mentioned that if you have thermal buoyancy, if you have solutal buoyancy, in that case the flow is going to be influenced by thermo solutal convection also.

So, the flow is going to be related to a transfer and the flow of heat also from one point to another point is going to be related to fluid flow.

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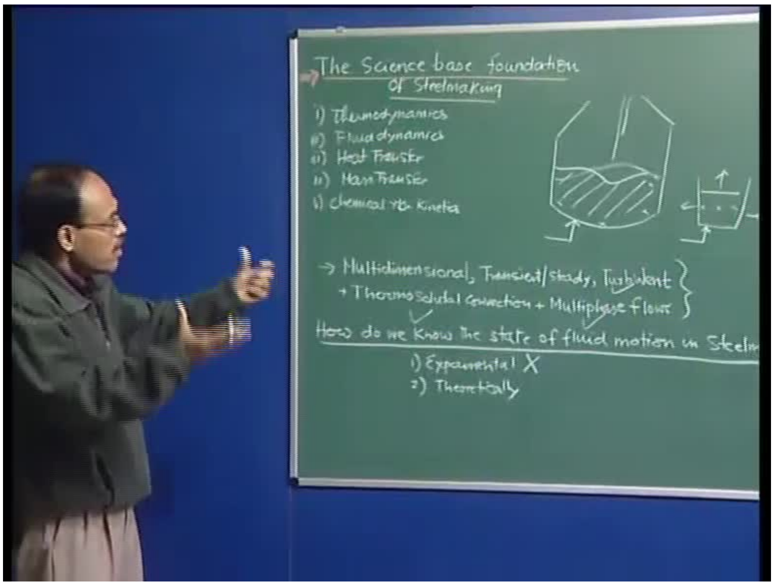

So, therefore, if there are thermo solutal convections which are important in this particular case, we understand number 1, the flow will then depend on the concentration gradient; flow will depend on the temperature gradient. Also the flow of heat or flow or mass from one point to another point is going to be related to the fluid flows also. Because the flow of fluid or melt will take material from one point to another point, because it will depend on the rate at which material will flow from this point to this point or heat will flow from this point to this point will depend on the extent of or the convection current present in the system.

So, in many situations, where thermo solutal convections are important, we will see that the fluid dynamics equation cannot be solved in an isolated fashion; they have to be solved with heat transfer equation, mass transfer equation, which will you know for constitute a more comprehensive and more detailed mathematical model.

So, therefore, the point that I am trying to make is that we are talking of solution of not just 1, 2, 3, 4 equations in steel making systems, where we have so much of complexity in that case, invariably we will see that in many situations we are going to have more than 6, 7 or 8 equations and solving these equations, you can imagine that when you have all this processes solidification and electromagnetic stirring for example in continuous casting, you have to solve the electro dynamics equation also and then additional equations will come into the picture.

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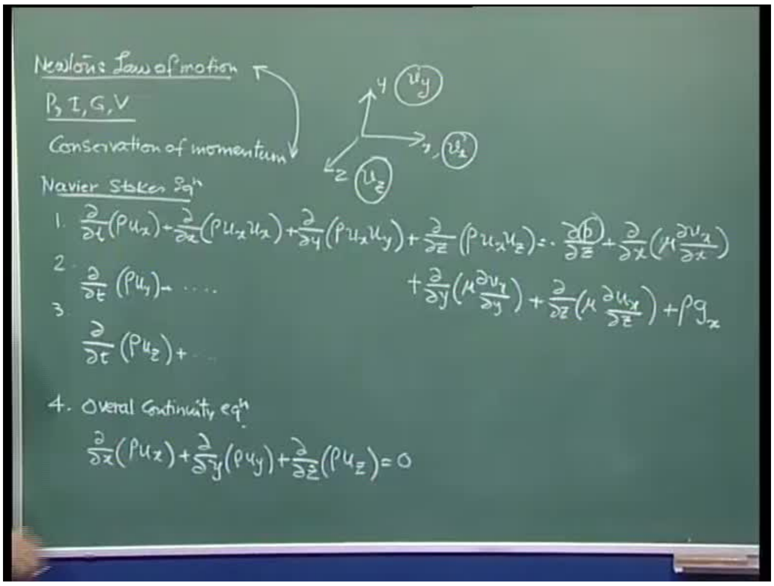

