Transport Phenomena.
Professor Sunando Dasgupta.
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Lecture-01.
Introduction Newton's Law of Viscosity.

Good morning, today we are going to start a very basic fundamental course in chemical engineering which is also of relevance in several other disciplines, for example in mechanical engineering, in biotechnology and several such disciplines where we would get a transport of momentum, mass or heat and in many cases these processes are coupled. So, in this course we are going to see how these seemingly different processes are interrelated and whether or not an unified approach to heat, mass and momentum transfer can be provided within the framework of several governing differential equations and their solutions.

But before we get into the course, let us 1st describe about the structure of how this is going to be, going to be conveyed, the, my name is Sunando Dasgupta and I am a professor of chemical engineering at IIT Kharagpur. I had been teaching this course for quite some time, so I have a fair idea of what is going to be needed when trying to convey some ideas to the students and this course will also have tutorial components, where 2 of the, 2 of my senior Ph.D. students would help me in designing and in answering some of the questions that you may have regarding whatever I have taught in the previous classes.

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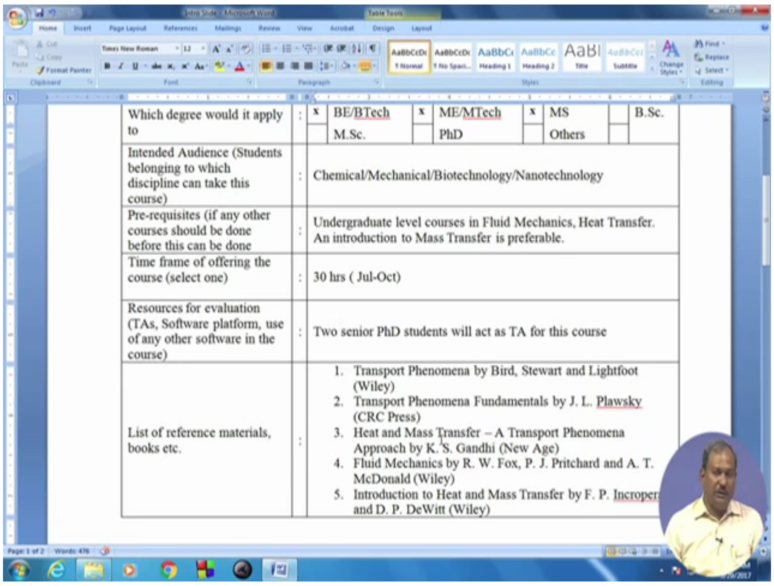

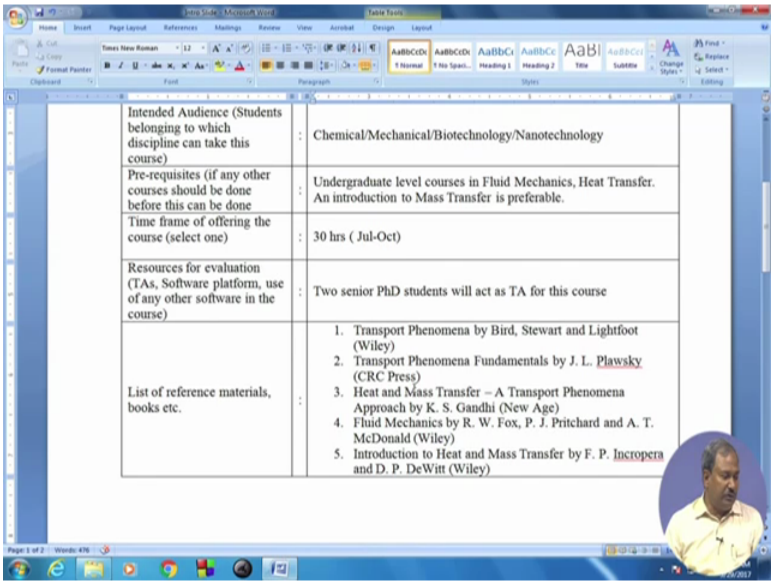

So this course is primarily designed for senior undergraduate students, final year undergraduate student as well as it would be of relevance to master students, MS and so on. And initially I have written down the disciplines in which this course should be relevant would be chemical, mechanical, biotechnology and nanotechnology but there would be several applications in other areas of engineering which would use same concepts as I am going to cover in this course.