So, we are talking of solving of a number of non-linear mutually interlinked partial differential equations and you know, solving them… Now, you have to use computer to solve them and every time if you want to write computer course to solve this equations like a program you know, debug the program it is going to take really long time.

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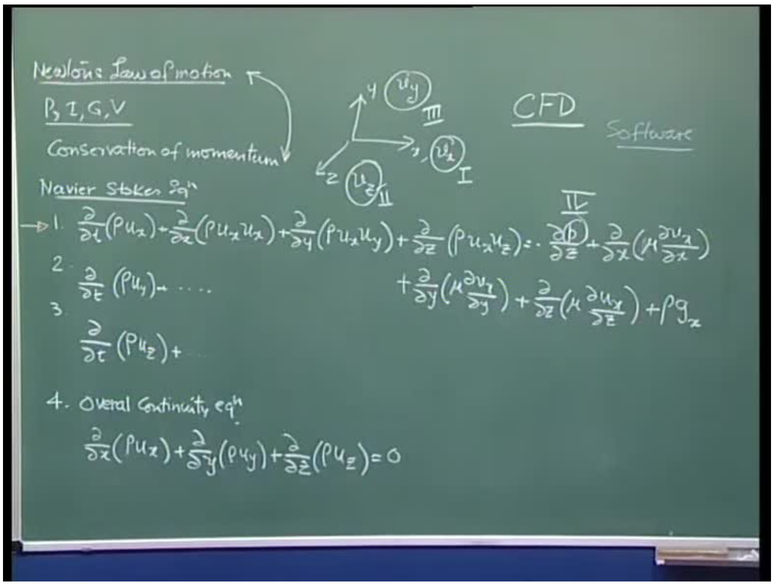

So, we have now very important software platforms, which are available to us and these softwares are basically CFD softwares - Computational Fluid Dynamics - softwares dedicated exclusively to the modeling of the kind of flow that we are talking about here; they can model multiphase flows; they can model multidimensional flow; they can model turbulent flow and… So, you do not write a computer program, but you formulate the problem, then you go to the computational or CFD software and use the CFD software to configure your problem and thereafter, you can solve the problems very conveniently.

So, when I talk of expertise in fluid dynamics, I talk of some knowledge in the theory of fluid flow; I am talking of some knowledge on computational fluid dynamics and some knowledge on CFD software.

But most of the time in order to know the state of the fluid flow, you will see that your theoretical background, your theoretical framework will comprise of the Navier strokes equation. This is the essential component and on top of this, we may have different segments also, the coming heat transfer, mass transfer, solidification, etcetera which may influence fluid flow.

But basically so far as the flow is concerned, in that case, we will have to solve the Navier Strokes equation and there we can take the course of to the computational fluid dynamics softwares, which are available in the market.

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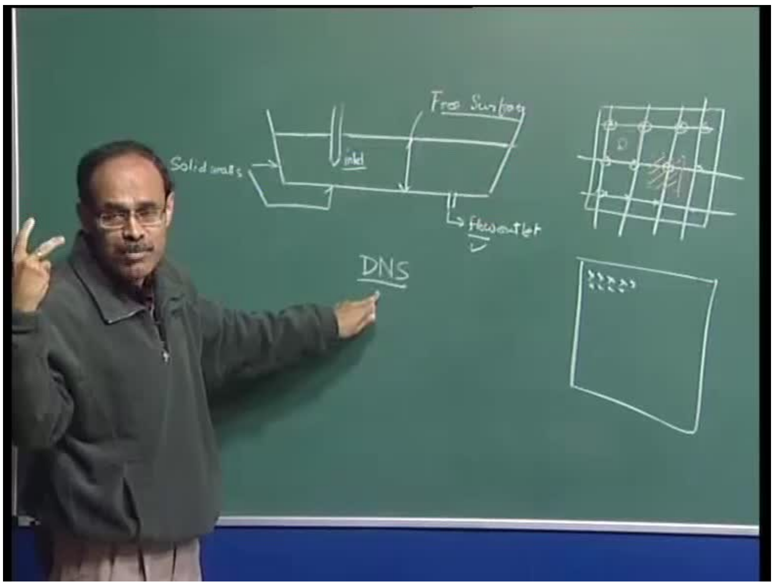

Let us now, you know discuss a little bit about the boundary conditions and boundary types that will give you some idea, because we have generated we will generate partial differential equations to predict fluid flow or melt flow in steel making systems and these equations will invariably require initial and boundary conditions. And let us look at typical characteristics of you know various physical boundaries in say steel making reactors.

So, always you will see that typically steel making reactors are going to be exhibiting solid walls, which will form the boundary of the vessels; this is also solid wall; we have a free surface. So, fiber forward surface in most of the cases when you are talking of melt flow in BOF, ladle, tundish, mold, etcetera four to five of our surfaces could be just the solid walls. For example, if you take the mold of continuous casting, you have copper coal mold and we have four surfaces of the mold, consider are the four physical walls or solid walls and also we have a free surface.

Free surface is a characteristic of steel making reactors. So, here because these are all batch reactors, you sometimes pour molten metal; you take out. So, you have a metal and ambient interface all the time. If you look at tundish, so this is the free surface; this is the these are the solid walls. So, you have in tundish there were front of solid wall, back solid wall, two side solid walls and the bottom solid wall.

So, you have five walls on the free surface and on top of that, you have a flow inlet and you have flow outlet, these are the general characteristics. of For example, at solid walls we know that there are can be no velocities. So, the velocities are going to be 0, no sleep condition. At the free surface, if it is stagnant, we know that the vertical component of the velocity is going to be 0, because it is stationary it is neither moving this way nor moving that way.

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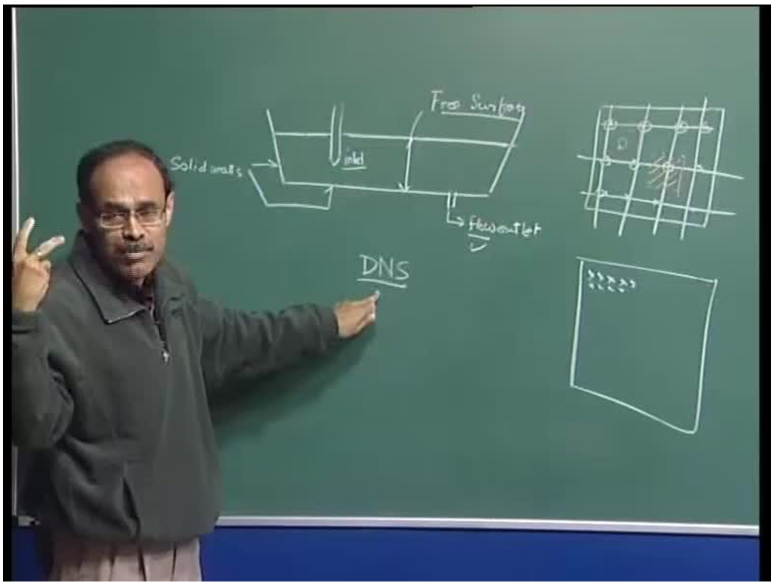

Note that we have three components of velocity, so on each of these surfaces, I have to write or to hide boundary conditions on each of the three velocity component; this is very important for us remember.