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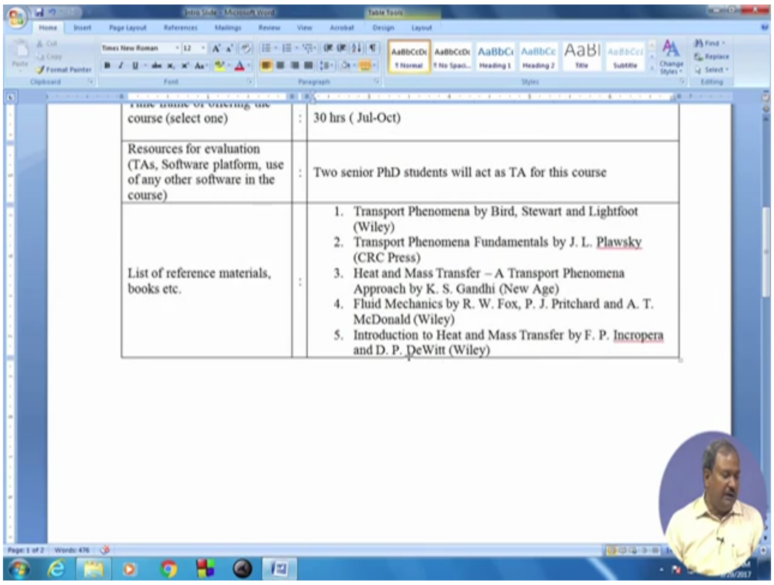

The prerequisite for this course, I expect that you would have an undergraduate level course in fluid mechanics and in heat transfers and introduction to mass transfer is preferable but is not mandatory. So you would see how these courses can be tied together through unified treatment. The courses will have a few textbooks and several reference books. The books that

I am going to follow, which you would get most of the information that I am going to present, they are transport fundamental, a very classical book by Bird, Stewart and Lightfoot.

Then transport phenomena fundamentals by JL Plawsky, heat and mass transfer, a transport fundamental approach by Prof KS Gandhi of IIC Bangalore, fluid mechanics by Fox and McDonald and introduction to mass transfer by Incropera and Dewitt. Now, I will talk about the course plan a little later but let us 1st try to see what is transport phenomena.

For example, when you have a flow of fluid through a conduit, then you could, you should we should be able to derive an equation which should give you the pressure drop and flow rate, the relation between the pressure drop and flow rate of a specific fluid through a conduit of known diameter. Since the geometry is known, you should be able to model the fluid flow process in such a way that the fundamental equation when integrated with appropriate boundary conditions would give you the velocity distributions of the fluid inside the tube.

Now this velocity distribution is very important, because the, the treatment of this equation, when you, let us take the gradient of this velocity profile near the wall, it can be used to calculate what is the force exerted by the solid on the fluid in a direction reverse to the flow. So when a fluid flows along an inclined plate, there will also be forces or interactions between the liquid and solid surface and the interaction is essentially governed by a property which is known as viscosity.

So whenever we have viscosity, whenever a fluid layer flows over another layer, there would be some interactions between the 2 layers, one on top and one at the bottom and as a result of which the faster moving fluid would try to drag the slower moving fluid along with it and as I move away from the faster moving layer, the velocity of the fluid layers will progressively decrease. So this is a unique process, unique phenomena which is prevalent in liquids to some extent, present in gases and this material property of the fluid essentially dictates how much pressure drop you can expect when the fluid flows through a pipe.

When you think about heat transfer, you all know that heat transfer takes place whenever there is a difference in temperature between 2 points. If we think about heat conduction, then it is not the temperature in between 2 points are important in calculating the total amount of heat transfer, it is also the distance between the 2 points that also plays a critical role in evaluating what is the total amount of heat transfer between 2 points. So it is not the temperature difference that is important, it is the temperature gradient within important.

Similarly mass transfer we would see that the total amount of mass transfer by the diffusive process, by the diffusion process which is molecular in nature would depend not only on the concentration difference of a species between 2 points but it would depend on the concentration gradient as well. Now these concepts are phenomenological concepts, you see the results, you try if there is a relation in between these processes and you come up with some relations with them becomes a governing or defining equation of certain material properties.