But nevertheless, inlet flows are known; outlet flows are also known in this particular case, because I am considering a steady state scenario. So, therefore, height remains same; so whatever is coming in, is exactly same, is going out. So, I will be knowing the velocities here; I will be knowing the velocities here, but I can… This is standard outflow procedure also that you will come to know later on as you know, take more advanced courses. So, the boundary conditions here can be prescribed in terms of the known flow rate coming from the ladle; here also it can be conveniently prescribed.

We have solid walls, the boundary conditions are standard forward straightforward, that is, all the velocity components are 0 and at the free surface, we say that the normal to the free surface component is 0 and transverse from radiant of the transverse components, these are the two transverse components on the free surface and their gradient is actually 0 at the free surface.

Alternatively, one can also calculate the geometry of the free surfaces through some standard techniques and then, impose the boundary condition, but these are really advanced things which I am not going to talk about here.

Now, so, we know the framework based on which the velocity field can be calculated; we have understood or we have at least appreciated the extent of complexity that is involved in calculating. those The equations that we generate are partial differential equations and we knowing the process, we should be able to provide the boundary conditions. So, there should not be any ambiguity as far as the key mathematical framework equations in boundary conditions are concerned in formulating fluid flow problem.

Now, coming to the issue of turbulence, I mention that, using solving the Navier strokes equation for turbulent flow is little bit difficult. Now, the point is that I mentioned, we want to we cannot solve the equations that I wrote here x component, y component and z component. You know by analytical means, you have to solve the equations in through numerical techniques. through a numerical technique. So, therefore, when you solve the equations through a numerical technique, we are oblige to use, the you know, suppose the reactor is there, I cannot have a continuous solution, but I have a discrete solution; I will select some points and then, say that I wish to get the value of the dependent variable; the dependent variables in this case are the velocity components v x v i v x, v y, v z , so I want to have the velocity in some discrete location.

So, I have a differential equation or a set of differential equations; I convert them into a set of algebraic equations and how do I convert? I apply a numerical method. So, the essential purpose of the numerical method is to convert the differential equation into algebraic equation.

Having obtain the algebraic equation, and these algebraic equations are derived for certain points so that continuous information of the differential equation is now lost, could not be discretized, you know the differential equation and derive the algebraic equations.

So, therefore, now, I can have solution here; I can have solution here; I can have solution here; I can have solution here. So, there are how do you know this points? These are the points that the person who is solving he desires.

For example, I can say, I need only 16 points on which the velocity distribution is needed. Someone else may say no, I do not want 16 points; I need 160 points. So, the person who is solving the equations, it is he who decides or you know the model or the person who calculates, he decides that how many locations he is going to need constitute these points.

So, this point at which the solution is sought is termed as a nodal point or the grid points. Now, we must understand that if you look at the structure here, so these are called the grid lines and the points are called the grid points.

Now, in turbulent flows, for example, you have eddying motions and the size of the eddies as you all know from your basic transport phenomena, can vary depending on where you are. You can have very smaller size eddies when you have go towards the wall; you have big eddies in the bulk of the liquid.

Now, if you want to resolve the motion within the small eddies, then obviously, these points need to be very close to each other. Now, if I have a motion here - an eddying motion here - and then, control volume is this big; I will not be able to see, that whether there is a gradient of velocity here or not here.

Because in this particular control volume, these nodes, it is a very big control volume and it has a characteristic velocity, so within this… So, every nodal point here, to make it specifically, every nodal point is associated with a control volume and the value of the v x is assumed to be prevalent generally over the entire control volume. So, if the size of the eddy is smaller than the control volume size, in that case the motion in the eddy cannot be resolved by the numerical thing itself.

So, therefore, when the flow is turbulent, when the length scales are very small, we are obligated to use points, which are not like this; but the points which may be extremely close to each other then only we can have tiny control volumes and these control volume size could be smaller than the size of the eddies and therefore, we should be able to resolve the turbulence motion of eddy.

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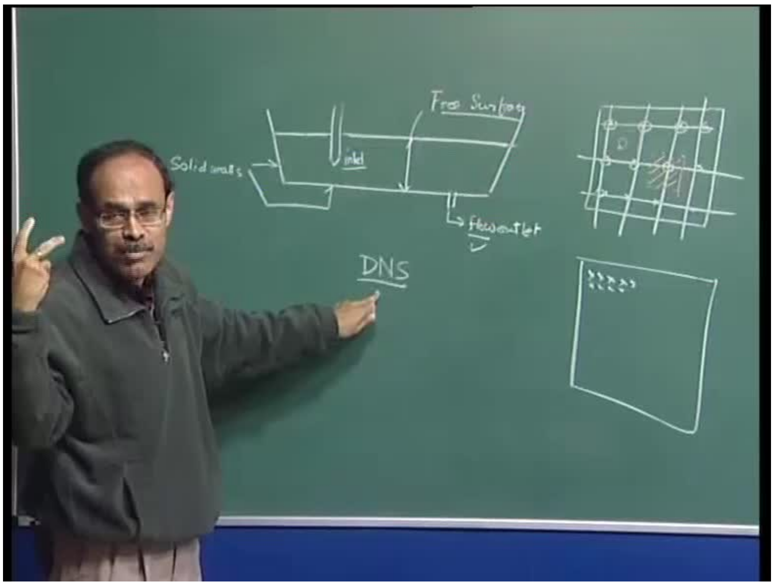

If that happens, then what we are talking of a huge steel making reactor 3 meter width, 3 meter depth. So, we are going to have, if the sizes of eddies are of the order of microns or millimeters, we can imagine that we can have millions of such nodal points and at every point. I have to solve equations, which are non-linear, multidimensional and not such one equation, I have to solve 8 to 10 equation.

So, we have to we will take an enormously long computed time in order to get a meaningful solution, if we consider construct extremely fine numerical grid in order to solve the fluid flow equations numerically.

So, therefore, this solution is basically termed as the direct numerical solution in turbulent flow regions. So, we will use Navier Strokes equation, but construct a very closely space nodal points or grid points while we seek the solution and then, solve the Navier strokes equation and obtain the details of the turbulent flow.

Solve the equations in an unsteady mode, because turbulence is rarely steady; it is time dependent process. Therefore, we will be constructing a very large number of nodal points and as a result of which as the number of nodal points are increasing, your computational class is also increasing

If I have these are means, there are so many unknowns to be known. In this case, there are, so for example 4 into 3 - 12 unknowns have to be obtained; in this case may be there may be 4000 unknowns. The way I have try to draw the nodal points, there may be 4000 or 5000 nodal points within and the domain itself.

So, finer is the grid or closer are the points, you will have to get more numbers. And therefore, to get more numbers, you have to do or the computer has to do more amount of computational work. Therefore, when you are talking of a practical size domain, we will see that well, the computational time may be going to one month, two month or three month therefore, as of now, with the largest computer on a routine daily basis, we cannot carry out DNS for steel making processes.

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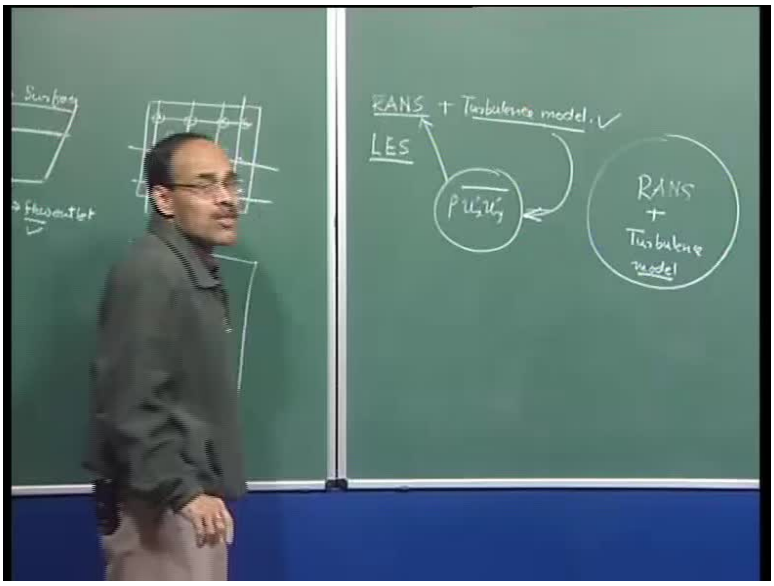