I will go into that a little bit later. But the fields of engineering have come a long way but we are still trying to find out what is the science behind any process. So it is extremely satisfying to model a process from fundamental principles and try to derive an equation which should be, which should, we can use to find out the processes in terms of mass transfer, in terms of heat transfer or in terms of momentum transfer.

So the 1st emphasis of or the 1st emergence of transport phenomena originated sometime in 1960 with the publication of seminal book transport phenomena by Bird, Stewart and Lightfoot, when these 3 faculties from University of Wisconsin, they have shown that it, it has been taught, the 3 processes, heat transfer, mass transfer, momentum transfer can be taught together, because the basic principles of operation that the ones these processes are similar in nature.

So it is the similarity or the thread in between these processes that we would like to explore in this specific course of transport phenomena. Another advantage of trying to design, trying to develop the fundamental equations from 1st principles is that many a times with the emergence of new technologies, new areas, new applications, you will come across situations where no fixed relation exists or even the correlation is also not present. So you would like to know, if you like to design something, if you like to apply, if you like to upgrade a laboratory process into pilot plant and beyond, you need to know the fundamental aspects of different processes.

What is important? Is the temperature difference important, temperature gradient important, is the velocity over which the liquid, the hot liquid flows over the cold surface is important, which Thermo physical properties are important, can these properties be grouped together in order to obtain certain dimensionless groups, dimensionless parameters, the similarity parameters that would, that would tell you about the similar behaviour of different fluids only if those numbers are the same.

So an offshoot of studying transport phenomena is not only understandings the process but also identifying the dimensionless groups, the numbers which are going to be important in deciding the amount of heat and mass transfer, the amount of momentum transfer that one would expect. Additionally these dimensionless numbers would also tell you that if these numbers are constant, then it is possible and I will show in the later part of the core how it would be possible to use the correlation developed for heat transfer as the correlation for mass transfer.

The only thing you need to know is that the appropriate mention less constants must be used for heat transfer, for mass transfer and for momentum transfer. So if you identify and if it is possible that the equation for let us say mass transfer can be solved for a specific process using certain simplifications, then you need not have to solve the heat transfer equation once again, you simply use the relation that has been obtained for mass transfer as the relation for heat transfer if you simply substitute the dimensionless numbers for relevant to mass transfer by that of the heat transfer and so on.

So it gives us that this specific course, the ideas developed in this course, they give us a very strong handle on the understanding part. It is the science of engineering with which we will be more interested and try to see what is the fundamental guiding principle of designing and modelling an engineering process and how universal the development is across the different processes.

So, that is extremely important, in the, as I mentioned before with the advent of new technologies, new areas, new concepts, you would always like to have a strong background of these transport processes for all these processes, new processes to scale up, how to scale up and go from the laboratory scale to the commercial production, unit to have an idea of the, of the determining steps in terms of fundamental concepts as developed in this course.

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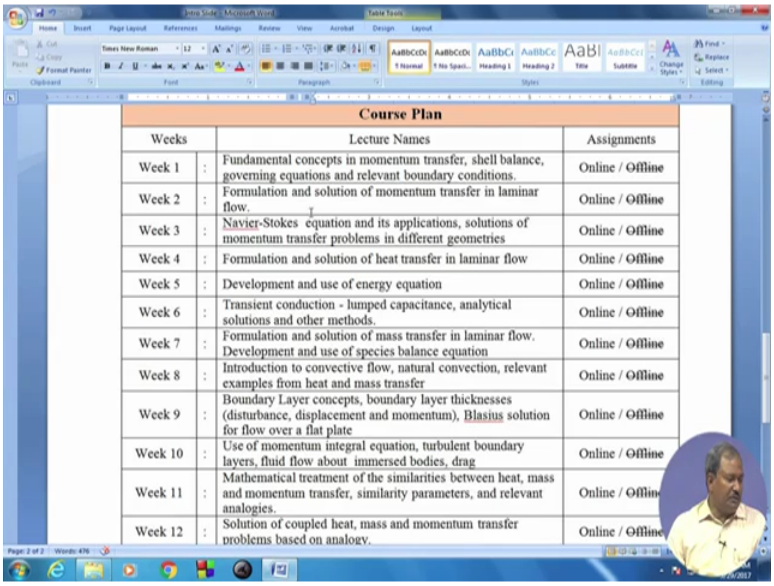