So, therefore, the equation - Navier Strokes equation - directly cannot be as of now applied. In principle, theoretically there is no problem, but because we face this practical difficulty that because our computers do not have that larger power today, that we can obtain the direct numerical solution just like that in 5 minutes; no it is not possible for such a big reactor.

So, because of this constraint, we seek an alternative approach and that alternative approach is called, I am just going to introduce this name and not discuss which is called the RANS- the Reynolds Average Navier Strokes equation.

So, some sort of a averaging of the Navier Strokes equation is done and thereby, the RANS equations are derived starting from the laminar flow equations or the exact Navier

Strokes equation to derive the RANS equation and this RANS equation then need a turbulence model.

So, RANS equation plus turbulence model, then we can use such as sparse grid; there is no problem, because we have averaged the behavior and we have other various techniques also. For example, there is a technique called LES - Large Eddy Simulation - just for your information I am giving you the name, but the point that I try to make is that the Navier Strokes equation, within extremely fine grid is still not a possibility for addressing all steel making problems.

So, we try to look at an alternative way of predicting the flow in steel making reactor and most commonly used approach is the Reynolds Average Navier Strokes plus the turbulence model.

So, the moment you replace the Navier Stroke exact Navier strokes equation, now you have you have averaged it you obtain the Reynolds and average navier stroke equation, but in that equation typically one sees that there is an unknown turbulent shear stress term.

Say for example, these are the fluctuating velocity components and this is the time averaged. the product of the fluctuating velocity component. So, this sort of a term terms will be time average this equation and to because this is now an unknown term. So, we have four equations; you remember you have four equations, four unknowns, but when we have time averaged it, additional unknowns come into the picture and these additional unknowns are known as the turbulence shear stresses.

And to calculate this turbulence shear stresses, because four equation five unknowns means, we cannot solve them; we have to specify this turbulence shear stresses somehow and it is through the turbulence model that the turbulence shear stresses are prescribed.

And we may have equations also; directly written conservation equation written for the turbulence shear stresses, but normally traditionally in steel making literature you will see that people have used turbulence model and that turbulence model basically is the platform for calculation of the turbulent shear stresses.

So, RANS equation and turbulence model equations are going to be used always as a RANS plus turbulence; this becomes our… they have to be applied in conjunction. So, our as far as steel making is concerned, if you want to calculate the flow of melt in steel making reactors, in that case the fluid flow component or the flow model or the theoretical framework for melt flow calculation will comprise of the RANS equation and along with this, we will require a turbulence model.

And the purpose of the turbulence model is to the provide estimation or you know provide information on the distribution of the turbulence shear stresses. So, I repeat again, that we have originally four unknown's u x, u y, u v, u z and p.

And you have four equations, three conservation equation of motion and one continuity equation. So, problem is well defined; therefore, you time average it; we still have four unknowns, those four unknowns and on top of that, we have additional unknowns which are turbulent gases.

So, unless these are prescribed, we cannot solve the four equations in a close form. And therefore, how do you calculate this? How do you know this? This comes from the turbulence model; it is sufficient for you to know up to this particular model itself.

So, therefore, we can say that a flow model for a steel making reactor will comprise of the Reynolds average Navier Stroke equation plus the turbulence model. If we apply them in conjunction, you can obtain the time average velocity now, because this time averaging is… because turbulent flow is what?

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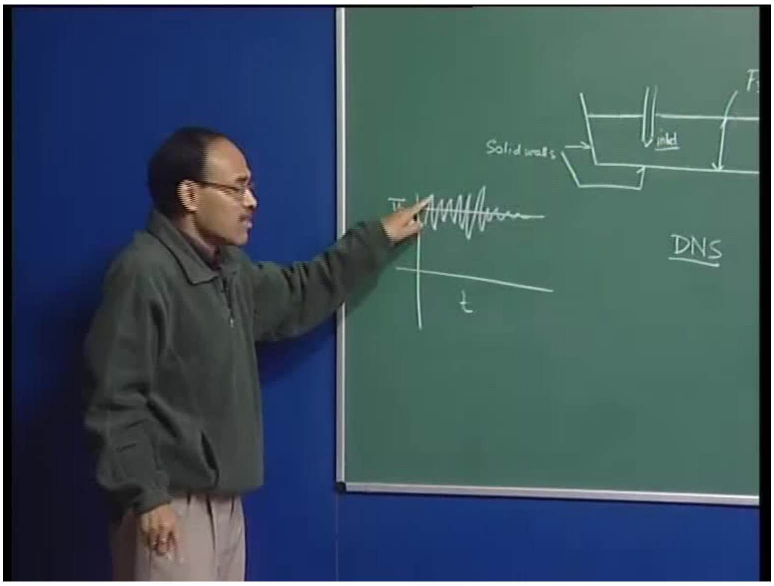

The turbulent flow, for example, if you see steady turbulent flow, for example, you can say that it goes random fluctuations at the characteristics of the turbulence and this is the steady state.

So, if you put a probe inside a turbulent flow, in that case you will see that there are random fluctuations with high frequency, which is the characteristics turbulent flow and then, this can be averaged and this now represents what is known as a time average velocity. And when you solve the RANS equation, you do not get the instantaneous velocity directly; you get an idea about the time average velocity and it is this time average velocity, you use in your melting weight calculation, mass transport calculation, two fluid interaction calculation, drag force calculation and so on.

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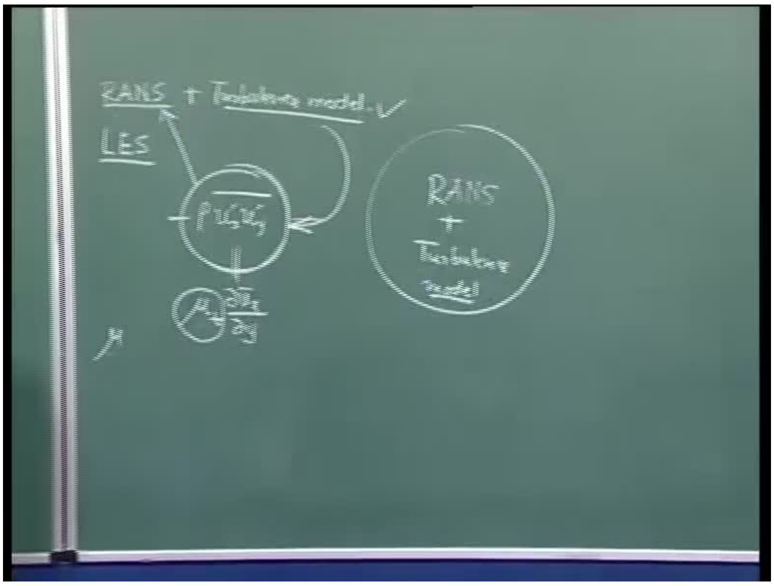

One last point that I want to say that this term -Reynolds stress term- is the essentially formulated in terms of, if you put a minus sign and you can say the turbulence viscosity and the velocity gradient, so we have if this is only in meaningful velocity gradient is this d v x over d y.