Course Plan			
Weeks		Lecture Names	Assignments
Week 1	:	Fundamental concepts in momentum transfer, shell balance, governing equations and relevant boundary conditions.	Online / Offline
Week 2	:	Formulation and solution of momentum transfer in laminar flow.	Online / Offline
Week 3	:	Navier-Stokes equation and its applications, solutions of momentum transfer problems in different geometries	Online / Offline
Week 4	:	Formulation and solution of heat transfer in laminar flow	Online / Offline
Week 5	:	Development and use of energy equation	Online / Offline
Week 6	:	Transient conduction - lumped capacitance, analytical solutions and other methods.	Online / Offline
Week 7	:	Formulation and solution of mass transfer in laminar flow. Development and use of species balance equation	Online / Offline
Week 8	:	Introduction to convective flow, natural convection, relevant examples from heat and mass transfer	Online / Offline
Week 9	:	Boundary Layer concepts, boundary layer thicknesses (disturbance, displacement and momentum), Blasius solution for flow over a flat plate	Online / Offline
Week 10	:	Use of momentum integral equation, turbulent boundary layers, fluid flow about immersed bodies, drag	Online / Offline
Week 11	:	Mathematical treatment of the similarities between heat, mass and momentum transfer, similarity parameters, and relevant analogies.	Online / Offline
Week 12	:	Solution of coupled heat, mass and momentum transfer problems based on analogy.	Online / Offline

So we are 1st going to see in this, the 1st few lectures would be on fundamental concepts of momentum transfer which you already know, which you already know through your studies of fluid mechanics. Then we are going to talk about a new concept which is Shell balance, it is essentially a force balance method that we would, we are going to see in this and how this Shell balance can lead to the governing equations for the case of let us say momentum transfer and what are the relevant boundary conditions one would expect in the case of fluid flow or momentum transfer.

So the formation and solution of momentum transfer in laminar flow we would see. And then it would automatically be apparent that many of the processes, many of the processes that can be handled by a simple Shell balance are very simple in nature. So whenever the geometry is slightly complicated, you would probably like to have more generalised approach and the Shell balance methods cannot be used in such cases.

So one of the generalised processes, generalised methods of analysing any momentum transfer comes from the application of Newton's 2nd law for open systems and this should give us an equation which is known as the equation of motion and or in more common terms it is known as the Naviar Stokes equation.

So Naviar Stokes equation is a very powerful equation, very powerful tool which can be applied, it is, it is a long equation but in many cases you would feel by simply using the geometrical constraints or your understanding of the length scales, you would be able to discard many or neglected many of the terms in Naviar Stokes equation and which would give you very compact differential equation to solve with appropriate boundary conditions giving rise to fundamentally what is the velocity distribution.

So this approach is also known as the differential approach. Anything that you, any equation that you, that comes out of your interest, of your work with differential approach is going to be valid at every point in the flow field. So the velocity expression that you are going to get if you can solve, if you can formulate the problem appropriately would be valid at every point.

So that is differential approach, which has, which is, which is important but there is another approach which is known as integral approach and we will work about that as well wherein we are not interested in what happens at every point in the flow field but what happens on an average basis. So we are talking about the average velocity and not the point velocity, so the integral approach will come later on.