And this is the now the time average velocity component. So, this is no more the unknown; this is as the part of this is there in the RANS equation. So, estimation of the shear stress - turbulent shear stress- essentially boils down to the knowledge what is known as the turbulence viscosity.

And this turbulence viscosity basically is a fictitious quantity; do not confuse it with laminar viscosity. Dynamic viscosity or mu is a property of the fluid, which depends on the state of the system; pressure and temperature are constant that means mu is constant.

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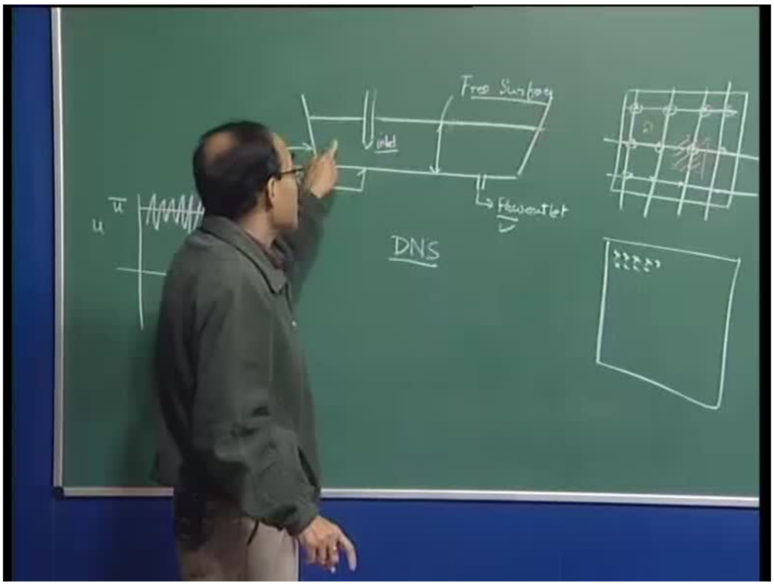

Mu t on the other hand is turbulence viscosity and that varies from one point to another point in the system, because it depends on… So, basically now going to the root of the problem, what does turbulence model do?

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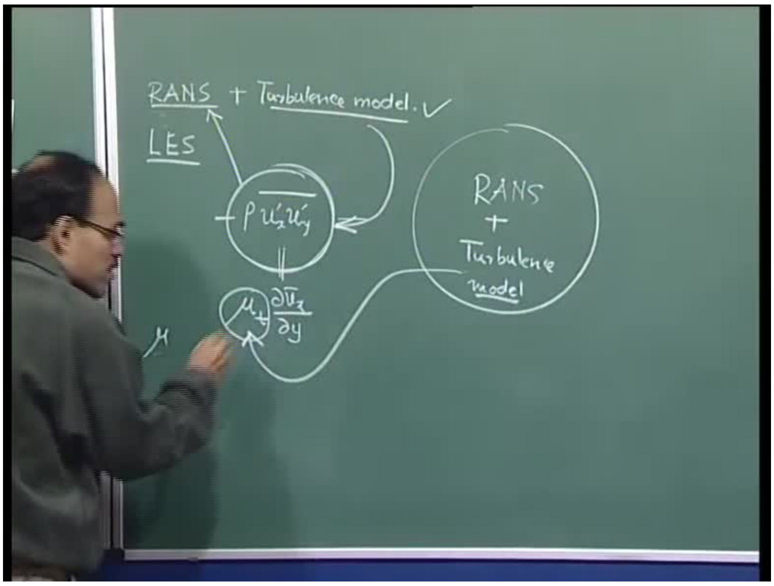

The turbulence model actually provides us the distribution of mu t in the domain through an appropriate mathematical framework. So, we obtain mu t from the turbulence model; we substitute that mu t into the RANS equation, then the RANS equation boils down to four equations, four unknowns and we are in a position to solve and obtain meaningfully the velocity fluid, which are prevalent in steelmaking reactor.

Thank you.