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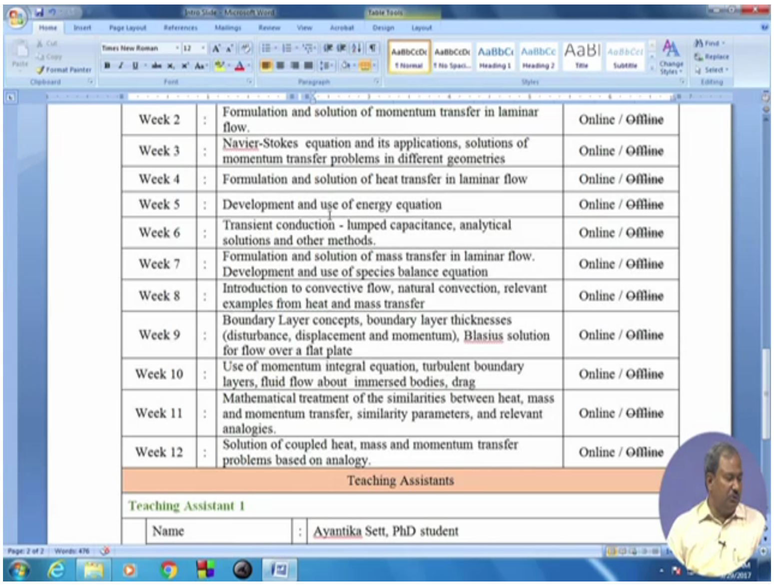

Week 2	:	Formulation and solution of momentum transfer in laminar flow.	Online / Offline
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Teaching Assistants			
Teaching Assistant 1			
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Similar to momentum transfer, we are going to formulate and solve few heat transfer problems in laminar flow and then again as with Naviar Stokes equation, we would try to develop an energy equation which is a fundamental equation that takes into account all sorts of energy transport modes. For example condition, convection and whenever there is in a system, it is possible that it, there may be heat generation, it could be a nuclear reactor which you are trying to model, so there will be heat generation term, there could be, the fluid is probably flowing at a very high velocity, so the layers of fluid will flow past each other with sufficiently high relative velocity such that there would be frictions between these liquid layers exactly same as that between 2 solid surfaces.

And these frictions will give rise to some heat generation. So heat generation by external sources, heat generation by the flow of fluids flowing past each other, the work done by the system author was done on the system, all these will constitute different terms of the energy equation. So we will derive and we will discuss, simplify and solve energy equations with relevant boundary conditions, again the goal is to obtain the temperature field, the temperature at every point in the flow field which can then be used to derive quantities of engineering importance, such as what is the convective heat transfer coefficient, we will see that subsequently.

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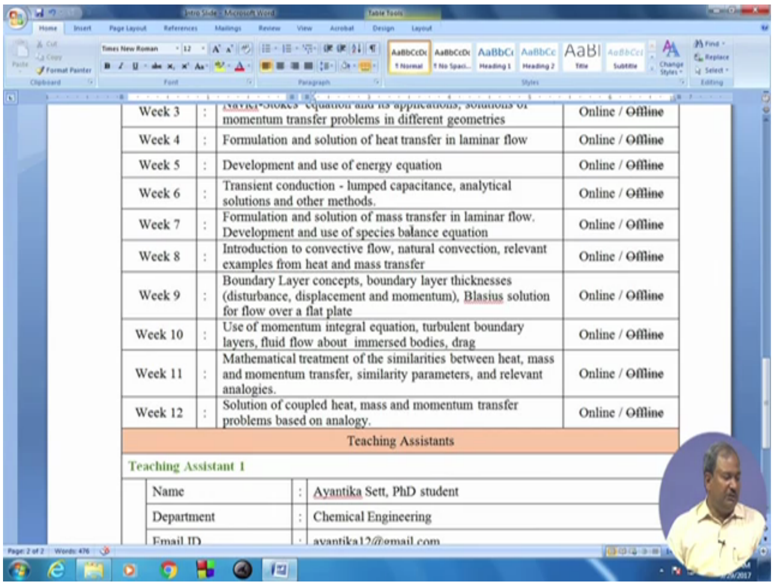

Uhh This the same can be, will be done also for mass transfer in laminar flow and we will use equation as in Naviar Stokes equation or in energy equation, the species balance the equation which is nothing but the mass balance equation, the equation of continuity, the conservation of heat and mass transfer. And towards the 2nd part of this course, we will introduce a very important concept which is known as the boundary layer concept.

What we would see later on, it becomes apparent that all these transport processes that we are talking about, discussing about will take place very, in a in a region very close to the interface. So if we are thinking about heat transfer and the liquid is in contact with a solid, then most of the heat transfer between the liquid and the solid takes place in a layer which is very close to the solid surface. So across the interface the temperature changes rapidly from the wall temperature to a temperature which more or less remains constant for throughout the body of the fluid.

So this region in which the temperature essentially drops from that of the wall to that of the liquid, to that of the liquid which more or less remains constant, this region is known as the boundary layer. The same concept is also valid when a fluid layers moves over a solid layer and then it is, it can be shown that the velocity of the fluid which is moving on the top, on the plate, on the stationary plate, I would vary from a value equal to 0 to a value equal to the free stream velocity, the velocity of the bulk air moving above the plate in a region which is very close to the solid surface.

So, this thin layer in which the velocity, the temperature or the species concentration changes from its value on the wall to the value which is the value at the bulk liquid is known as the boundary layer. And this boundary layer has immense uses fundamentally, conceptually as well as in terms of deriving equations for heat, mass and momentum transfer between a solid surface and a liquid surface when there is relative motion, when there is a difference in temperature or when there is a difference in concentration of one of the species on the surface and in the liquid.

The concept of boundary layer, the historical perspective of boundary layer, the additional simplicities, simplifications that it brings to everyday problems is going to be extremely important and that is what we are going to study, the boundary layer thickness, the behaviour of the heat, mass and momentum transfer in the thin boundary layer that we will extensively discuss and try to get the science behind, the science involved in those transport processes in that part of the course.

We will also show that in some cases the solution of boundary layer equations, the boundary layer would be simplified if we use an integral approach. So there is something called a momentum integral equation which we would see and which we would extensively used for the solution of turbulent boundary, turbulent flows, turbulent boundary layers and it also leads to an associated part which is like fluid, what is going to be the drag, the expression for drag.

When fluid flows over an immersed body, there will, there will be a force experienced by the immersed body when the fluid flows over it which is commonly known as drag. We see that in everyday when we come to the classes, when we use our bicycles, when we use our cars, in planes and in rockets and in every , in any application where there is a moving part, there would be some force exerted by the surrounding fluid on that moving part which is known as drag.

So, how to measure drag, how to reduce drag, how to predict drag, that is a fundamental problem that any automotive engineer or any engineer would be would love to get in handle on. So we will try to see what are the fundamental expressions, the fundamental ideas, concepts which can be described, which can be explained by boundary layers and how that can give rise to situations where it will be possible to model such processes.

And finally we would come to the objective of the course. Is it possible to explain heat, mass and momentum transfer by same type of equations, by some sort of analogy which would tell as that under these specific conditions it is sufficient to have an idea of the heat transfer mechanisms, heat transfer processes that are taking place. So if you would like to know what is going to be the corresponding mass transfer equations for the same situations, you need not have to derive it once again.

The expression that we have obtained for heat transfer can be used as the expression for mass transfer. So what is the fundamental, what is the mathematical basis of making such a statement? When these seemingly different transport processes are equivalent such that one solution can be used for the other type of transport processes as well. So these analogies are extremely powerful tools because in many real-life applications you would come across situations where it would be extremely difficult to conduct experiments, develop a relation and then do another set of experiments and try to develop another set of expressions for let us say mass transfer.

So it is possible to do heat transfer experiments that are supposed that are easy to do but it is difficult to do the mass transfer experiment. So you do not do mass transfer experiments at all, you take the system in such a way that these 2 systems are geometrically similar and you ensure based on the ideas, based on the knowledge that you have gathered in these courses that what do you have to do in order to make the mass transfer process, the mass transfer situation equal well into a heat transfer situation.

So if you can make these 2 things equivalent, you do not need to work with mass transfer, the complicated mass transfer experiments anymore. So you drop that, you do all your experiments on the heat transfer which is let us say easy to do. So you do the experiments on your heat transfer system, derive relations and then simply project these relations for the mass transfer case that you have not done any experiment on.

So these similarities, analogies between heat, mass and momentum transfer is an extremely powerful tool for practising engineers as well as for scientists to predict what would be the transport process, what would be the quantity of heat transfer or mass transfer or momentum transfer if you know what is going to be the amount of transport in any one of these processes. So there are hundreds of different types of situations one can encounter, one will encounter in these cases where these processes are coupled.

Heat transfer is coupled with mass transfer and so on. So these coupled transport processes are mathematically very difficult to handle, okay. They would give rise to differential equations which depend on each other and a comprehensive solution of those cases in many of the situations would be extremely difficult. So these these analogies give us a powerful tool in to analyse, to understand, to analyse and to obtain results for similar such cases. So in a nutshell, that is what we are going to cover in this course.

So starting with the very fundamental transport phenomena modelling type of cases where with a shell transport, shelf balance, you would be able to obtain a difference equation, from a difference equation to a differential equation, you need to identify the boundary conditions, solve differential equation with these boundary conditions and obtain an expression of velocity. That is what we are going to do in the 1st few classes.

Then it would automatically comes to, automatically the apparent that these simple approaches would not, would not be viable for cases which are complex geometric, complex flow type and so on, so a generalised approach is needed. And we come up with Naviar Stokes equation.

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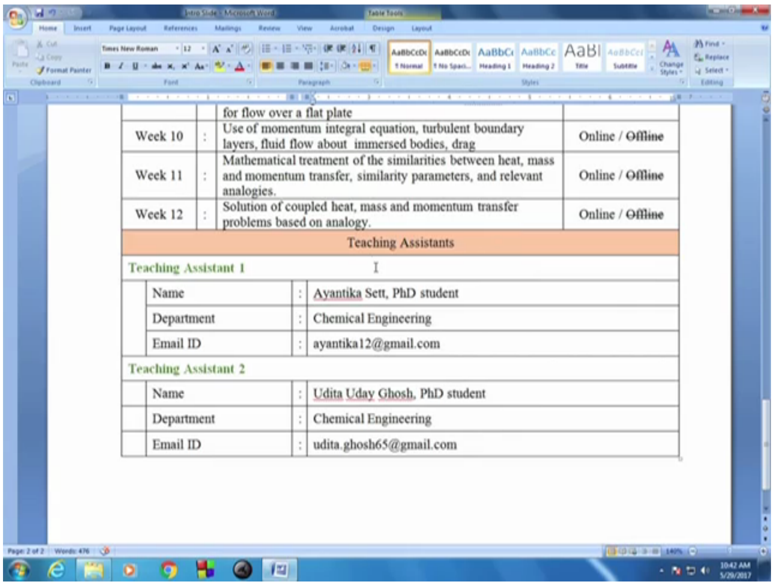

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So what I have tried to give you is in a nutshell what is the objective of the course, what are the topics that I am going to cover in this course, how they are structured and so on. So for, after I teach, maybe 3 or 4 such lectures, there would be tutorial components and the 2 TAs, which are 2 of my Ph.D. students, these 2 TAs would be available to you to answer any of your queries and also to assist you in in understanding because sometimes you will definitely have questions.

I expect that you are going to have questions and I would encourage questions all the time from you and these 2 Ph.D. students of mine, they would help you in your understanding, they would give you problems to work on and they would they would also provide you with assignments that you need to solve, submit and which would be continuously evaluated by by the TAs, and so together I think we are embarking on a journey to understand the transport phenomena, the transport processes starting with the very basic fundamentals, okay.

And it is going to be an interesting course because you are going to you are going to, you are going to have a paradigm shift of your understanding, of your understanding about how different processes can be modelled. And whenever you start to see the beauty of looking at different things in the same way, then it would not only broaden your horizon, it would give you a scientific impetus to solve problems, to model systems, to model unknown systems and at least try to see if you can get an approximate solutions to certain situations that are almost intractable if you would like to go through the rigorous mathematical way.

So there is a rigorous mathematical way for problems, for trying to model a situation and there is a simpler way if you understand the process. If you understand the interplay of the forces and their effects in any system, if you can understand the interplay of the different forces from different factors, different sources and if you can clearly identify under which condition a specific type of force is going to be important, a specific type is going to predominate, so that you need to consider only that and neglect all others.

So when you, when you would be able to decide about the importance of these forces, importance of these processes, then you would see that modelling a system from the fundamental point of view is going to be as fun exercise. So my objective of this course and I hope you would be able to appreciate and together we would come up with solutions of unique problems, unique problems that we encounter which seems very difficult.

But with your transport phenomena understanding, I am sure that you would be able to we will be able to work together in a more structured way or solutions that you would have never thought possible is in just these taking the 3 courses heat, mass, momentum transfer separately. So any suggestion is the key to this course, thank you.